The effect of hearing loss configuration on cochlear implantation uptake rates: an Australian experience

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Abstract

Objective: Recent changes to cochlear implant (CI) candidacy criteria have led to the inclusion of candidates with greater levels of hearing in the contralateral and/or implanted ear. This study assessed the impact of various hearing loss configurations on CI uptake rates (those assessed as eligible for CI, who proceed to CI).

Design: Retrospective cohort study.

Study sample: Post-lingually deaf adult CI candidates ($n = 619$) seen at a Western Australian cochlear implant clinic.

Results: An overall CI uptake rate of 44% was observed. Hearing loss configuration significantly impacted uptake rates. Uptake rates of 62% for symmetrical hearing loss, 48% for asymmetrical hearing loss (four-frequency average hearing loss (4FAHL) asymmetry ≤60 dB), 25% for highly asymmetrical hearing loss (4FAHL asymmetry >60 dB), 38% for hearing losses eligible for electric-acoustic stimulation, and 22% for individuals with single-sided hearing loss were observed. Hearing loss configuration and age were both significant factors in relation to CI uptake although the impact of age was limited.

Conclusion: CI clinics who apply or are considering applying expanded CI candidacy criteria within their practice should be aware that candidates with greater levels of residual hearing in at least the contralateral ear are less likely to proceed to CI.

Keywords: Cochlear implant; uptake rates; asymmetrical hearing loss; single-sided hearing loss; electroacoustic; post-lingual hearing loss

Introduction

For over thirty years, cochlear implantation has been widely accepted as the gold standard for the treatment of bilateral severe-profound hearing loss (Wilson and Dorman 2008). Over recent years significant changes in cochlear implant (CI) technology, speech coding strategies and improved preservation of residual hearing have led to substantial improvements in hearing outcomes (Wilson and Dorman 2008). As a result, candidacy criteria for cochlear implantation have seen continual and rapid evolution (Leigh et al. 2016; Snel-Bongers et al. 2018). In many countries, CI candidacy criteria have broadened to include individuals with increasingly greater levels of residual hearing in one or both ears. Whilst such individuals do not fit the traditional candidacy criteria, there is mounting evidence of the benefit CIs can provide for individuals with various hearing loss configurations. These include highly asymmetrical (e.g. mild–moderate hearing loss in the better ear and severe-profound hearing loss in the poorer ear) hearing losses (Arndt et al. 2017; Boisvert et al. 2015; Firszt et al. 2012; Leigh et al. 2016); ski-slope (e.g. very good low-frequency hearing thresholds and very poor high-frequency hearing thresholds) hearing losses (Irving et al. 2014; Li, Kuhlmey, and Kim 2019; Welch, Dillon, and Pillsbury 2018); and even single-sided (i.e. normal hearing in the better ear, severe-profound hearing loss in the poorer ear) hearing loss (Arndt et al. 2017; Haussler et al. 2019).

Australia, like many Western countries, has an ageing population resulting in a growing proportion of the population experiencing severe levels of hearing impairment (Access Economics 2006). Thus, it could be extrapolated that there will be an increasing population of potential CI candidates in the future. When combined with expanded CI candidacy criteria, it could be projected that CI uptake rates (i.e. the number of individuals assessed as eligible for a CI, who proceed to CI) would experience exponential growth. However, recent research has shown that the CI uptake rate among adults is <10% in Western countries and lower in developing countries (Looi, Bluett, and Boisvert 2017; Raine et al. 2016; Sorkin and Buchman 2016). This is of significance as research has shown that untreated hearing loss can have significant impacts on the quality of life and mental health of severe-to-profoundly hearing-impaired individuals (Chia et al. 2007; Jayakody et al. 2018; Keidser and Seeto 2017).

Whilst the expansion of CI candidacy criteria has seen a significantly broader range of hearing loss configurations becoming eligible for CI, to date there has been little research into how hearing loss configuration can influence CI uptake rates. CI candidates, and recipients, with non-standard candidacy can have very different needs and concerns compared to those who fall within the more conventional, bilateral severe-profound hearing loss candidacy criteria. Furthermore, they may require additional clinical resources, both preoperatively with regard to candidacy assessment and counselling, and post-operatively with regard to counselling, mapping devices and rehabilitation requirements (Li, Kuhlmey, and Kim 2019; Tavora-Vieira and Marino 2019). This can have a significant impact on the resources of an implant clinic.

The CI uptake rates of CI candidates with various hearing loss configurations within a clinical population, and the incidence of candidates with each type of hearing loss configuration within the clinical population, are valuable information for health care professionals. Determination of the proportions of each hearing loss configuration within the clinic, whilst not indicative of general population prevalence, allows the clinic to identify changes in referral habits over time. Additionally, it may help to identify potential gaps in the knowledge base of referrers, and the community at large, regarding changes to CI candidacy criteria. Such information could assist clinicians to identify hearing loss configuration groups with lower CI uptake and provide guidance to clinics who utilise expanded candidacy criteria with regard to allocation of clinical resources. Finally, determination of differences in the uptake of CIs based on hearing loss configuration may help clinicians provide more hearing loss specific recommendations and counselling, and provide more focussed community education, potentially facilitating more eligible CI candidates to proceed to implantation.

The aim of this study was to 1) determine the incidence of various hearing loss configuration groups meeting the expanded CI candidacy criteria, as implemented within our clinic, and 2) review the subsequent CI uptake rates within each of these groups.

Method

Design and candidates

In this retrospective cohort study, we included patients, who had attended a large implant clinic for a CI candidacy assessment (first ear only), were 18 years of age or older and had been deemed audiologically suitable candidates for a CI based on CI candidacy criteria used at the clinic between 2010, when the clinic first started implanting individuals with single-sided deafness, and 2017.

Candidacy criteria at the clinic were based on a combination of hearing thresholds and aided speech perception with well-fitted hearing aids set to either NAL-NL1 or NAL-RP hearing aid gain prescription targets (pre-2012) or NAL-NL2 targets (for newly fitted recipients) from 2012 onwards. It should be noted that the candidacy criteria at the clinic evolved over this time period. Prior to 2016, CI candidates were required to have phoneme scores of <45% in the poorer hearing ear, as per the Clinical Guidelines for Adult Cochlear Implantation in WA (Health Networks Branch 2011). From 2016 onwards, candidacy criteria were modified to include individuals with phoneme scores of ≤55% in the ear to be implanted based on Leigh et al’s recommendations (Leigh et al. 2016). Electric-acoustic candidacy was based on a combination of candidacy recommendations from both Cochlear Ltd and Med-El (Cochlear Ltd 2016; Med-El 1999), requiring individuals’ hearing thresholds to fall within the specified range, i.e. hearing threshold levels ≤65 dBHL up to 500 kHz and >75 dBHL from 2 kHz onwards, and monosyllabic word scores in the ear to be implanted to be ≤60%. Single-sided deafness criteria required clients to have unaidable hearing and very limited/no speech discrimination in the ear to be implanted and have duration of hearing loss of ≤10 years in the ear to be implanted. In all cases, additional consideration was given to duration and onset of hearing loss and consistent use of amplification.

A total of 619 individuals were included in the study. Audiological assessments to determine candidacy included the following: 1) pure tone audiometry, air (250–8000 kHz), and bone (500–4000 kHz) conduction hearing thresholds assessed in a sound proof booth and 2) aided speech perception testing assessed in the sound field at a distance of one metre in front of the speaker, performed in a sound proof booth with hearing aids optimised to either NAL-NL1, NAL-RP, or more recently NAL-NL2 fitting targets. Speech perception assessments included the Australian versions of the CNC word test (Skinner et al. 2006) and the City University of New York (CUNY) sentence test (Boothroyd, Hanin, and Hnath 1985).

Implant candidates were sorted into one of five hearing loss configurations based on the criteria listed below. To assist in this categorisation, a four-frequency average (4FAHL, i.e. the average hearing loss across 500, 1000, 2000 and 4000 kHz (dBHL)) was calculated for each ear (see Figure 1).

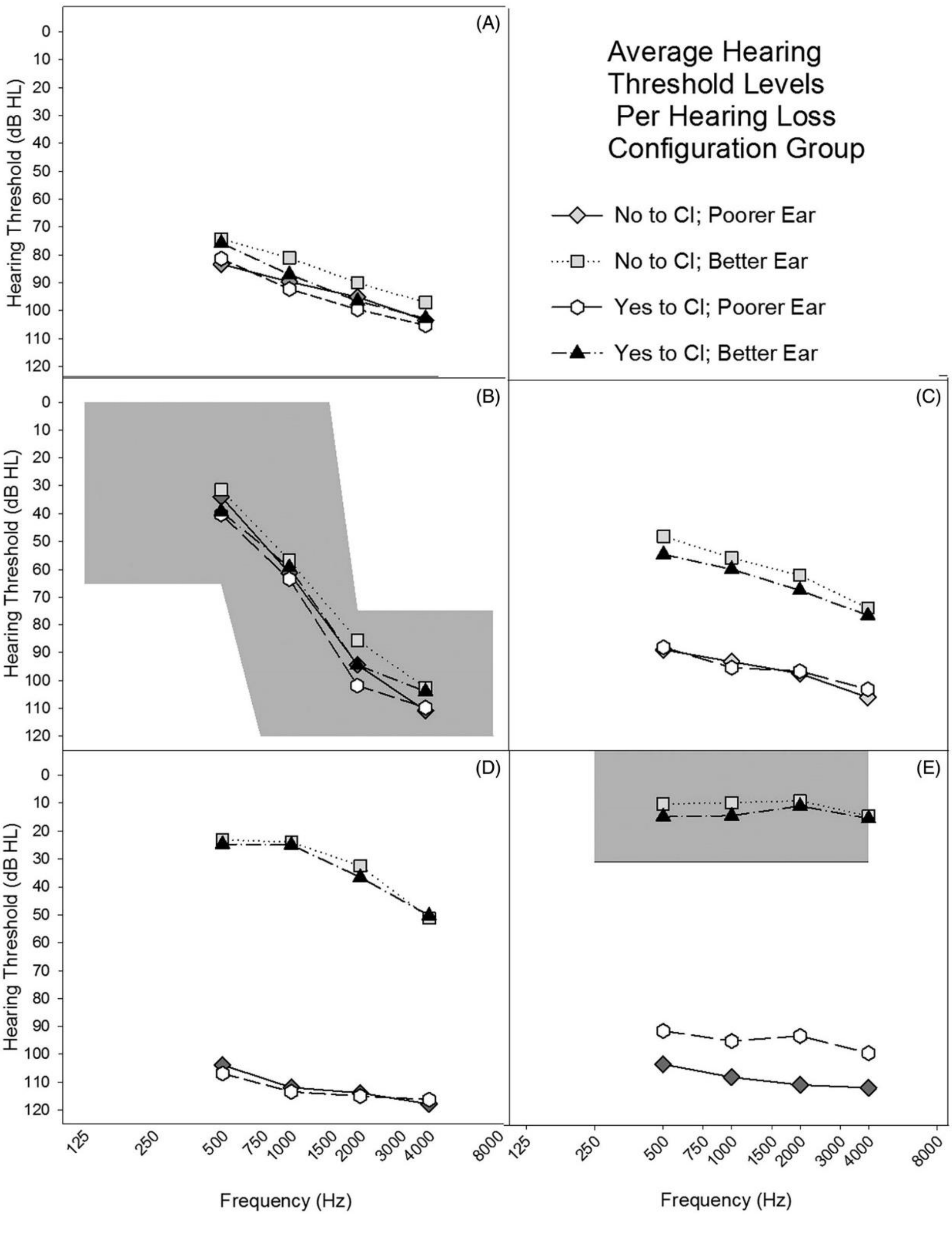

Figure 1. Hearing Loss Configuration Group Candidacy and Average Hearing Threshold Levels (dB HL) for the better, and poorer hearing ears for candidates who either proceeded to implant or declined implant. Panel A shows the SYM group (criteria: difference in 4FAHL between ears <20 dB HL. Panel B: EAS group (criteria: Hearing Threshold levels must fall within the shaded region). Panel C: AHL1 group (criteria: 4FAHL asymmetry ⩽60 dB HL but >20 dB HL, with at least one threshold in the better ear >30 dB HL between 250 and 4000 kHz). Panel D: AHL2 group (criteria: 4FAHL asymmetry >60 dB HL with at least one threshold in the better ear >30 dB HL between 250 and 4000 kHz). Panel E: SSD group (criteria: HTLs ⩽30 dB HL in the shaded region, unaidable hearing in the poorer hearing ear).

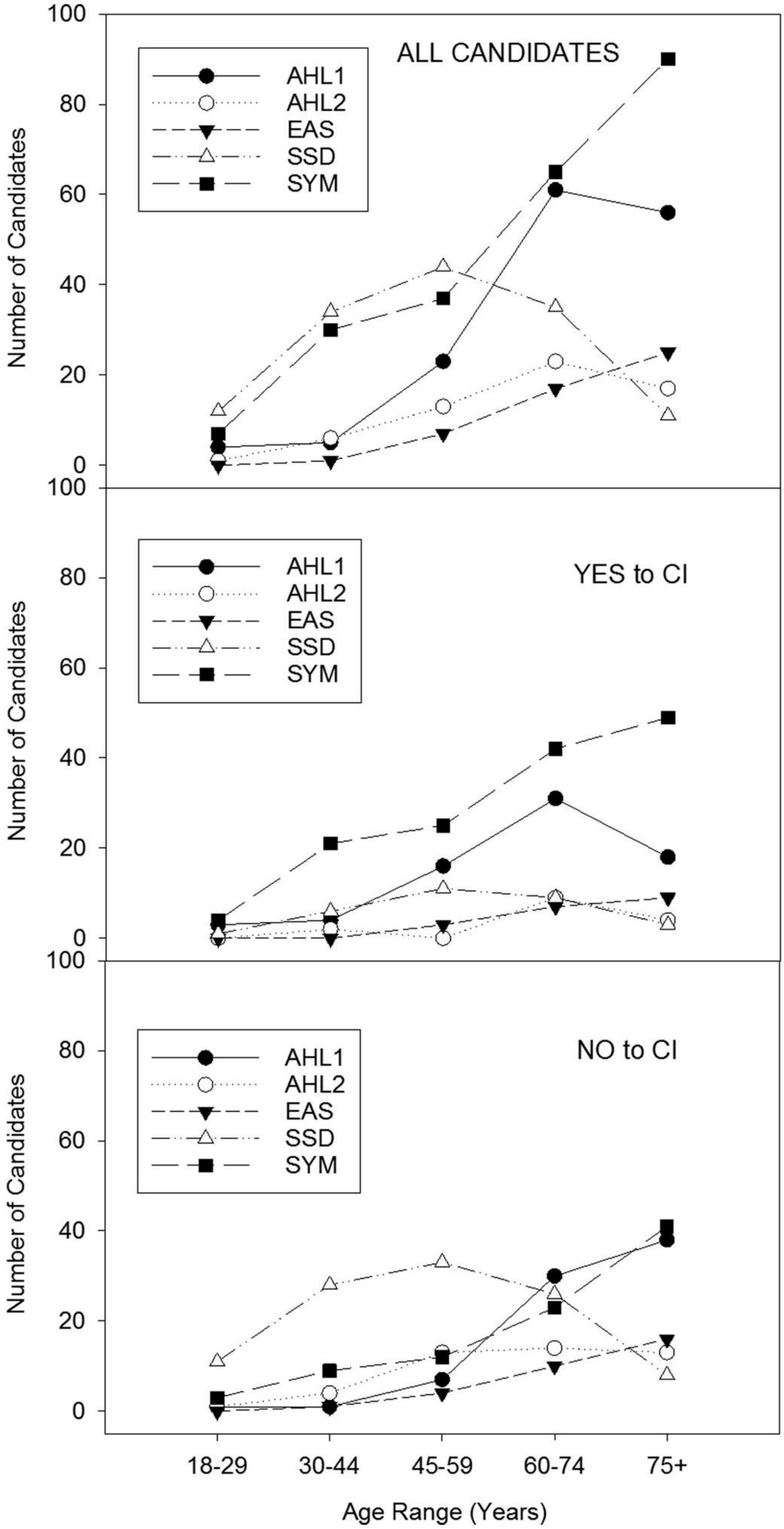

Figure 2. Number of audiologically suitable CI candidates categorised with respect to age and hearing loss configuration.

1. Symmetrical (SYM) hearing loss: individuals with ≤20 dB difference in 4FAHL between ears but who did not fall within electric-acoustic (EAS) candidacy criteria (Leigh et al. 2016).
2. Electric-acoustic (EAS) hearing loss: individuals whose audiogram and speech perception data fell within either the Cochlear Ltd. “Hybrid Candidacy Criteria” (Cochlear Ltd 2016) or Med-El “ElectroAcoustic Candidacy Criteria” (Med-El 1999) for electric-acoustic stimulation but would otherwise have been categorised as having a symmetrical hearing loss.
3. Asymmetrical (AHL) hearing loss: The exact definition of hearing loss asymmetry is contentious (Arndt et al. 2017; Firszt et al. 2012; Margolis and Saly 2008). For the purpose of this study, individuals with >20 dB difference in 4FAHL between ears but who did not fall within single-sided deafness (SSD) candidacy criteria were categorised as having AHL. This group was further split up into two groups;

   a AHL1: those with asymmetry between 21–60 dBHL (AHL ≤ 60)

   bAHL2: those with asymmetry >60 dBHL (AHL > 60)

4. Single-sided (SSD) hearing loss: individuals with hearing thresholds of 30 dBHL or better between 500 and 4000 kHz in the better ear and unaidable hearing on the poorer hearing ear (>70 dB 4FAHL sensorineural hearing loss and very poor speech perception) (Kitterick and Lucas 2016).

The demographics of individuals deemed to be CI candidates are shown in Table 1.

Statistics

Data were analysed using Sigma Stat software (SyStat 2016) using descriptive statistics, such as mean, median and standard deviation to describe the proportions of candidates within each hearing loss configuration category, and those who proceeded to CI. T tests and Wilcoxon rank-sum tests, ANOVA on Ranks (all pairwise multiple comparison procedure using Dunn’s method) and Chi^2 analysis were used to compare the various differences between those proceeding and those not proceeding with cochlear implantation. Multiple logistic regressions were used to determine the probability of CI uptake in relation to hearing loss configuration and age.

Table 1: Mean age of eligible candidates, those who proceeded to implant and those who did not comparing different hearing loss configurations.

	All Candidates		**Proceeded to Implant**		**Declined Implant**		**Difference in age between declined and proceeded to implant**
HL configuration Group	**Mean Age (years) ±SD, (range)**	**Gender (M:F)**	**Mean Age (years) ±SD, (range)**	**Gender (M:F)**	**Mean Age (years) ±SD, (range)**	**Gender (M:F)**	**p-value**
AHL1 (n=139)	69.29 ±14.62 (23-97)	86:53	64.08 ±14.97 (23-89)	39:24	74.16 ±12.54 (27-97)	47:29	$p < 0.001^{***}$
AHL2 (n=62)	63.3 ±15.21 (23-95)	40:22	65.53 ±12.81 (32-77)	7:9	62.56 ±15.99 (23-95)	33:13	$p > 0.05$
EAS (n=51)	71.56 ±11.83 (35-91)	32:19	72.05 ±9.98 (50-89)	13:6	71.26 ±12.98 (35-91)	19:13	$p > 0.05$
SSD (n=135)	51.51 ±15.91 (19-85)	56:79	54.43 ±14.10 (28-79)	9:21	50.68 ±16.35 (19-85)	47:58	$p > 0.05$
SYM (n=232)	66.54 ±17.63 (21-99)	107:125	64.38 ±16.61 (22-95	67:77	69.99 ±18.75 (21-99)	40:48	$p = 0.007^{**}$
All subjects (n=619)	64.01 ±18.01 (19-99)	321:298	63.82 ±15.74 (22-95)	135:137	64.16 ±18.51 (19-99)	186:161	

Results

Subject demographics

Hearing loss configuration

Each of the five hearing loss configurations was represented among the 619 implant candidates assessed. Thirty-seven per cent of candidates fell within the traditional CI candidacy criteria of a bilateral severe-profound hearing loss, 24% in the AHL1 group, 10% in the AHL2 group, 8% in the EAS group and 22% in the SSD group. Table 1 shows patient characteristics of age and gender for each of the HL configuration groups.

Age

Comparisons between groups using a Kruskal–Wallis one-way ANOVA on Ranks (all pairwise multiple comparison procedure using Dunn's method) indicated that the SSD candidates (mean age: 51.51 years ± 15.91) were significantly younger than all other hearing loss configuration groups; EAS (mean age: 71.56 years ± 11.83), $p < 0.001$, AHL1 (mean age: 69.29 years ± 14.62), $p < 0.001$, SYM (mean age: 66.55 years ± 17.67), $p < 0.001$, and AHL2 (mean age: 63.30 years ± 15.21), $p < 0.001$. There were no other significant differences between groups.

Gender

An ANOVA on Ranks (all pairwise multiple comparison procedures using Dunn's method) revealed significantly more females than males were represented in the SSD group ($p = 0.044$). There were no other significant differences noted between groups.

CI uptake rates

Hearing loss configuration

CI uptake rates (i.e. the number of candidates who proceeded to implant as a percentage of all candidates) were calculated for all candidates (44.39%), and for each hearing loss configuration, AHL1 (48.32%), AHL2 (25.00%), EAS (38.00%), SSD (22.06%), and SYM (61.57%). An ANOVA on Ranks (all pairwise multiple comparison procedures using Dunn's method) revealed that individuals within the SYM group were significantly more likely to proceed to implant than those within the SSD or AHL2 groups ($p < 0.001$). Individuals within the AHL1 group were significantly more likely to proceed to implant than the SSD group ($p = 0.001$). No other significant differences were noted between the groups.

Age

A Kruskal–Wallis one-way ANOVA on Ranks indicated no significant difference in age between those who proceeded to implant (median age: 67.00 years) compared with those who did not (median age 68.00 years), $p = 0.551$, (see Figure 2).

For the candidates who proceeded to implant, the SSD group were significantly younger (mean age 54.43 years ± 14.10) than the EAS group (mean age 72.05 years ± 9.98, $p = 0.001$), the AHL1 group (mean age 64.08 years ± 14.97, $p = 0.046$) and the SYM group (mean age

69.01 years ± 17.10, $p = 0.010$). There was no significant difference in age between the SSD group and the AHL2 group (mean age 65.53 years ± 12.81, $p = 0.295$) or between any of the other pairs of groups.

Of those who declined implant, the SSD group (mean age 50.68 years ±16.35) were significantly younger than the AHL1 group (mean age 74.16 years ± 12.54, $p < 0.001$) the EAS group (mean age 71.26 years ± 12.98, $p < 0.001$) and the SYM group (mean age 69.99 years ± 18.75, $p < 0.001$). The SYM group was also significantly older than the AHL1 group ($p < 0.001$) and the AHL2 group (mean age 62.56 years ± 15.99, $p < 0.001$), and the AHL1 group was significantly older than the AHL2 group ($p = 0.025$).

Gender

Chi^2 analysis indicated no significant differences in gender between those who proceeded to implant (males; $n = 135$, total percentage 21.8%: females $n = 137$, total percentage = 22.1%) and those who declined implant (males; $n = 186$, total percentage = 30.0%: females; $n = 161$, total percentage = 26.0%), ($p = 0.390$) overall.

When analysed with respect to the various HL configuration groups, Kruskal–Wallis one-way ANOVA on Ranks tests did not reveal any significant gender effect on CI uptake for any of the HL configuration groups among candidates who proceeded to CI ($p = 0.062$). However, significantly more females declined CI within the SSD group ($n = 59$, or 74% of female SSD candidates) compared to the AHL2 group ($n = 12$, or 60% of female AHL2 candidates), see Table 1. No other differences were observed.

Influence of hearing loss configuration and age on CI uptake rates

Multiple logistic regression including hearing loss configuration, with groups as dummy variables and the SYM group as reference, and age as independent variables, showed that, if correcting for age (OR: 0.984 95% CI 0.973–0.994), hearing loss configuration was still significantly correlated with the likelihood of proceeding. Patients within AHL1, AHL2, EAS and SSD groups were less likely to proceed to CI than those with SYM hearing loss (see Table 2).

Table 2: Multiple Logistic Regression Analysis results comparing the dependent variable of proceeding with cochlear implant or not with the independent variables of Age and Hearing Loss Configuration.

Variable	Coefficient	Standard Error	Wald Statistic	P value	Odds Ratio 95% C.I. (lower- upper)
Age	-0.02	0.01	8.46	0.004	0.98 (0.97-0.99)
SSD	-2.00	0.27	55.36	<0.001	0.14 (0.08-0.23)
AHL2	-1.65	0.33	24.65	<0.001	0.19 (0.10-0.37)
AHL1	-0.51	0.22	5.53	0.019	0.60 (0.40-0.92)
EAS	-0.90	0.32	7.64	0.006	0.41 (0.22-0.77)
Constant	1.54	0.40	15.15	<0.001	4.68 (2.15-10.19)

Discussion

In this study, we assessed the CI uptake rate of eligible CI candidates, using expanded candidacy criteria, which included individuals with hearing up to and including normal hearing in the better ear, and individuals eligible for electric acoustic implants. Our aims were to determine the incidence of various HL configuration groups eligible for CI referred to the clinic, and to determine the CI uptake rates within each of these groups. Collection of such demographic data is vital to enable better understanding of the prospective candidates and allows us to provide more patient-centred care.

The incidence of hearing loss configurations within implant clinics will vary based upon referral guidelines, referrer education and practices, and even cultural attitudes towards hearing interventions. A small number of studies have looked at EAS incidence within tertiary care implant clinics. For example, von Ilberg et al. (1999) reported that approximately 1.64% of the clinical population in a European implant centre fell within EAS candidacy criteria. Similarly, Saito et al. (2019) reported low numbers of referred individuals (0.71%) who met EAS candidacy criteria at a Japanese implant centre. The number of candidates falling within EAS candidacy criteria in the current study was somewhat higher at 8%. It should be noted that Saito et al. (2019) included hearing losses of all degrees in the calculation of hearing loss incidence, unlike this study which only included candidates eligible for CI. Thus, the method of incidence calculation used in Saito's study is a likely reason for the somewhat lower EAS numbers compared to our study. Alternatively, the higher prevalence of EAS candidates in our study may also be related to improved education and acceptance of electric-acoustic stimulation among referrers and clinicians within our clinic.

There are few studies looking at the prevalence of SSD or AHL within an adult population. Those that do tend to look at prevalence within the general population, not a clinical setting. Differences in definitions of both SSD and AHL among studies can also result in highly variable outcomes. Margolis and Saly (2008) studied a database of hearing-impaired individuals obtained from a US ENT department. They found an AHL incidence of 50%. The degree of asymmetry was not specified and the final rules to identify AHL were unclear; however, a 4FAHL difference of 15 dB was part of the classification criteria. SSD and AHL both fell within the same category for Margolis' study. When SSD and AHL groups are added together in this study, the incidence of AHL was 56%, similar to Margolis and Saly (2008). Golub et al. (2018) attempted to determine the prevalence of adult unilateral hearing loss (SSD) in the US population using criteria of hearing ≤25 dB PTA in the better ear and at least >25 dB PTA in the poorer hearing ear. They found the prevalence of moderate-or-worse unilateral hearing loss was 1.5% of the population. The higher incidence of SSD within our study (22%) is related to the clinical population referred to the implant clinic and is not representative of SSD within the general population.

Within our study cohort of first-time CI candidates, an overall CI uptake rate of 44.4% was observed. Looi, Bluett, and Boisvert (2017) reported a significantly lower CI uptake rate of 19%, using stricter CI candidacy criteria (i.e. 4FAHL >65 dB HL in the better hearing ear and CNC phoneme scores <50% in both ears) among 11 Australian adult first-time CI candidates. In a larger American study, Holder et al. (2018) reported significantly higher CI uptake rates (84%) among 228 first-time post-lingually deaf adult CI candidates. It was noted that 65% of Holder's candidates were traditional CI candidates with symmetrical, severe-profound hearing loss. Only 34% of candidates in our study fell within traditional CI candidacy criteria

(SYM group). Among the SYM group, the CI uptake rate was closer to Holder's study at 62%. Considerably lower uptake rates were obtained within the HL configuration groups with better hearing, particularly in the contralateral ear. This is consistent with the observations made by Holder et al. (2018) who found that those who did not proceed to cochlear implantation had, on average, more hearing in both the implanted and non-implanted ears. Saito et al. (2019) reported very low levels of CI uptake (5.9%) among eligible EAS candidates. This rate is substantially lower than the rate reported in our study of 38%. A large reason for the lower rate of uptake in Saito's study appears to have been lack of information provided to eligible candidates about EAS options (47% of cases).

The clinical protocol used in this study, in most cases, resulted in candidates proceeding to medical review for implant candidacy following their audiological assessment indicating audiological candidacy. Thus, one must consider that a proportion of individuals did not proceed to CI for medical reasons identified at the medical review. Medical reasons for declining CI candidacy may include cochlear nerve deficiency, acoustic neuroma, central auditory processing disorders and cochlear ossification, some of which may occur more commonly in cases of single-sided or highly asymmetric hearing loss. Studies have shown variability in common aetiologies between more standard CI and EAS recipients and AHL and SSD recipients. For instance, among Japanese CI recipients, Usami et al. (2017) reported idiopathic sudden sensorineural hearing loss (SSD 55%, AHL 16%) and chronic otitis media/cholesteotoma (SSD 13%, AHL 30%) to be the most common aetiologies for post-lingually deaf recipients ($n = 182$), whereas among more standard CI and EAS recipients Miyagawa, Nishio, and Usami (2016) ($n = 81$) reported the most common aetiologies as unknown (58%), genetic (36%), otosclerosis (2%), chronic otitis media (2%) and acoustic neuroma (1%). Both studies also found pre-lingually deaf recipients' aetiologies to vary considerably. For example for SSD and AHL recipients ($n = 210$), cochlear nerve deficiency (SSD 40%, AHL 28%) and cytomegolovirus (SSD 6%, AHL 29%) were found to be most common, whereas generic (60%), syndromic (9%), cytomegolovirus (5%) and inner ear malformation (5%) were most common for standard CI/EAS recipients ($n = 92$). Whilst aetiology prevalence among CI recipients may vary between countries, such factors should be considered in the context of this study. Unfortunately, it was not possible to access medical records in this study; thus, it was not possible to ascertain any medical reasons for why recipients may not have meet CI candidacy.

The lower CI uptake rates observed within the groups with more residual hearing are multifactorial. Those with greater levels of hearing may perceive lower levels of hearing disability. Arndt et al. (2017) showed higher subjective hearing ability, using the Speech and Spatial Hearing Questionnaire (SSQ), pre-operatively among CI candidates with SSD compared to those with AHL. Holder et al. (2018) reported greater levels of residual hearing and better pre-operative speech discrimination among their cohort who did not proceed to implant than those proceeding to implant. Arndt et al. (2017) reported better localisation in some conditions pre-operatively for subjects with SSD compared with subjects with AHL. In studies looking at hearing aid uptake, Golub et al. (2018) showed that around two-thirds of individuals with moderate-or-worse unilateral hearing loss reported, no or mild, subjective hearing difficulty; however, only 11% of these individuals used hearing aids. Barnett et al. (2017) showed that hearing impaired individuals who perceive a lower level of hearing disability were less likely to pursue intervention (Barnett et al. 2017). In the absence of published studies relating to CI uptake, it is reasonable to assume that similar issues would be in play for CI candidates.

Lower CI uptake rates may also be related to uncertain outcomes for less traditional hearing loss configurations. Whilst there is a large body of research documenting outcomes for individuals with symmetrical hearing loss (Leigh et al. 2016; Sorkin 2013), outcomes for other HL configurations are less widely known. Candidates may also have been influenced by the cost of surgery (Barnett et al. 2017; Sorkin 2013) or fear of, or medical contraindications for, surgery (Saito et al. 2019). Aesthetics of the external sound processor may also influence candidates' decision to proceed with a CI. Candidates, particularly within the SSD, AHL2 and EAS groups, may be accustomed to either not using hearing aids at all or using aids that are significantly smaller than any speech processors currently available. Research has shown that the stigma associated with use of a visible sound processor, and the perception of negativity both socially and in the workplace, towards individuals with communication difficulties may result in a reluctance to pursue cochlear implantation (Barnett et al. 2017). Thus, a candidate may choose to hide their hearing loss, which is easier to do if they can rely on hearing relatively well through their better hearing ear in some situations.

Previous studies have shown variable influence of age on CI uptake. Sorkin and Buchman (2016) indicated lower levels of CI use among younger adults aged under 30 years compared with adults over the age of 65, whilst Raine (2014) showed lower CI penetrance levels but a greater number of implant surgeries with increasing age. In this study, the candidate's age was found to be a significant factor in CI uptake rate for some HL configurations. The mean age of referred SSD candidates was significantly lower than other HL configurations. Numbers of individuals with SSD will predictably drop over time due to presbyacusis. The younger age of the SSD candidates could also be due to referrer bias relating to the balance between hearing disability and surgical risk. Alternatively, younger SSD candidates may perceive greater hearing disability if they are exposed to more complex sound environments both socially and in the workplace. Our results suggested that those individuals who declined a cochlear implant were younger among the AHL2 and SSD groups than the other hearing loss configurations. With increasing age, deterioration in overall hearing, vision and central auditory processing may increase the individual's perceived hearing handicap, motivating them to pursue intervention (Barnett et al. 2017).

The impact that the growing number of non-traditional candidates has on an implant clinic must be considered. Pre-operatively, compared to traditional CI candidates, additional assessments, more sensitive to varying hearing difficulties, comparing a variety of management options, are required (Van de Heyning et al. 2016). Additional counselling, particularly in relation to the management of expectations, is also recommended (Tavora-Vieira and Marino 2019). Post-operatively, recipients with relatively good hearing in the non-implanted ear, i.e. a dominant ear, may either subconsciously, or consciously, focus on the sound from the better hearing ear, potentially slowing progress with the implant in comparison with traditional recipients who generally hear better from the implant than their non-implanted ear (Tavora-Vieira and Marino 2019). Those within the EAS category can require additional rehabilitation and mapping appointments (Li, Kuhlmey, and Kim 2019) to combine electric and acoustic stimulation to ensure that the recipient obtains optimum benefit from their implant.

In order to improve CI uptake rates further, research is required into CI outcomes relating to both speech and quality of life with assessments sensitive to changes across all HL configurations. Such information would allow for more accurate counselling and creation of more accurate prediction models. Additional research into CI candidates' motivation to proceed, potential drivers and barriers to implantation is also required. Finally, further research into ways in which speech processor aesthetics can be improved to make them more acceptable to a broader range of individuals is required.

Conclusion

CI candidates with greater levels of residual hearing in at least the contralateral ear are less likely to proceed to CI, in the most part, regardless of age or gender. This should be considered when allocating clinician resources and considering potential future programme funding within an implant clinic applying expanded candidacy criteria. Further research is required into the barriers to uptake experienced by audiologically suitable CI candidates with greater levels of hearing in both the implanted and non-implanted ears.

Acknowledgements

The authors thank Azadeh Ebrahimi for valuable assistance and suggestions in the final review of this paper and the clinicians of the Ear Science Clinic for their diligent work in assessing individuals for CI candidacy.

Declaration of interest

No potential conflict of interest was reported by the authors.

This project was funded by the Ear Science Institute Australia.

Data availability

Data used in the study is held at the Ear Science Institute. Due to the de-identified nature of the data used in the study, the University of Western Australian Human Research Ethics Office provided exemption from ethics review (Ref: RA/4/20/5592).

References

Access Economics. 2006. “Listen hear! the economic impact and cost of hearing loss in Australia.” https://apo.org.au/node/2755

Arndt, S., R. Laszig, A. Aschendorff, F. Hassepass, R. Beck, and T. Wesarg. 2017. “Cochlear Implant Treatment of Patients with Single-Sided Deafness or Asymmetric Hearing Loss.” *HNO* 65 (Suppl 2): 98–108. doi:10.1007/s00106-016-0297-5.

Barnett, M., B. Hixon, N. Okwiri, C. Irungu, J. Ayugi, R. Thompson, J. B. Shinn, and M. L. Bush. 2017. “Factors Involved in Access and Utilization of Adult Hearing Healthcare: A Systematic Review.” *The Laryngoscope* 127 (5): 1187–1194. doi:10.1002/lary.26234.

Boisvert, I., C. M. McMahon, R. C. Dowell, and B. Lyxell. 2015. “Long-Term Asymmetric Hearing Affects Cochlear Implantation Outcomes Differently in Adults with Pre- and Postlingual Hearing Loss.” *PLoS One* 10 (6): e0129167. doi:10.1371/journal.pone.0129167.

Boothroyd, A., L. Hanin, and T. Hnath. 1985. “A Sentence Test of Speech Perception: reliability, Set Equivalence, and Short Term Learning.” *CUNY Academic Works:* 1–18.

Chia, E. M., J. J. Wang, E. Rochtchina, R. R. Cumming, P. Newall, and P. Mitchell. 2007. “Hearing Impairment and Health-Related Quality of Life: The Blue Mountains Hearing Study.” *Ear and Hearing* 28 (2): 187–195. doi:10.1097/AUD.0b013e31803126b6.

Cochlear Ltd. 2016. “Determining Candidacy for the Cochlear™ Nucleus® Hybrid™ System.” https://www.cochlear.com/us/for-professionals/products/cochlear-nucleus-hybrid-implant-system/candidacy

Firszt, J. B., L. K. Holden, R. M. Reeder, L. Cowdrey, and S. King. 2012. “Cochlear Implantation in Adults with Asymmetric Hearing Loss.” *Ear and Hearing* 33 (4): 521–533. doi:10.1097/AUD.0b013e31824b9dfc.

Golub, J. S., F. R. Lin, L. R. Lustig, and A. K. Lalwani. 2018. “Prevalence of Adult Unilateral Hearing Loss and Hearing Aid Use in the United States.” *The Laryngoscope* 128 (7): 1681–1686. doi:10.1002/lary.27017.

Haussler, S. M., V. Kopke, S. Knopke, S. Grabel, and H. Olze. 2019. “Multifactorial Positive Influence of Cochlear Implantation on Patients with Single-Sided Deafness.” *Laryngoscope* 130 (2): 500–506. doi:10.1002/lary.28007.

Health Networks Branch. 2011. “Clinical Guidelines for Adult Cochlear Implantation.” Perth, Western Australia: Health Networks Branch, Department of Health. https://ww2.health.wa.gov.au/~/media/Files/Corporate/general%20documents/Health%20Networks/Neurosciences%20and%20the%20Senses/Clinical-Guidelines-for-Adult-Cochlear-Implantation.pdf

Holder, J. T., S. M. Reynolds, L. W. Sunderhaus, and R. H. Gifford. 2018. “Current Profile of Adults Presenting for Preoperative Cochlear Implant Evaluation.” *Trends in Hearing* 22: 2331216518755288. doi:10.1177/2331216518755288.

Irving, S., L. Gillespie, R. Richardson, D. Rowe, J. B. Fallon, and A. K. Wise. 2014. “Electroacoustic Stimulation: Now and Into the Future.” *BioMed Research International* 2014: 350504. doi:10.1155/2014/350504.

Jayakody, D. M. P., P. L. Friedland, R. H. Eikelboom, R. N. Martins, and H. R. Sohrabi. 2018. “A Novel Study on Association between Untreated Hearing Loss and Cognitive Functions of Older Adults: Baseline Non-Verbal Cognitive Assessment Results.” *Clinical Otolaryngology* 43 (1): 182–191. doi:10.1111/coa.12937.

Keidser, G., and M. Seeto. 2017. “The Influence of Social Interaction and Physical Health on the Association between Hearing and Depression with Age and Gender.” *Trends Hear* 21: 2331216517706395. doi:10.1177/2331216517706395.

Kitterick, P. T., and L. Lucas. 2016. “Predicting Speech Perception Outcomes following Cochlear Implantation in Adults with Unilateral Deafness or Highly Asymmetric Hearing Loss.” *Cochlear Implants Int* 17 Suppl 1 (Suppl 1): 51–54. doi:10.1080/14670100.2016.1155806.

Leigh, J. R., M. Moran, R. Hollow, and R. C. Dowell. 2016. “Evidence-Based Guidelines for Recommending Cochlear Implantation for Postlingually Deafened Adults.” *International Journal of Audiology* 55 Suppl 2 (Suppl 2): S3–S8. doi:10.3109/14992027.2016.1146415.

Li, C., M. Kuhlmey, and A. H. Kim. 2019. “Electroacoustic Stimulation.” *Otolaryngologic Clinics of North America* 52 (2): 311–322. doi:10.1016/j.otc.2018.11.008.

Looi, V., C. Bluett, and I. Boisvert. 2017. “Referral Rates of Postlingually Deafened Adult Hearing Aid Users for a Cochlear Implant Candidacy Assessment.” *International Journal of Audiology* 56 (12): 919–925. doi:10.1080/14992027.2017.1344361.

Margolis, R. H., and G. L. Saly. 2008. “Asymmetric Hearing Loss: Definition, Validation, and Prevalence.” *Otology & Neurotology: Neurotology* 29 (4): 422–431. doi:10.1097/MAO.0b013e31816c7c09.

Med-El. 1999. “MedEL Candidacy for EAS.” https://www.medel.com/eas-candidacy.

Miyagawa, M., S. Y. Nishio, and S. Usami. 2016. “A Comprehensive Study on the Etiology of Patients Receiving Cochlear Implantation with Special Emphasis on Genetic Epidemiology.” *Otology & Neurotology* 37 (2): e126–134. doi:10.1097/MAO.0000000000000936.

Raine, C. 2014. “Access to and Uptake of Cochlear Implants in the UK.” https://www.entandaudiologynews.com/features/audiology-features/post/access-to-and-uptake-of-cochlear-implants-in-the-uk

Raine, C., H. Atkinson, D. R. Strachan, and J. M. Martin. 2016. “Access to Cochlear Implants: Time to Reflect.” *Cochlear Implants International* 17 (sup1): 42–46. doi:10.1080/14670100.2016.1155808.

Saito, K., T. Fujita, Y. Osaki, H. Koyama, K. Shiraishi, T. Kobayashi, M. Sato, T. Seo, and K. Doi. 2019. “Prevalence of Potential Candidates for Electric-Acoustic Stimulation Implant in a Hearing-Impaired Population.” *Auris Nasus Larynx*. doi:10.1016/j.anl.2019.07.006.

Skinner, M. W., L. K. Holden, M. S. Fourakis, J. W. Hawks, T. Holden, J. Arcaroli, and M. Hyde. 2006. “Evaluation of Equivalency in Two Recordings of Monosyllabic Words.” *Journal of the American Academy of Audiology* 17 (5): 350–366. doi:10.3766/jaaa.17.5.5.

Snel-Bongers, J., A. P. Netten, P. B. M. Boermans, L. J. C. Rotteveel, J. J. Briaire, and J. H. M. Frijns. 2018. “Evidence-Based Inclusion Criteria for Cochlear Implantation in Patients with Postlingual Deafness.” *Ear and Hearing* 39 (5): 1008–1014. doi:10.1097/AUD.0000000000000568.

Sorkin, D. L. 2013. “Cochlear Implantation in the World's Largest Medical Device Market: Utilization and Awareness of Cochlear Implants in the United States.” *Cochlear Implants International* 14 (Suppl 1): S4–S12. doi:10.1179/1467010013Z.00000000076.

Sorkin, D. L., and C. A. Buchman. 2016. “Cochlear Implant Access in Six Developed Countries.” *Otology & Neurotology* 37 (2): e161–164. doi:10.1097/MAO.0000000000000946.

SyStat. 2016. Sigma Stat Version 4.0. (4.0).

Tavora-Vieira, D., and R. Marino. 2019. “Re-Training the Deaf Ear: Auditory Training for Adult Cochlear Implant Users with Singlesided Deafness.” *Cochlear Implants International* 20 (5): 1–6. doi:10.1080/14670100.2019.1603652.

Usami, S. I., Kitoh R., Moteki H., Nishio, S. Y., Kitano, T., Kobayashi Watanabe, Shinagawa, J., Yokota, Y., Sugiyama K., and K. Watanabe. 2017. “Etiology of Single-Sided Deafness and Asymmetrical Hearing Loss.” *Acta Oto-Laryngologica* 137 (sup565): S2–S7. doi:10.1080/00016489.2017.1300321.

Van de Heyning, P., D. Tavora-Vieira, G. Mertens, V. Van Rompaey, G. P. Rajan, J. Muller, J. M. Hempel, et al. 2016. “Towards a Unified Testing Framework for Single-Sided Deafness Studies: A Consensus Paper.” *Audiology & Neuro-Otology* 21 (6): 391–398. doi:10.1159/000455058.

von Ilberg, C., J. Kiefer, J. Tillein, T. Pfenningdorff, R. Hartmann, E. Sturzebecher, and R. Klinke. 1999. “Electric-Acoustic Stimulation of the Auditory System. New Technology for Severe Hearing Loss.” *ORL: Journal for Oto-Rhino-Laryngology and Its Related Specialties* 61 (6): 334–340. doi:10.1159/000027695.

Welch, C., M. T. Dillon, and H. C. Pillsbury. 2018. “Electric and Acoustic Stimulation in Cochlear Implant Recipients with Hearing Preservation.” *Seminars in Hearing* 39 (4): 414–427. doi:10.1055/s-0038-1670707.

Wilson, B. S., and M. F. Dorman. 2008. “Cochlear Implants: A Remarkable past and a Brilliant Future.” *Hearing Research* 242 (1–2): 3–21. doi:10.1016/j.heares.2008.06.005