Predicting Sequential Cochlear Implantation Performance: A Systematic Review

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Keywords

Predict · Sequential · Bilateral · Cochlear implantation · Adult · Hearing loss

Abstract

This systematic review of the literature reveals which preoperative factors affect sequential cochlear implantation outcomes in adults. The findings can help health care professionals provide evidence-based advice on the expected benefits from a second cochlear implant (CI). We searched PubMed, EMBASE, and the Cochrane database from November 1977 to August 26, 2017, using the terms “sequential cochlear implantation”; the most frequently cited predictors for unilateral cochlear implantation performance and other potential predictors for sequential implantation outcome; and “speech perception,” “localization” as well as synonyms of all of the above. Ten studies were included. The effects of age, duration of hearing loss, time between implantations, preoperative hearing, etiology of hearing loss, hearing aid use and duration of follow-up on sequential cochlear im-

plantation performance were studied. The literature has shown that duration of deafness, age at onset of deafness, etiology of hearing loss, and preoperative speech perception score are (inversely) related to unilateral cochlear implantation outcome in adults. One would expect that these factors would also affect sequential bilateral implantation outcome. However, the best available evidence to date shows that advanced age, a long duration of deafness, or a long interval between implantations should not be considered negative factors when considering sequential bilateral cochlear implantation.

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Introduction

Bilateral cochlear implantation is becoming a common treatment for bilateral hearing loss in a growing number of countries. It is widely recognized that bilateral implantation provides important hearing benefits including enhanced sound localization, greater speech-in-noise un-

Fig. 1. Article selection process according to the PRISMA guidelines.

derstanding, and an improved quality of life [Dunn et al., 2012; Laszig et al., 2004; Litovsky et al., 2006; Müller et al., 2002; Nopp et al., 2004; Tyler et al., 2007; Verschuur et al., 2005]. Bilateral cochlear implantation enables use of the head shadow, loudness summation, and binaural squelch effects [Kraaijenga et al., 2016; Van Deun et al., 2010]. Cochlear implant (CI) teams often make cost-benefit decisions of the sequential implant based on the literature, which is primarily focused on unilateral cochlear implantation. This shows that duration of deafness, age at onset of deafness, etiology of hearing loss, and preoperative speech perception score are (inversely) related to unilateral cochlear implantation outcome [Blamey et al., 2013; Friedland et al., 2010; Green et al., 2007; Holden et al., 2013; Leung et al., 2005; Rubinstein et al., 1999]. With the increasing demand for bilateral cochlear implantation, it would be useful if we could predict the level of benefit from a second CI. This would improve preoperative counseling, allow early identification of slow progress after implantation and ultimately ensure that patients who will benefit will receive a second CI. The goal of this systematic review of the literature is to analyze which preoperative factors affect outcomes, as defined by speech recognition and localization after sequential bilateral cochlear implantation according to the best available evidence to date.

Methods

Search Strategy

In conducting this systematic review, we followed the PRISMA guidelines [Moher et al., 2009]. To identify studies that assessed the factors that have an influence on cochlear implantation outcome, we searched PubMed, EMBASE, and the Cochrane database from November 1977 to August 2017, using the terms “sequential cochlear implantation” and its synonyms as the domain; the most frequently cited predictors for unilateral cochlear implantation performance, other potential predictors for sequential implantation outcome, and their synonyms as the determinants; and “speech perception or localization” and their synonyms as the outcome. The exact search strategy was: Cochlear implant* AND (sequent* OR bilateral OR second*) AND (predict* OR factor OR characteristic* OR variable* OR aetiol* OR etiol* OR age OR hearing preserv* OR hearing loss OR hearing depriv* OR duration of deaf* OR duration of hearing loss OR cause of deaf* OR speech intel* OR speech percept* OR hearing aid OR amplificat* OR gender OR comorbid* OR general health* OR delay OR inter implant* OR time OR interval) AND (speech* OR sound perception OR hearing OR listening OR in noise OR performance OR localis* OR localiz* OR lateralis* OR lateralize* OR speech). In addition, the titles and abstracts of the references of the relevant papers and related articles were screened (Fig. 1).

Study Selection

The first two named authors of this review independently screened all identified titles and abstracts. Potentially relevant studies were obtained and the full texts were obtained and read.

Table 1. Relevance and risk of bias

Study	Study design	Relevance ¹			Risk of bias ²					
		domain	deter- minant	out- come	study parti- cipation	study attrition	PF measure- ment	outcome measure- ment	study con- founding	statistical analysis and reporting
Nopp et al., 2004	cohort	+	+	+	–	+	–	+	–	+/-
Schleich et al., 2004	cohort	+	+	+	–	+	–	+	–	–
Ramsden et al., 2005	cohort	+	+	+	+/-	+/-	–	+	–	–
Zeitler et al., 2008	cohort	+	+	+	+	+/-	+/-	+	–	+
Laske et al., 2009	cohort	+	+	+	+	–	+/-	+	–	+
Dorman et al., 2012	cohort	+/-	+	+	–	–	+/-	+	–	+/-
Boisvert et al., 2012	cohort	+	+	+	+	+	+	+	+/-	+
Reeder et al., 2014	cohort	+	+	+	+	+/-	+/-	+	+/-	+
Boisvert et al., 2016	cohort	+	+	+	+/-	+/-	+/-	+	+/-	+
Ohta et al., 2017	cohort	+	+	+	+/-	–	+/-	+	–	+/-

¹ Domain: the patients included were adults who underwent sequential cochlear implantation. Determinant: the study describes predictive factors for performance with bilateral cochlear implants or performance with a second implant. Outcome: either speech understanding (in silence or noise) or localization. Relevant (+) and article is relevant but the main focus was on a different group of patients (+/-).

² Study participation: the sample represents the population of interest on key characteristics, sufficient to limit potential bias of the observed relationship between predictive factor and outcome. Study attrition: loss to follow-up (from baseline sample to study population analyzed) is not associated with key characteristics (i.e., the study data adequately represent the sample) sufficient to limit potential bias to the observed relationship between prognostic factor and outcome. Prognostic factor (PF) measurement: PF is adequately measured in study participants to sufficiently limit potential bias. Outcome measurement: outcome of interest is adequately measured in study participants to sufficiently limit potential bias. Study confounding: important potential confounders are appropriately accounted for, limiting potential bias with respect to the relationship between PF and outcome. Statistical analysis and reporting: appropriate for the design of the study, limiting the potential for presentation of invalid or spurious results. A low risk of bias (+), a moderate risk of bias (+/-), and a high risk of bias (–) according to a summary of the QUIPS tool for assessment of bias [Hayden et. al., 2013].

Criteria for inclusion and exclusion are shown in Figure 1. The relevance of studies was assessed by the same two researchers. We considered a study relevant when it conveyed the results of adult patients undergoing sequential cochlear implantation (domain), potential factors influencing the outcome (determinants) and when the outcome measure was either hearing, speech recognition, and/or sound localization (outcome) (Table 1). Subsequently, we assessed the chance of bias in each study. We used an approach based on the QUIPS tool [Hayden et al., 2013]. This is appropriate for prognostic factor review questions and has been recommended by the Cochrane Prognosis Methods Group. We assessed the risk of bias concerning 6 domains: study participation, study attrition, prognostic factor measurement, outcome measurement, study confounding, and statistical analysis and reporting (Table 1).

Data Extraction

From each study, we extracted the age at test, duration of deafness at test, duration of bilateral cochlear implant use, time interval between sequential implantations, and which outcome measures were used. Due to heterogeneity in the presentation of results from individual studies, we extracted information from graphs or directly calculated the results from data presented in tables when not originally reported. When we performed this, we indicated it with an asterisk. Due to large heterogeneity between the studies included, pooling of data was not possible. We therefore summarized the outcomes per study (Table 2).

Results

Our initial search generated a total of 3,216 possible relevant titles. After the removal of duplicates, 2,634 titles remained. Titles, abstracts, and full-text articles were consecutively screened for the inclusion and exclusion criteria (Fig. 1). Ten papers were included in this systematic review. The quality of the papers is summarized in Table 1. In most studies, the data were gathered retrospectively. Randomization did not take place in any of the studies.

Table 1 provides a summary of the study designs and quality assessment of the reviewed studies. All included studies were cohort studies. In order to be included in this systematic review, the domain, determinant, and outcome had to be relevant. The study of Dorman et al. [2012] included both bilaterally implanted patients and bimodal patients (wearing a CI and a hearing aid). The right 6 columns summarize the various risks of bias. They are further explained in the table footnote.

Table 2 shows the study characteristics of each study. It also indicates the total numbers of participants included in each study and performing the various tests. In the

Table 2. Study characteristics

Study	N	Age at the test, years	DOD at the test, years	Duration of bilateral CI use	Interval between implantation of CI1 and CI2, years	Test outcome
Nopp et al., 2004	20	45.1 [17–67]	13.6 [3–48]	>1 month	2.27 [0–5.62]	Localization (<i>n</i> = 20) Deviation (<i>n</i> = 20)
Schleich et al., 2004	21	44 [17.5–66.5]	12.9 [0.6–47.8]	>1 month	2.23 [0–5.67]	OST in noise (<i>n</i> = 21)
Ramsden et al., 2005	28	57 [29–82]	7.31 [1–15]	>9 months	3 [1–7]	CNC words in quiet (<i>n</i> = 25) CUNY in quiet (<i>n</i> = 26) and in noise (<i>n</i> = 25)
Zeitler et al., 2008	22	46.9	32.1 [3–58.3]	3 months	5.6 [0.5–10]	CNC words in quiet (<i>n</i> = 19) HINT and in quiet (<i>n</i> = 19)
Laske et al., 2009	29	31 (16) (age at CI1)	5.4 ^a (6.4)	>6 months	5.6 (5.7) [0–19]	OST in quiet (<i>n</i> = 23) and in noise (<i>n</i> = 16) Localization (<i>n</i> = ?)
Dorman et al., 2012	61	[19–81]	11.7	3.8 years	?	CNC words in quiet (<i>n</i> = 61)
Boisvert et al., 2012	10	61 [37–88] (age at CI2)	38.9 [23–72] (DOD before CI1) 28.9 [6–61] (DOD before CI2)	1 year	46 [13–83] months	Average of: CNC words in quiet (<i>n</i> = ?) CUNY in quiet (<i>n</i> = ?) and in noise (<i>n</i> = ?)
Reeder et al., 2014	21	48.5 (8.7) [36–74] (age at CI1) 53.8 (8.0) [44–75] (age at CI2)	16.8 (14.6) [<1–45] (DOD before CI1) 21.4 (16.8) [<1–55] (DOD before CI2)	1, 3, 6, 9, and 12 months	5.2 (4.6) [1–17]	CNC words (<i>n</i> = 17–21) HINT sentences (<i>n</i> = 16) ^b TIMIT sentences in quiet and in noise (<i>n</i> = 17–21) BKB-SIN test (<i>n</i> = 17–21) Localization (<i>n</i> = 17–21)
Boisvert et al., 2016	67	62.6 (10.1) (age at CI1) 67.1 (10.4) [50–87] (age at CI2)	11.8 (13.5) (DOD before CI1) 12.5 (14.2) (DOD before CI2)	1 year	4.5 (4.6)	CNC phoneme score for each individual ear (<i>n</i> = 67) CNC phoneme score with 2 CIs (<i>n</i> = 40)
Ohta et al., 2017	34	54 [25–75] (age at CI1) 60 [33–79] (age at CI2)	6.9 [0.25–59] (DOD before CI1)	≤1 year	6 [1 month– 24.4 years]	In silence: WRS (<i>n</i> = 21) and SRS (<i>n</i> = 22) In noise: WRS (<i>n</i> = 13) and SRS (<i>n</i> = 13)

Values are expressed as mean (SD) [range], unless otherwise indicated. DOD, duration of deafness; CNC, consonant-nucleus-consonant; HINT, hearing-in-noise test; CUNY, City University of New York sentence test; OST, Oldenburger sentence test; BKB-SIN, Bamford-Kowal-Bench speech-in-noise test; TIMIT, database of sentences in different American dialects, joint effort between Texas Instruments (TI), the Massachusetts Institute of Technology (MIT) and the Stanford Research Institute; WRS, word recognition score; SRS, sentence recognition score.

^a Data derived from graphs or tables.

^b CI2 data at the 9-month interval were available for only 16 patients.

study of Boisvert et al. [2012], it was not clear if all 10 participants participated in each test. Reeder et al. [2014] also did not indicate how many participants performed each test.

Table 3 shows which preoperative factors were analyzed in each study and which factors had an effect on hearing performance. A factor could be correlated to the study outcome or be a predictor.

Discussion

This systematic review summarizes which preoperative factors play a role in the prediction of sequential cochlear implantation performance according to the literature available to date. This knowledge can assist health care professionals to provide evidence-based advice when managing the expectations from a second CI. The includ-

Table 3. Preoperative factors and statistical approach

	Age		Hearing loss		Other preoperative factors					Statistical methods				
	at the at test	at CI1	at CI2	age at onset (1st ear)	age at onset (2nd ear)	duration (bilateral)	duration (1st ear)	duration (2nd ear)	time between implantations	PTA	phoneme score with first CI	hearing loss etiology	hearing aid use	follow-up duration
Nnopp et al., 2004	×	–	–	○	○	–	×	×	○	–	–	×	×	×
Schleich et al., 2004	×	–	–	–	–	–	○	○	○	–	–	×	–	×
Ramsden et al., 2005	×	–	–	–	–	–	×	–	○	×	–	–	×	×
Zeitler et al., 2008	–	–	○	–	–	–	○	○	○	×	–	×	×	×
Laske et al., 2009	–	–	–	–	–	–	○	–	+	–	–	–	–	○
Dorman et al., 2012	○	–	–	–	–	×	–	–	–	–	–	–	–	×
Boisvert et al., 2012	×	×	○	–	–	○	×	○	○	○	–	×	×	×
Reeder et al., 2014	×	×	×	○	○	–	×	○	○	×	×	×	×	×
Boisvert et al., 2016	×	×	+	–	–	–	○	○	○	○	○	–	–	–
Ohta et al., 2017	–	×	×	–	–	○	–	–	○	×	○	×	×	–
CI, cochlear implant; PTA, pure tone audiometry; ANOVA, analysis of variance; GLM, generalized linear model; LOD, length of deafness. The preoperative factor is not mentioned in the article at all (–); the preoperative factor is mentioned in the article (data are known by the authors) but not included in any further analyses (×); the effect of the preoperative factor on the study outcome is analyzed and there is no correlation with the outcome (○), the effect of the preoperative factor on the study outcome is analyzed and there is a significant correlation (+) (the factor is, however, not a significant predictive factor); the effect of the preoperative factor on the study outcome is analyzed and identified as a significant predictive factor (○).														

ed studies are, unfortunately, heterogeneous and predominately retrospective chart review studies, with level 3 evidence [Shekelle et al., 1999]. The goal of most studies was to examine the benefit of sequential bilateral implantation over unilateral implantation [Laske et al., 2009; Nopp et al., 2004; Ohta et al., 2017; Ramsden et al., 2005; Reeder et al., 2014; Schleich et al., 2004]. Whether or not certain prognostic factors influenced the study outcome was a secondary outcome in these studies. As displayed in Table 1, the prognostic factors of interest were inadequately defined in a number of studies. For example, while some studies defined “deafness” as severe-to-profound [Boisvert et al., 2012; Dorman et al., 2012; Laske et al., 2009; Ramsden et al., 2005; Reeder et al., 2014; Zeitler et al., 2008], Ohta et al. [2017] described it as an average of ≥ 110 dB HL and the remaining 3 papers provided no definition at all for deafness [Boisvert et al., 2016; Nopp et al., 2004; Schleich et al., 2004]. Due to the abovementioned issues, the pooling of data was not possible and drawing straightforward conclusions was challenging.

Correlations and Predictors

Several studies reported correlations between preoperative factors and the study outcome [Dorman et al., 2012; Nopp et al., 2004; Zeitler et al., 2008]. Correlation is a measure of association between two variables. The correlation coefficient (r) tells how much one variable tends to change when the other one does, and when $r = 0$, there is no relationship. When r is positive, there is a trend that one variable increases as the other one does, and when r is negative, there is a trend that one variable decreases as the other one does. To examine the strength between a possible predictive factor and outcome, or to create a prediction model, a stepwise multiple-regression analysis would be required. This is only possible when a study sample is large enough, because for each factor studied in such a regression analysis, a minimum of 10 patients is required.

Sequential cochlear implantation performance may be influenced by a long duration of deafness. Reeder et al. [2014] found that a prolonged duration of severe-to-profound deafness before the second cochlear implantation was a predictor for poor performance after sequential cochlear implantation with CI1, CI2, and both implants (consonant-nucleus-consonant [CNC] words, HINT in noise, TIMIT in noise, TIMIT in quiet, localization, and BKB-SIN with noise from the front). However, they noted that this effect could possibly be attributed to other time-based hearing history variables as they found a significant correlation between the duration of deafness in

the second implanted ear on the one hand, and duration of deafness in the first implanted ear, age at the onset of severe-to-profound hearing loss, and time between surgeries on the other. Unfortunately, their sample size was not large enough to differentiate each time-based effect. Boisvert et al. [2012] showed that the duration of bilateral severe hearing loss was a predictor for sequential implantation outcome (speech recognition with CI1 and CI2). However, they based their conclusions on a study involving only 10 patients, who had been included in the study because they had a long-standing hearing loss before the first cochlear implantation (selection bias). No significant correlation between the duration of hearing loss and sequential cochlear implantation outcome was found in 5 other studies [Boisvert et al., 2016; Laske et al., 2009; Ohta et al., 2017; Schleich et al., 2004; Zeitler et al., 2008]. The current literature does not consistently measure and analyze all of the important time-based hearing history variables such as duration of deafness in each ear and both ears together, age at onset of hearing loss and implantation, and time between implantations. Therefore, robust conclusions cannot be made as to what effect the duration of severe-to-profound deafness has on the outcomes of sequential bilateral cochlear implantation.

Boisvert et al. [2016] showed that the most reliable predictor of phoneme recognition scores in quiet for the second CI and for bilateral CIs was the phoneme recognition score with the first CI. Ohta et al. [2017] did not find a significant correlation between word and sentence recognition scores in silence with the first and second CIs, but their study was less robust (Table 1). Although speech understanding with the first CI seems an important factor and is possibly the best predictor of sequential implantation performance, unfortunately, no other studies assessed its predictive value. In order to examine if speech understanding with the first CI is indeed a reliable predictor, more studies should be performed.

In the 4 studies that analyzed the effect of age, there was an agreement that advanced age at implantation did not lead to a reduced sequential implantation outcome [Boisvert et al., 2012, 2016; Dorman et al., 2012; Zeitler et al., 2008]. Boisvert et al. [2016] did find a negative correlation between age and phoneme recognition performance in quiet with CI1, CI2 and bilateral CIs, but concluded that it was not a predictor for poor outcome. The upper limit of the patients' ages in this review study was 87 years. Unfortunately, in 5 studies, the ages were reported but the authors did not describe the relationship between age and study outcome. While patients worldwide are getting older and cochlear implantation becomes

available for an increasing amount of elderly patients, studying the effect of age will remain important.

The degree of hearing loss (pure tone average) before implantation had no influence on the phoneme recognition score with the second CI or with both CIs together according to Boisvert et al. [2016]. The study of Boisvert et al. [2012] reported no correlation between the pure tone average and the average speech reception score (SRS) with CI1 or CI2 (averaging the results of the City University of New York sentence test in quiet and in noise and CNC word lists).

The effect of the length of the interval between implantations was analyzed in all studies but one. Intervals varied between 1 month and 24.4 years, but did not affect sequential cochlear implantation performance in any of the studies [Boisvert et al., 2012, 2016; Laske et al., 2009; Nopp et al., 2004; Ohta et al., 2017; Ramsden et al., 2005; Reeder et al., 2014; Schleich et al., 2004; Zeitler et al., 2008]. For that reason, a long interval between implantations should not be considered a contraindication for sequential cochlear implantation. This is different from the pediatric population. Neurophysiological background studies have shown that implantation of both implants before the age of 3.5 years is important for binaural pathway development [Sharma et al., 2005]. In postlingually deafened adults, the binaural auditory system and auditory cortex are well developed and early second implantation seems less vital [Eggermont, 2008].

Comparison with Literature on Predictive Factors in Unilateral Cochlear Implantation

Several large studies have been published on the factors that may affect unilateral cochlear implantation performance. Duration of deafness and age at onset of hearing loss have consistently been reported as being inversely related to unilateral cochlear implantation outcome. [Blamey et al., 2013; Green et al., 2007; Holden et al., 2013; Leung et al., 2005; Rubinstein et al., 1999]. However, these correlations are not as apparent in studies on sequential bilateral implantation. It is possible that age at implantation and duration of deafness have an impact on the performance of the first CI, but as soon as the brain has adapted to the listening situation with one CI, those factors may no longer be important for the benefit of the second CI. The performance level with the first CI may be a more important predictor than other preoperative factors that played a role in unilateral implantation.

The literature has shown that there is no consensus on the effect of age at the time unilateral implantation. Some studies described poorer results for patients older than

60/65 years [Blamey et al., 2013; Friedland et al., 2010; Holden et al., 2013], but then others observed no difference in speech recognition scores between younger and older CI recipients [Budenz et al., 2011; Carlson et al., 2010]. Blamey et al. [2013] found that etiology was significantly related to speech recognition; meningitis patients had lower speech recognition while patients with Meniere's disease had higher speech recognition than patients with other etiologies. The effect of etiology on sequential bilateral implantation outcome has not yet been described in the literature.

Clinical Relevance

Prior to cochlear implantation, audiologists and otologists usually discuss what performance levels and outcomes a patient may expect. In their judgment, when considering which patients are suitable candidates for implantation, they take into account each patient's characteristics and medical and hearing history. Much has been written about the preoperative factors affecting unilateral cochlear implantation outcome, but literature on sequential bilateral implantation outcome is rather scarce. This systematic review shows that the success of sequential bilateral implantation performance does not depend on the same factors as in unilateral cochlear implantation. Based on the best evidence available to date, the factors advanced age, a long duration of deafness, or a long interval between implantations, do not necessarily lead to poor sequential cochlear implantation outcome. The level of performance of the first CI may be an important predictor for sequential implantation performance, but, to our knowledge, this has only been examined in 2 studies.

CI teams can use the current information to manage their patients' expectations. Importantly though, in order to offer patients accurate tailor-made advice, studies are needed that review the effect of all possible relevant preoperative factors and create a prediction model.

Disclosure Statement

The authors of this review study report no conflicts of interest.

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