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Speech-recognition Outcomes in Older Adults with Cochlear Implants: A Systematic Review

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ABSTRACT

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Health innovations are contributing to the ever-increasing human lifespan, but with humans living longer, new health challenges arise. Hearing loss that severely impacts the ability to understand oral communication is increasingly becoming a reality as humans live longer. For many older adults with hearing loss, hearing aids do not provide sufficient benefit to communication. An abundance of literature exists detailing the benefits of cochlear implantation on speech-recognition for post-lingually deafened adults. Research on the benefits of implantation for older adults is only beginning to emerge, and the outlook is promising. This systematic review provides evidence that, though more research is still needed, cochlear implantation in older adults is a viable treatment option.

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INTRODUCTION

A cochlear implant is an electronic device that enables sound to bypass damaged hair cells in the inner ear, thus providing sound to those with sensorineural hearing loss who receive very limited benefit with traditional amplification. The device consists of internal and external parts. The internally implanted parts include an electrode array placed in the scala tympani, receiver stimulator, antenna, and magnet. The external parts include a coil (or headpiece) that magnetically attracts to the internal magnet, cable connecting the coil to the processor, microphone, and battery pack. Sound picked up by the microphone is converted into a digital code that is transmitted via the antenna. Electrical impulses then traverse the electrode array, which in turn stimulates the auditory nerve.

Since receiving Food and Drug Administration (FDA) approval in 1985, cochlear implantation candidacy criteria continue to expand to enable the device to be applicable to increasingly wider groups of persons with sensorineural hearing loss. Initially, cochlear implants were approved for adults with post-lingual bilateral, profound sensorineural hearing loss and 0% speech-recognition score. In 1990, the cochlear implant criteria expanded to include children older than 24 months with pre- or post-lingual profound sensorineural hearing loss and 0% speech-recognition score. The criteria further expanded in 1998 to include (a) adults with pre- and post-lingual bilateral severe to profound sensorineural hearing loss with speech-recognition scores not exceeding 40%; and (b) children at least 18 months of age with bilateral, severe to profound sensorineural hearing loss and speech-recognition scores below 20%. Recently, criteria for cochlear implantation in adults have broadened to include those with bilateral, moderate to profound sensorineural hearing loss with an aided speech-recognition scores of 50% or poorer in the ear to be implanted in conjunction with an aided speech-recognition score of 60% or poorer in the opposite ear. The cochlear implantation criteria for children now includes bilateral, severe to profound sensorineural hearing loss and lack of auditory progress when utilizing amplification. Candidacy continues to expand as successful outcomes are documented and technological and surgical advances are made.

The hybrid cochlear implant, a device that preserves acoustic hearing in the low frequencies, received FDA approval as recently as 2014.

Successful speech-recognition outcomes for implanted children and adults have been well documented. For example, Leigh et al. (2013) examined the language development of 120 children who were implanted between 6 to 24 months of age. They found that children who undergo implantation by their first birthday demonstrate the same language growth rates as their peers with normal hearing. Following 3 years of consistent implant use, these children are able to achieve age-appropriate receptive language scores. On the other hand, children who undergo implantation between 13 and 24 months of age demonstrate significantly delayed language ability at their 3-year follow-up. Niparko et al.'s (2010) findings, based on a longitudinal investigation, are similar to those of Leigh et al; they also concluded that the age of implantation significantly affects language ability. Svirsky et al. (2000) concluded that children with cochlear implants develop language significantly more rapidly than the predicted rate of development for deaf children who do not receive a cochlear implant.

Gaylor et al. (2013) conducted a meta-analysis of speech-recognition outcomes for post-lingually deafened adults, based on 42 studies. They concluded that the findings of the vast majority of studies showed significant improvement in speech-recognition performance post-implantation as compared with pre-implantation. These findings are in agreement with those of Krueger et al. (2008) who observed, based on analysis of over 864 adult recipients of cochlear implants,that significant improvement in speech-recognition ability continues over time post-implantation in both quiet and noise conditions.

A paucity of studies exists on speech-recognition outcomes for older adults who have undergone cochlear implantation. The aim of this systematic review is to examine speech-recognition performance in quiet and noise for older adults who have received cochlear implants. A secondary aim is to compare these findings for older adults with the findings in younger adults who have received cochlear implants.

METHODS

A comprehensive search of the literature was performed via the Graduate Center of the City University of New York Mina Rees library using Medline Complete and Google Scholar with the aim of identifying studies on speech-recognition outcomes in quiet and noise for older adults (65 or more years of age) who have undergone cochlear implantation. The search strategy utilized the keywords “cochlear implant” and “speech recognition” or “speech perception”. The criteria for inclusion of studies were age 65+ years and publication in the English language. Abstract review then was conducted to eliminate irrelevant or duplicative studies. All studies included in this review involve participants with post-lingual sensorineural hearing impairment that use unilateral or bilateral cochlear implants.

RESULTS

Based on an extensive review of the literature, fourteen studies were identified that are appropriate for analysis in this systematic review. Table 1 details study design and outlines participant characteristics. As can be seen from inspection of Table 1, all studies included in the analysis are retrospective

Table 1. Participant characteristics.

Authors, year	Research design	OA[a] sample size (N)	YA[b] group sample size (N)	OA mean (SD) AAI[c] in years	YA mean (SD) AAI in years	OA duration of deafness mean (SD) in years	YA duration of deafness mean (SD) in years	Etiology of hearing loss in the OA	Etiology of hearing loss in the YA
Budenz et al 2011	Retrospective case-control	N=60	N=48	76.0 (4.0) Range 70-86	47.9 (10.8) Range 22-62	34 (21.4) Range 0.33–74	23.4 (17.9) Range 0.5-55	Progressive, SSNHL[d], otosclerosis, familial, Meniere’s, infection, noise exposure, autoimmune	Progressive, SSNHL, otosclerosis, familial, Meniere’s, infection, noise induced, autoimmune, trauma, ototoxicity, neoplastic
Dillon et al 2013	Retrospective chart review	N=14 M[e]=8 F[f]=6		70 (4.5) Range 65-80				Idiopathic	
Friedland et al 2010	Retrospective case-control	N=78 N=28	N=28	73.3 (6.7) Range 65-87	46.7 (13.4) Range 18-64	5.75 (19.1) Range 1-74			
Hast et al 2015	Retrospective case-control	N=25 M=14 F=11	N=25 M=14 F=11	79 (3) Range 70-89	59 (12) Range 35-74			Idiopathic, SSNHL, otosclerosis, familial, Meniere’s, noise exposure	Idiopathic, SSNHL, otosclerosis, familial, Meniere’s, noise exposure
Labadie et al 2000	Retrospective case-control	N=16	N=20	71.5 (1.2) Range 65-?	46.9 (2.6) Range 18-64	12.5 (3.4)	9.6 (2.3)	Idiopathic, SSNHL, noise exposure, syphilis, progressive congenital syndrome	Idiopathic, noise exposure, Lyme disease, rheumatic, ototoxicity, progressive congenital syndrome, cholesteatoma, neoplasm, SSNHL
Mahmoud and Ruckenstein 2014	Retrospective case-control	N=43 M=23 F=20	N=27 M=11 F=16	75.7 (-) Range 65-87	53 (-) Range 20-64	4.1 (-)	4.8 (-)	Idiopathic, familial, otosclerosis	Idiopathic, autoimmune, familial, infection, otosclerosis,
Olze et al 2012	Retrospective case-control	N=20 M=10 F=10	N=35 M=10 F=25	74.4 (4.6) Range 70-84	- Range 19-67	13.1 (16.1) Range 1–70	13.4 (14.5) Range 0.4–41	Idiopathic, noise exposure, familial, otosclerosis, ototoxicity, measles, viral, scarlet fever	Idiopathic, noise exposure, familial, measles, Meniere’s, meningitis, autoimmune
Park et al 2011	Retrospective case-control	N=50 M=20 F=30	N=61, 50 M=42 F=69	73 (-) Range 66-85	40 (-) Range 21-50 59 (-) Range 51-65			Idiopathic, familial progressive, early progressive, otosclerosis, Meniere’s, autoimmune, chronic serous otitis media	
Roberts et al 2013	Retrospective case-control	N=67 M=37 F=30	N=46 M=25 F=21	75.5 (0.9) Range 65-?	49.5 (1.5) Range ?-64	24.23 (2.1)	18.73 (2.03)		
Sanchez et al 2013	Retrospective case-control	N=37	N=44	73 (-) Range 70-82	64 (-) Range 60-69			Progressive, ototoxicity, Meniere's, trauma, familial, otosclerosis, SSNHL, infection, chemotherapy	
Vermeire et al 2005	Retrospective case-control	N=25	N=33, 31	74 (-) Range 70-83	42 (-) Range 17-55 62 (-) Range 56-69			Progressive, otosclerosis, familial, meningitis, other	Progressive, other, familial, otosclerosis, temporal bone fracture, meningitis, ototoxicity
Waltzman et al 1993	Retrospective chart review	N=20 M=9 F=11		70.9 (-) Range 65-85				Idiopathic, meningitis, otosclerosis, trauma	
Wong et al 2015	Retrospective chart review	N=150 M=57 F=93		- (-) Range 75-79; 80-84; 85-?					
Zwolan et al 2013	Retrospective case-control	N=18 M=11 F=9	N=20 M=9 F=11	74.88 (-) Range 65-89	53.51 (-) Range 18-64	27.44 (-)	18.58 (-)	Idiopathic, noise exposure, familial, otosclerosis, measles, Scarlet fever, viral, ototoxicity	Idiopathic, noise exposure, autoimmune, measles, familial, Meniere’s, meningitis

Table 1. [a]OA=older adult [b]YA=young adult control [c]AAI=age at implantation [d]SSNHL=sudden sensorineural hearing loss [e]M=male [f]F=female S=significant difference between groups NS=no significant difference between groups -=not statistically analyzed

in design, with eleven being case-control studies and three being chart reviews. Participants were separated into two groups: an implanted older adult group essentially consisting of participants 65 years old or older and an implanted younger adult control group consisting of participants 18-64 years old. Eleven of the 14 studies (79%) utilized a control group of younger adults with cochlear implants. Nine of the 14 studies (64%) compared older adults' pre-implantation scores to their post-implantation scores at various follow-up times. Four studies (29%) included in the analysis utilized 70 rather than 65 years of age as the lower limit for the older group (Hast et al. 2015; Park et al., 2011; Sanchez et al, 2013; Vermeire et al., 2005). The upper age limit is identified in eleven of the 14 studies (79%), with the mean upper age limit being 85 years old, as can be seen in Table 1.

As can be seen from inspection of Table 1, the sample size in the older adult group ranged from 14-150 with 50% of studies comprising fewer than 30 older adults. The sample size in the control group ranged from 20-61 with 45% of studies comprising fewer than 30 younger adults. In the nine studies that identified participant gender, the number of males and females tended to be evenly split. The overall mean age of participants in the older adult group across studies was 74 years, compared with 48 years in the control group. Duration of deafness was closely matched between groups, although the older adults were more likely to have a longer duration of deafness. Etiologies of hearing loss are listed in the order of prevalence, with idiopathic hearing loss implicated as the most common in both groups.

Table 2 shows the cochlear implant status and type of cochlear implant in both participant groups.

Table 2. Implant information.

Authors, year	CI status	Control CI status	(# of CIs) type of CI	Control (# of CIs) type of CI
Budenz et al., 2011	Unilateral=60 Bilateral=0	Unilateral=48 Bilateral=0	(52) Cochlear Corporation (8) Advanced Bionics	(46) Cochlear Corporation (6) Advanced Bionics
Dillon et al., 2013	Unilateral=14 Bilateral=0		(3) Advanced Bionics (2) Cochlear Corporation (9) Med-el	
Friedland et al., 2010				
Hast et al., 2015	Unilateral=22 Bilateral=3	Unilateral=18 Bilateral=7		
Labadie et al., 2000			(16) Advanced Bionics CLARION Multi-Strategy	(20) Advanced Bionics CLARION Multi-Strategy
Mahmoud and Ruckenstein, 2014	Unilateral=43 Bilateral=0	Unilateral=27 Bilateral=0		
Olze et al., 2012	Unilateral=20 Bilateral=0	Unilateral=35 Bilateral=0		
Park et al., 2011	Unilateral=50 Bilateral=0	Unilateral=61, 50 Bilateral=0		
Roberts et al., 2013	Unilateral=67 Bilateral=0	Unilateral=46 Bilateral=0	(18) AB HiRes 90K/HiFocus Helix (29) AB HiRes 90K/HiFocus 1j (4) Cochlear Freedom/Contour (11) Nucleus CI512/Contour Advance	(10) AB HiRes 90K/HiFocus Helix (2) AB HiRes 90K/HiFocus 1j (7) Cochlear Freedom/Contour (13) Nucleus CI512/Contour Advance
Sanchez et al., 2013			(49) Med-El (32) Cochlear	
Vermeire et al., 2005			(13) Med-el (11) Cochlear Nucleus	(22,19) Med-el (10, 12) Cochlear Nucleus (1, 2) LAURA
Waltzman et al., 1993			(20) Cochlear Nucleus	
Wong et al., 2015	Unilateral=140 Bilateral=10		(160) Cochlear Nucleus	
Zwolan et al., 2013	Unilateral=18 Bilateral=0	Unilateral=20 Bilateral=0	(28) Cochlear Nucleus 5	

Implant status was unspecified for the older adults in four of the studies (29%) and was unspecified for the younger adults in five of the studies (36%). In 7 of the 10 studies on the older adults in which implant status was specified, all of the participants had unilateral implants and none had bilateral implants. In 6 of the 8 studies including younger adults, all of the participants had unilateral implants and none had bilateral implants. In the remaining studies, in both groups, the number of participants with bilateral implants was very small compared with the number of participants with unilateral implants. Across all of the studies that identified whether participants wore unilateral or bilateral implants, only 20 participants were noted to be bilaterally implanted. The three FDA approved cochlear implant manufacturers were represented in the studies, with the majority of participants utilizing Cochlear Corporation, followed by Advanced Bionics, and finally, Med-el. One study (Vermeire et al., 2005) included 3 participants who utilized the Antwerp Bionic Systems LAURA device that no longer is being manufactured.

Table 3 compares the speech-recognition scores of older adults to those of younger adults at different follow-up times. Speech recognition scores are accompanied by markings in the younger adult column that indicate if there was a statistically significant difference between group scores at that measurement interval ("S" for significant, "NS" for not significant, and "–" when analysis was not performed).

Table 3. Speech recognition outcomes of cochlear implantation.

Authors, year	Speech-recognition material	Mean % (SD)[c] pre-op SRS[x]		% SRS at 3 months post-op*		% SRS at 6 months post-op		% SRS at 1 year post-op		% SRS at 2 years post-op		% SRS at non-specific f/u[d] time		% SRS change (post-op minus pre-op)	
		OA[a]	YA[b]	OA	YA	OA	YA	OA	YA	OA	YA	OA	YA	OA	YA
Budenz et al 2011		N[w]=60	N=48	N=60	N=48			N=60	N=48	N=60	N=48				
	CNC[e] phonemes	16.4 (16.4)	14.79 (18)[-]	~59	~62[NS]			~67	~75[NS]	68.9	74.9[S]			52.5	60.11
	CNC words	5.6 (7.4)	4.9 (7.7)[-]	~40	~44[NS]			~48	~56[NS]	~56	~60[NS]			~50.4	~55.1
	CUNY sent.[f] Q[g]	20.6 (25.8)	16.8 (24.1)[-]	~70	~70[NS]			~83	~86[NS]	~84	~87[NS]			~63.4	~70.2
	CUNY sent. N[h]	10.4 (18.7)	11.4 (17.5)[-]	~61	~68[NS]			~72	~72[NS]	~74	~75[NS]			~63.6	~63.6
Friedland et al 2010		N=28	N=28					N=28, 28, 21	N=26, 28, 27						
	CNC							38.1 (23)	52.8 (21.6)[S]						
	HINT-Q	22.4 (22.0)	23.0 (23.0)[NS]					70.4 (25.9)	83.2 (23.9)[S]					48	60.2
	HINT-N							58.3 (27.6)	65.2 (25.6)[NS]						
Hast et al 2015												Minimum 1 year			
												N=25	N=25		
												Median/IQR[i]			
	Freiburg mono[i]											59 (10-85)	66 (25-92)[NS]		
	Göttingen Q											83 (26-100)	78 (32-100)[NS]		
	Göttingen CCITT[j]											25 (0-95)	13 (0-40)[NS]		
	Göttingen Fastl[k]											30(0-93)	28 (0-70)[NS]		
Labadie et al 2000		N=16	N=20	N=14	N=18/17	N=14	N=18								
		Median	Median	Median	Median	Median	Median							Median	
	CNC[m]	0	0[NS]	27	28[NS]	32	36[NS]							32	36
	CID	8.5	0.5[NS]	81	90[NS]	77	88[NS]							68.5	84.5
Mahmoud and Ruckenstein 2014												Minimum 3 months			
												N=43	N=27		
	CNC											55.3 (3.3)	63.9 (3.4)[NS]		
	AzBio											59.5 (4.5)	74.6 (4.1)[S]		
Olze et al 2012												Minimum 6 months			
												N=20	N=35		
	Freiburg mono											56.0 (29)	59.5 (29.1)[NS]		
	HSM[o] noise											55.8 (28.1)	48.4 (32.5)[NS]		
Park et al 2011		N=50	N=61, 50									~1 year			
												N=50	N=61, 50		
	HINT[p]	15 (2.1)	15.3 (2.0)[NS] 23.1 (3.3)[NS]									77.2 (0.9)	74.7 (9.6)[NS] 73.3 (10.4)[NS]	62.2	59.4 50.2
Roberts et al 2013		N=67	N=46									Minimum 5 months			
												N=67	N=46		
	CNC	~4	~5[NS]									~54	~64[S]	~50	~59
Sanchez-Cuadrado et al 2013	Spanish disyllables:	Median/IQR										Minimum 1 year			
		N=81										N=37	N=44		
	w/ lr, w/ m[q]	~47 20-75[-]										72.00	84.94[NS]		
	w/ lr, w/o m[r]	~40 10-71[-]										81.09	92.65[NS]		
	w/o lr, w/ m[t]	~21 2-55[-]										42.06	67.38[S]		
	w/o lr, w/o m[u]	~32 8-55[-]										64.45	77.06[NS]		
Vermeire et al 2005		N=25	N=33, 31									~2 years			
												N=25	N=33, 31		
	NVA[v] phonemes	4 (7)	7 (13)[-] 4 (9)[-]									46 (28)	68 (19)[S] 59 (28)[S]	42	61 55
Zwolan et al 2013		N=18	N=20	N=18	N=20	N=18	N=20	N=18	N=20						
	CNC	~5	~5[NS]	~43	~53[NS]	~49	~57[NS]	~48	~64[NS]					~43	~59
	HINT-Q	~43	~38[NS]					~76	~83[NS]					~33	~45
	HINT-N	~26	~27[NS]					~62	~78[NS]					~36	~51
	AzBio-Q	~9	~9[NS]	~49	~60[NS]	~56	~68[NS]	~59	~78[NS]					~50	~69
	AzBio-N	~3	~3[NS]					~11/42	~24/53[NS]					~8/39	~21/50

[a] OA=older adult [b] C=young adult [c] SD=standard deviation [d] f/u=follow-up [e] CNC=consonant-nucleus-consonant [f] CUNY sent.= City University of New York sentences [g] Q=quiet [h] N=noise [i] mono=monosyllables [j] CCITT=continuous, speech-simulating noise [k] Fastl=fluctuating noise IQR[i]=Interquartile Range [m] CID=Central Institute of the Deaf sentences [NS]=no significant difference between older [o] HSM=Hochmair-Schulz-Moser sentences [p] HINT=hearing in noise test [q] w/ lr=with lipreading [r] w/o lr=without lipreading [S]=significant difference between older adults and control adults and control [t] w/ m=with masking [u] w/o masking [V] NVA=Dutch CNC wordlist -=significance not specified [w] N=sample size [x] SRS=speech-recognition score *in some cases, follow-up was at post-activation, not post-implantation and is addressed in the text

Note that some investigators indicated follow-up interval as the number of months post-implantation whereas others used number of months post-activation. In this review, the terminology presented in each study is used. Furthermore, some investigators did not indicate a specific follow-up time, so such studies were represented in the table as having unspecified follow-up time. The final column details the mean or median gain at the most recent follow-up interval for studies that provided pre-operative scores. Eight of the 11 studies (73%) included in Table 3 utilized a consonant-nucleus-consonant (CNC) word list for at least one measure of speech recognition. Note that the NVA (*Nederlandse Vereniging voor Audiologie*, Dutch Audiological Society) word list utilized by Vermeire et al. (2015) is a Dutch CNC wordlist and the Freiburg monosyllable word list utilized by Hast et al. (2015) and Olze et al. 2012) is a German CNC word list. Eight of the 11 studies (73%) used a sentence test for at least one speech-recognition measure. The sentence tests employed include: CUNY (City University of New York) sentences, HINT (Hearing in Noise Test) sentences, Göttingen sentences (a German sentence test), CID (Central Institute of the Deaf) sentences, HSM (Hochmair-Schulz-Moser) sentences (a German sentence test), and AzBio sentences. The Göttingen and HSM sentences comprise German sentences that approximate the distribution of phonemes in the German language. Four of these 8 studies assessed speech-recognition in a noise condition for at least one measure of speech-recognition ability. Hast et al. (2015) utilized CCITT and Fastl noise when assessing speech outcomes. CCITT noise is a continuous signal with a frequency spectrum corresponding with the long-term spectrum of speech. Fastl noise is based on CCITT noise and is amplitude modulated at a randomized modulation frequency with the spectral distribution of the modulating signal peaking at 4 Hz. Only one study (Sanchez et al., 2013) assessed speech-recognition using disyllables with and without lipreading in both masked and unmasked conditions, for a total of 4 variations.

Table 4 details changes in older adult speech-recognition scores over time, comparing each performance at a given follow-up interval to the performance at the immediately preceding assessment.

Table 4. Pre-operative and post-operative speech-recognition scores (SRS) in the older adults.

Authors, year	Speech recognition material	Mean % (SD) pre-op SRS[m]	% SRS at 3 months post-op*	% SRS at 6 months post-op	% SRS at 1 year post-op	% SRS at 2 years post-op	% SRS at 5 years post-op	% SRS at 10 years post-op	% SRS at unspecified f/u	SRS change (post-op minus pre-op)
Budenz et al 2011		N[l]=60	N=60		N=60	N=60				
	CNC[a] phonemes	16.4 (16.4)	~59[S]		~67[S]	~70[S]				~53.6
	CNC words	5.6 (7.4)	~40[S]		~48[S]	~56[S]				~50.4
	CUNY[b] sentences Q	20.6 (25.8)	~70[S]		~83[S]	~84[S]				~63.4
	CUNY sentences N	10.4 (18.7)	~61[S]		~72[S]	~74[S]				~63.6
Dillon et al 2013		N=14		Median/IQR[c]	Median/IQR		Median/IQR	Median/IQR		
				N=14	N=14		N=14	N=14		
	CNC	2		~42 31-67[-]	~44 39-55[NS]		~60 50-69[S]	~59 49-73[NS]		
	HINT[d] Q[e]	7		~84 48-93[-]	~78 71-90[NS]		~90 76-93[S]	~89 78-92[NS]		
	HINT N[f]	0		~57 31-79[-]	~63 60-70[NS]		~68 63-79[S]	~68 49-83[NS]		
Labadie et al 2000		N=16	N=14	N=14						Median
		Median	Median	Median						
	CNC	0	27[S]	32[NS]						32
	CID[g]	8.5	81[S]	77[NS]						68.5
Park et al 2011		N=50							~1 year	62.2
									N=50	
	HINT N	15 (2.1)							77.2 (0.9)[S]	
Roberts et al 2013		N=67							Minimum 5 months	~50
									N=67	
	CNC	~4							~54[S]	
Vermeire et al 2005		N=25							~2 years	42
									N=25	
	NVA[h]	4 (7)							46 (28)[S]	
Waltzman et al 1993		N=20				N=20				
	Accent test	29.2				54.6[S]				25.4
	question/statement test	47.4				74.3[S]				26.9
	Iowa sentences w/o context	36.9				70.8[S]				33.9
	MAC[i] initial consonant test	24.3				45.0[S]				20.7
	MAC final consonant test	28				55.2[S]				27.2
	four-choice Spondee	31.1				66.3[S]				35.2
	CID	0.25				20.8[S]				20.55
	W-22[j]	0				10.3[S]				10.3
	NU-6[k]	0				11.8[S]				11.8
Wong et al 2015		Median/IQR	Median/IQR		Median/IQR					Median
		N=150	N=?		N=?					
	CNC phonemes	~9 0-21	~52 36-68[S]		~67 49-76[S]					~58
	CNC words	~0 ?-4	~23 13-44[S]		~39 22-55[S]					~39
	CUNY sentences Q	~0 ?-10	~72 48-89[-]		~79 46-91[NS]					~72
	CUNY sentences N	~0 ?-?	~26 10-62[S]		~42 21-63[NS]					~42
Zwolan et al 2013		N=18	N=18	N=18	N=18					
	CNC	~5	~43[S]	~49[S]	~48[-]					~43
	HINT Q	~43			~76[S]					~33
	HINT N	~26			~62[S]					~36
	AzBio Q	~9	~49[S]	~56[S]	~59[-]					~50
	AzBio-N	~3			~11/42[S]					~8/39

Table 4. [a]CNC=consonant-nucleus-consonant [b]CUNY=City University of New York [c]IQR=interquartile range [d]HINT=hearing in noise test [e]Q=quiet [f]N=noise [g]CID=Central Institute of the Deaf sentences [h]NVA=Dutch CNC [i]MAC=minimal auditory capabilities [j]W-22=CID wordlist [k]NU-6-Northwestern University wordlist [l]N=sample size [m]SRS= speech-recognition score [S]=significant improvement since previous assessment [NS]=No significant improvement since previous assessment -=significance not specified *in some cases, follow-up was at post-activation, not post-implantation and is addressed in the text

Whereas Table 3 compared older and younger groups at particular time intervals, Table 4 examines older adult improvement at each successive interval. Only nine (64%) of the 14 studies statistically analyzed changes in speech-recognition scores for older adults over time. Studies also discussed the overall significance from pre- to the final post-implantation assessment, which is discussed within the review. The final column details the mean or median gain in speech recognition scores from pre-implantation to the most recent assessment. Waltzman et al. (1993) use a number of speech tests not yet discussed. The accent test and question/statement test examine suprasegmental features. The Iowa sentences without context test includes lipreading. The MAC (minimal auditory capabilities) initial consonant test, the MAC final consonant test, and the four-choice Spondee are also utilized.

COMPARISON OF OLDER AND YOUNGER ADULT SPEECH-RECOGNITION OUTCOMES

Consonant-nucleus-consonant phonemes in quiet

Budenz et al. (2011) assessed older and younger adult CNC phoneme scores pre-operatively and post-operatively at 3 months, 1 year, and 2 years. Nonparametric tests were utilized for data analysis because the speech scores were ordinal measurements and not ratio scale measurements. The Mann-Whitney exact test compared CNC phoneme outcomes at each evaluation. The Wilcoxon exact signed rank test was utilized to determine if both groups showed improvement at each follow-up time. The younger adults performed better than the older adults at every post-operative follow-up interval, however, the difference was only statistically significant at 2-years post-implantation. The mean scores of the older and younger groups were 68.9% and 74.9% respectively. The mean gain for CNC phonemes was 52.5% for the older group and 60.11% for the younger group. When controlling for duration of deafness prior to implantation, the difference in mean CNC phoneme score at 2 years between groups was no longer significant. The investigators concluded that the difference in CNC phoneme scores is not correlated with age, but rather, is correlated with duration of deafness, with a mean duration of deafness being 34 years (SD 21.4, range 0.33–74) for the older adults as compared with 23.4 years (SD 17.9, range 0.5-55) for the younger adults.

Consonant-nucleus-consonant words in quiet

Budenz et al. (2011) also assessed performance on CNC words in older and younger adults. The Mann-Whitney exact test allowed for comparison between both group’s CNC word scores at each evaluation point and over the 2-year period. The Wilcoxon exact signed rank test was used to determine if there was improvement at each follow-up interval. Statistical analysis showed no significant difference in mean CNC scores between groups, despite the younger group performing better at every follow-up visit. Mean gain on CNC word scores was 50% and 55% for the older and younger groups, respectively.

Friedland et al. (2010) compared the mean CNC scores for older and younger adults at 1-year post-implantation. The participants in each age group were matched by pre-operative HINT in quiet score. The *t* test was used to assess group differences in mean CNC score. The mean CNC score (38%) for the older adult group was significantly poorer than that (53%) for the younger adult group at 1-year post-implantation.

Labadie et al. (2000) measured performance for older and younger adults using CNC words in quiet pre-implantation and 3 and 6 months post-activation. The median CNC scores for the older group improved from 0% pre-implantation to 32% at 6 months post-activation, yielding a median gain of 32%. The median CNC scores for the younger group improved from 0% to 36% at 6 months post-activation, yielding median gain of 36%. Based on nonparametric statistical analysis, investigators observed no statistically significant difference in median performance between the younger and older adults at both follow-up times.

Mahmoud and Ruckenstein (2014) measured performance using CNC words in quiet at 3 or more months after cochlear implant activation. The mean scores for the older and younger groups were 55.3% (3.3) and 63.9% (3.4) respectively. The investigators used nonparametric testing because of the non-normal distribution of speech scores. Analysis using the bivariate Mann-Whitney *U* test revealed no significant difference in mean CNC word score between age groups. The results of multivariate linear regression showed a trend towards poorer scores with increasing age at implantation. Zwolan et al. (2013) also analyzed performance for CNC in quiet in users of the Cochlear Nucleus 5 pre-operatively and at follow-up intervals of 3 months, 6 months, and 1 year. No significant differences were obtained in mean pre-operative pure-tone averages or duration of deafness between the younger and older adult groups. Approximate mean pre-operative scores were 5% for both groups. Approximate 1-year post-operative mean scores were 48% for the older group and 64% for the younger group. Thus, the mean scores improved by approximately 43% in the older group and by 59% in the younger group. The results of repeated-measures linear regression analysis revealed the absence of statistical differences between groups at any time interval. Roberts et al. (2013) utilized multivariate regression analysis to determine whether statistically significant differences in CNC score in quiet were seen between the age groups pre-operatively or at 5+-months post-operatively. No statistically significant difference was obtained between groups on the mean pre-operative CNC score, which was approximately 4% in the older group and 5% in the younger group. But statistically significant differences in mean CNC score in quiet were obtained between groups post-operatively: the mean post-operative score was approximately 54% in the older group and 64% in the younger group. Thus, the approximate mean gain in CNC score was 50% in the older group and 59% in the younger group. Further analysis by decade of life showed that CNC scores trended downward with age, with the 22 participants who were aged 80 years or older performing significantly more poorly than the rest of the group.

Hast et al. (2015) measured speech-recognition performance using Freiburg monosyllables in older and younger adults who had at least one year of implant experience. Comparison of the median values were performed using the Wilcoxon signed rank test and revealed no significant differences in median scores between the age groups with the median scores being 59% and 66% for the older and younger groups, respectively. Olze et al. (2012) also assessed speech-recognition outcomes using the Freiburg monosyllable test in quiet at 6 or more months after activation. The mean score for the older group was 56% and the mean score for the younger group was 59.5%. No statistically significant difference was found in mean speech-recognition score between the age groups. Vermeire et al. (2005) measured NVA phoneme performance pre-implantation and at approximately 2 years post-implantation in three age groups: 17-55, 56-69, and 70-83 years old. The mean score for the oldest group was 4% pre-implantation and 46% post-implantation. The mean score for the middle-aged group was 4% pre-implantation and 59% post-implantation. The mean score for the youngest group was 7% pre-implantation and 68% post-implantation. The mean gain in NVA phoneme score from the oldest to youngest group was 44%, 55%, and 61%. The results of repeated-measures ANOVA indicated the oldest group performed significantly more poorly than the other two groups at post-implantation assessment.

Disyllables in quiet

Sanchez-Cuadrado et al. (2013) examined disyllable performance with and without lipreading at 1 or more years post implantation. The mean scores for the older group were 81.09% with lipreading and 64.45% without lipreading. The mean scores for the younger group were 92.65% with lipreading and 77.06% without lipreading. The results of statistical analysis using the Mann-Whitney *U* test revealed no statistical difference in the mean scores between groups at the post-implantation assessment.

Sentences in quiet

Budenz et al. (2011) examined older and younger adult scores on CUNY sentences in quiet pre-operatively and post-operatively at 3 months, 1 year, and 2 years. The mean gain at 2 years was 63.4% in the older group and 70.2% in the younger group. The Mann-Whitney test and the Wilcoxon exact signed rank test were used for analysis. No significant differences in mean score on CUNY sentences in quiet existed between groups at any time, even though the younger group performed better than the older group at every assessment.

Friedland et al. (2010) compared mean HINT in quiet scores at 1-year post-implantation. The older adults were matched with younger adults on pre-operative HINT in quiet scores. The mean post-operative scores were 70.4% for the older participants and 83.2% for the younger participants, reflecting improvements of 48% and 60.2% in the older and younger groups respectively. Statistical analysis with the *t* test revealed significantly poorer performance for the older group as compared to the younger group at the 1-year follow-up. Zwolan et al. (2013) also analyzed performance on the HINT in quiet pre-operatively 1-year post-operatively. The gain in mean HINT in quiet score was 33% in the older group and 45% in the younger group. The results of repeated-measures linear regression analysis revealed no statistical difference between age groups at any time interval.

Zwolan et al. (2013) furthermore analyzed performance on AzBio sentences in quiet pre-operatively and 1-year post-operatively. The mean AzBio sentence scores improved by 50% in the older group and by 69% in the younger group. The results of repeated-measures linear regression analysis revealed the absence of statistically significant differences in mean AzBio score between groups was found at any time interval. Mahmoud and Ruckenstein (2014) observed the mean scores on AzBio sentence in quiet at 3 or months post implant activation to be 59.5% and 74.6% respectively; the results of the Mann-Whitney *U* test revealed significantly poorer performance in the older than younger group.

Hast et al. (2015), using Göttingen sentences in quiet, observed the absence of significant differences in median score (based on the Wilcoxon signed rank test) between the older and younger adults at the postoperative assessment (at least 1 year post implantation). The median scores for the older and younger adults were 75% and 73.5% respectively.

Labadie et al. (2000) examined CID sentence performance in quiet at pre-implantation and 3 and 6 months post-activation. The older group's median CID scores improved from 23.2% pre-implantation to 40.9% at 6 months post-activation, yielding a gain of 21.6%. The younger group's CID scores improved from 21.9% to 45.8% at 6 months post-activation, yielding a gain of 24.0%. Based on nonparametric statistical analysis, the investigators observed no statistically significant difference in median performance between the younger and older adults at both follow-up times.

Disyllables in noise

Sanchez-Cuadrado et al. (2013) analyzed Spanish disyllable performance with lipreading and with masking as well as without lipreading and with masking post-operatively (1 or more years of implant use). The results of statistical analysis using the Mann-Whitney *U* test showed a statistical difference in mean in the without lipreading and with masking condition, with the older group performing significantly poorer (42% compared to 67%). The mean gain for both groups could not be determined as pre-operative scores were not available.

Sentences in noise

Budenz et al. (2011) analyzed each group's performance on CUNY sentences in noise pre-operatively and at 3 months, 1 year, and 2 years post-operatively. The mean gain from pre-operative to 2-year post-operative assessment was 63.6% in both groups; the results of statistical analysis using the Wilcoxon exact signed rank test revealed no significant difference between groups.

Friedland et al. (2010) and Park et al. (2011) analyzed HINT performance. Friedland et al. (2010) examined mean HINT scores at 1-year post-implantation. The mean gain could not be determined as a pre-operative HINT (in noise) was not performed. The *t*-test revealed the absence of a statistically significant difference in performance between groups at the 1-year follow-up. Park et al. (2010) compared pre-implantation HINT scores to the scores obtained at approximately 1-year post-implantation. The mean gain from pre- to post-implantation was 62.2% for the oldest group, 50.2% for the middle group, and 59.4% for the youngest group. A student's *t*-test was utilized to compare group performance at pre-implantation and approximately 1 year post-implantation. The results of student's *t*-test analysis revealed the absence of significant differences on the mean HINT score between age groups for both assessment times. Zwolan et al. (2013) looked at HINT performance pre-operatively and 3, 6, and 12 months post-operatively. The mean gain in HINT score was 36% for the older group and 51% for the younger group; no statistically significant differences between groups were obtained at any time interval, based on repeated-measures linear regression analysis.

Based on the results of repeated-measures linear regression analysis, Zwolan et al. (2013) observed no statistically significant difference between age groups on the mean score for AzBio sentences in noise pre-operatively and at all follow-up intervals. The mean gain was 8% for older adults and 21% for younger adults post-operatively. The mean gain using the Cochlear Nucleus 4 SmartSound program was 39% for older adults and 50% for younger adults post-operatively.

Olze et al. (2012), who examined performance on the HSM sentence test in noise at 6 or more months after implant activation, observed no statistically significant difference in mean HSM score between age groups. The mean gain could not be determined as pre-implantation scores were unavailable.

Hast et al. (2015) evaluated performance on Göttingen sentences with CCITT and Fastl noise for older and younger adults having at least 1 year of implant experience. Hast et al. did not assess performance pre-operatively. The median scores for the older group were 25% with CCITT noise and 30% with Fastl noise. The median scores for the younger group were 13% with CCITT noise and 28% with Fastl noise. The results of statistical analysis using the Wilcoxon signed rank test revealed no significant difference on the median Göttingen sentences scores in either noise condition at the post-implantation assessment.

Suprasegmentals

Waltzman et al. (1993) compared pre-operative and 2-year post-operative scores on the accent test and question/statement test. The results of statistical analysis using the student's *t*-test revealed significant post-operative improvement, with a mean gain of 25.4% on the accent test and 26.9% on the question/statement test.

Phonemes in quiet

Waltzman et al. (1993) also analyzed scores on the MAC initial and final consonant test pre-operatively and 2-years post-operatively. The mean gain, 20.7% and 27.2% for each test respectively, was statistically significant based on the student's t-test. Budenz et al. (2001) observed significant improvement (53.6%) in the mean post-operative CNC phoneme score at 2 years compared with the preoperative score, based on the results of the Wilcoxon exact signed rank test. Wong et al. (2015), who examined phoneme recognition pre-operatively and at 3 months and 1-year post-implantation, found statistically significant gains in scores from baseline to both postoperative test sessions, based on the results of the student’s *t*-test. Vermeire et al. (2005) obtained statistically significant gain in mean NVA phoneme scores (42%) from the pre-operative session to the session at approximately 2 years post-implantation, based on the results repeated-measures ANOVA.

Consonant-nucleus-consonant words in quiet

Wong et al. (2015) examined CNC word recognition pre-operatively and at 3 months and 1-year post-implantation. The results of statistical analysis revealed significant improvement from pre-operatively to the 3 months and 1-year post-operative test session with a mean gain of 43%. Budenz et al. (2001) observed a mean gain in CNC words of 50.4%. Improvement in mean speech-recognition performance over tat 2-years post-implantation was statistically significant, based on the results of the Wilcoxon exact signed rank test. The greatest improvement was seen at three months post-implantation, with continuous improvement at each successive assessment.

Dillon et al. (2013) analyzed the stability of CNC performance over the course of 10 years, with assessment occurring at 6 months, 1 year, 5 years, and 10 years post-activation. The results of preplanned paired *t*-tests revealed that the CNC scores were stable between the 6-month and 1 year assessments as well as between the 5-year and 10-year assessments; significant improvement was seen between the 1-year and 5-year follow-up sessions, with a median gain 16% at that time. The median gain from pre-operative assessment to 10-years post-operatively cannot be determined as the investigators reported pre-operative mean only. Zwolan et al. (2013) measured CNC words scores pre-operatively and at 3, 6, and 12 months post-operatively. The participants demonstrated significant improvement in the score for CNC words at each post-implant time frame (compared with the pre-operative score), well as significant improvement from 3 to 6 months. The mean gain 12 months after implantation was 43%. Labadie et al. (2000) found that the median CNC scores improved significantly from the pre-operative test session to the post-operative session at 3 months and at 6 months; but no statistically significant difference in median speech-recognition scores between the 3- and 6- months follow-up times, based on the results of the Kruskal-Wallis 1-way ANOVA and the Dunn method. The participants in Roberts et al. (2013) study showed significant improvement on CNC words at the 5+-month post-operative follow-up as compared with the pre-operative assessment when the results were analyzed with the unpaired *t*-test. The mean gain was 50%. Further analysis by decade of life showed that the results trended downward with age, with the 22 participants aged 80 years or older performing significantly more poorly than the rest of the group. Waltzman et al. (1993)

saw mean gains of 10.3% and 11.8% for W-22 and NU-6 word scores, respectively at the 2-year performance assessment. The pre-operative scores were 0% for both tests. The results of statistical analysis confirmed significant improvement at the 2-year post-operative assessment.

Disyllables in quiet

Waltzman et al. (1993) statistically analyzed scores on the four-choice Spondee pre-operatively and 2-years post-implantation. The mean gain was 35.2%. The results of statistical analysis using the student's *t*-test showed significant improvement on the four-choice Spondee over time.

Sentences in quiet

Budenz et al. (2011) and Wong et al. (2015) utilized CUNY sentences in quiet for measurement of speech-recognition outcome. The results of statistical analysis using the Wilcoxon exact signed rank test revealed that performance was significantly improved at the 2-year post-operative assessment (Budenz et al., 2011). The mean gain over time was approximately 63.4%. Wong et al. (2015) observed significant improvement at 3 months post implantation, based on the results of the student’s *t*-test; the gains plateaued after the 3-month post-operative assessment. The mean gain was 42%.

Dillon et al. (2013), using preplanned paired *t*-tests to evaluate the changes in scores over time, observed stable performance on the HINT in quiet between the 6-month and 1-year assessments as well as between the 5-year and 10-year assessments. Significant improvement was seen between the 1-year and 5-year follow-up, with the median gain 12%. Zwolan et al. (2013) found statistically significant improvement on the HINT in quiet from the pre-operative session to the session 1-year post-operatively; the mean gain over time was 33%.

Labadie et al. (2000) observed that the median gain in CID sentence score at 6-months post-activation (compared with the score pre-operatively) was 68.5%; the gain in median score was statistically significant at the 3- and 6-months postoperative sessions but no statistically significant difference (based on analysis with the Kruskal-Wallis 1-way ANOVA and the Dunn method) was obtained between the 3- and 6- months follow-up times.

Zwolan et al. (2013) obtained mean AzBio sentence in quiet at 3 months, 6 months, and 1-year post-implantation. They found statistically significant improvement on each measure of speech-recognition when compared to pre-implant scores at every assessment. The mean gain at 1-year was 50%.

Waltzman et al. (1993) analyzed scores on the Iowa sentence without context test pre-operatively and 2-years post-implantation. The mean gain was 33.9% at the 2-year assessment. Using the student's *t*-test, scores on Iowa sentence test showed significant improvement.

Sentences in noise

Budenz et al. (2011), using the Wilcoxon exact signed rank test, found that performance on the CUNY sentences in noise were significantly improved at every post-operative assessment as compared with the pre-operative assessment. The mean gain was 63.6% at the 2-year visit. Wong et al. (2015) also saw significant improvement on CUNY sentences in noise from the pre-operative test to the 1-year assessment. The median score improved from 0% to 42% 2-years post-operatively. Both studies saw the greatest increase in scores at the first visit post-implantation, with scores only slightly improving at every follow-up after that.

Park et al. (2011) obtained significant improvement in mean HINT score from the pre-operative session to the follow-up evaluation at 1-year post implantation. The mean gain over that 1-year period was 62.2%. When excluding patients younger than 70 years old, significant improvement in mean score was still seen, although the authors did not disclose the number of patients who were 70-85 years old.

Similar to their findings for the HINT in quiet, Dillon et al. (2013) observed no significant change (based on preplanned paired t-test analysis) on the HINT in noise between the 6-month and 1-year post-operative visits as well as between the 5-year and 10-year visits. Significant improvement was seen between the 1-year and 5-year follow-up with a median gain of 5%. Zwolan et al. (2013) saw statistically significant improvement on the HINT from the pre-operative session to the session at 1-year post implantation. The mean gain was 36%.

Zwolan et al. (2013), who assessed mean AzBio sentences in noise pre-operatively and at 3 months, 6 months, and 1-year post-implantation found statistically significant improvement at every post-operative assessment. The mean gain at 1-year post-implantation was 8% when using the everyday program and was 39% when using the Cochlear Nucleus 4 SmartSound program. The investigators concluded the participants who scored greater than 40% pre-operatively on HINT sentences were responsible for the significant improvement in speech recognition.

DISCUSSION

The purpose of this systematic review was to examine speech-recognition performance in quiet and noise for older adults who have received cochlear implants. A secondary purpose was to compare these findings for older adults with the findings in younger adults who have received cochlear implants.

In total, this review examined the results of 29 speech-recognition tests from 14 studies comparing outcomes of older and younger adults following cochlear implantation were reviewed, based on. The results of both studies on CNC phoneme accuracy (Budenz et al., 2011 and Vermeire et al., 2005) revealed that older adults performed significantly more poorly than younger adults at approximately 2 years after implantation. Older adults performed significantly more poorly than older adults on CNC words at the 1-year follow-up and at the follow-up time of at least 5 months in the Friedland et al. (2010) and Roberts et al. (2013) investigations, respectively. The results of these two studies contradict the results of six studies in which no statistically significant differences in CNC word scores were obtained between age groups at any time interval. (Budenz et al., 2011; Hast et al., 2015; Labadie et al., 2000; Mahmoud and Ruckenstein, 2014; Olze et al., 2012; and Zwolan et al., 2015). Sanchez-Cuadrado et al. (2013) found no difference between age groups on disyllable recognition with and without lipreading in quiet at one year after implantation. The results of five sentence tests in quiet (CUNY sentences, Göttigen sentences, CID sentences, the HINT, and AzBio sentences) revealed no significant difference in sentence performance between age groups at any follow-up time (Budenz et al., 2011; Hast et al., 2015; Labadie et al., 2000; Zwolan et al., 2013). In only two studies (Mahmoud and Ruckenstein, 2014; Friedland et al., 2010) did the results show that older adults performed significantly more poorly than younger adults ; Mahmoud and Ruckenstein employed the AzBio at 3 or more months post-implantation and Friedland et al. employed the HINT in quiet at 1-year post-implantation.

Sanchez-Cuadrado et al. (2013) found no significant difference between groups on disyllable recognition without masking, but with masking, they found that the older group performed significantly worse than the younger group at the one-year assessment. The findings of all sentence in noise testing (CUNY sentences, Göttigen sentences with CCITT, Göttigen sentences with Fastl, HSM sentences, AzBio sentences, and three studies utilizing the HINT) revealed no significant differences between groups at any measurement time (Budenz et al., 2011; Friedland et al., 2010; Hast et al., 2015; Olze et al., 2012; Park et al., 2012; Zwolan et al., 2013).

In nine studies, the investigators analyzed speech-recognition performance in older adults over time, for a total of 30 different speech-recognition tests. The results of all of these investigations indicated that speech-recognition in older adults was significantly improved at the follow-up session of at least one year post implantation, with the greatest improvement from the pre-operative baseline seen at the first post-operative visit. Continuous improvement or a plateau in scores was seen for all 30 speech-recognition tests; no significant decline is scores was noted at any time.

Generalizability of the findings in these studies is limited because of the variety of speech-recognition materials. Generalizability of the findings in these studies also is limited because of the variability in follow-up time. Although many investigators used regular time intervals for assessment, others approximated follow-up time or only specified follow-up in an open-ended way. Mahmoud and Ruckenstein (2014), for example, examined AzBio sentence outcome at 3 or more months post-implantation. Investigators did not examine long-term performance beyond the two-year follow-up was not evaluated in these studies with the exception of Dillon et al. (2013) who examined speech-recognition performance at 10 years post-implantation. Another limitation of some of the studies is that the mean score was reported instead of the median when non-parametric analyses were employed. (Budenz et al., 2011; Mahmoud and Ruckenstein, 2014; Sanchez-Cuadrado et al., 2013). Further, 5 of the 14 studies (36%) did not specify measures of central tendency, and therefore only approximations of these measures could be made from the graphs.

More long-term longitudinal research is needed to be able to draw conclusions about long-term outcomes. Standardization of protocols for speech-recognition assessment would allow a body of research to be generated using similar speech-recognition materials and procedures so that research findings are more generalizable.

CONCLUSIONS

The results of this systematic review provide overwhelming evidence that older adults see significant improvement in speech-recognition ability following cochlear implantation, and that their performance is comparable to that of younger adults. Phoneme, word, and sentence recognition in quiet and noise significantly improved for deafened adults at post-implantation as compared with pre-implantation. Therefore, cochlear implantation is a viable option for post-lingually deafened older adults who do not benefit from hearing aids. More research is needed to determine the long-term speech-recognition outcomes beyond two years post implantation, as only one study reported outcomes beyond that time. Audiologists who encounter patients unable to benefit from amplification should not rule out recommendations for cochlear implantation based on advanced age.

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