Children using a unilateral cochlear implant and contralateral hearing aid: bimodal hearing outcomes when one ear is outside the UK (NICE 2009) audiological criteria for cochlear implantation – a single site case–control study

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ABSTRACT

Introduction In the new revised National Institute for Health & Care Excellence (NICE, TA56, 2019) guidelines for cochlear implantation (CI) there has been a clear stipulation that the hearing loss must be bilateral. Prior to this revision, children and young people (CYP) with asymmetrical thresholds had been considered for unilateral CI when one ear was in audiological criteria. Children with asymmetrical hearing loss represent an important cohort of potential CI candidates, who wait to be prevented from benefiting from CI unless evidence is produced to support implantation and maximise subsequent benefit.

The aim of this study is to evaluate the ‘real-life’ hearing performance in a group of children who have received a unilateral CI and who have hearing thresholds in the contralateral ear that are outside the current UK NICE 2019 audiological criteria for CI. The contralateral ear will be aided using a conventional hearing aid (HA). The outcomes from this ‘bimodal’ group will be compared with a group of children who have received bilateral CI, and a group of children using bilateral HA, to extend the current knowledge about the different performance levels between bilateral CI, bilateral HA and bimodal hearing in CYP.

Methods and analysis Thirty CYP aged 6–17 years old, 10 bimodal users, 10 bilateral HA users and 10 bilateral cochlear implant users will be subjected to a test battery consisting of: (1) spatial release from masking, (2) complex pitch direction discrimination, (3) melodic identification, (4) perception of prosodic features in speech and (5) TEN test. Subjects will be tested in their optimal device modality. Standard demographic and hearing health information will be collected. In the absence of comparable published data to power the study, sample size was determined on pragmatic grounds. Tests are exploratory and for hypothesis generating purposes. Therefore, the standard criterion of p<0.05 will be used.

Ethics and dissemination This has been approved by the Health Research Authority and NHS REC within the UK (22/EM/0104). Industry funding was secured via a competitive researcher-led grant application process. Trial results will be subject to publication according to the definition of the outcome presented in this protocol.

STRENGTHS AND LIMITATIONS OF THIS STUDY

⇒ This study will use measures of ‘real-life’ performance, such as music perception and speech-in-noise, rather than mainstream outcome measurement instruments which may not provide sufficient detail to elucidate benefit. This could help provide evidence that could aid preoperative decision-making for borderline cochlear implantation (CI) candidates.

⇒ The secondary outcome will offer insight into how feasible it is to conduct a battery of ‘real-life’ tests clinically in children and young people that can be used to support borderline CI candidates.

⇒ The primary limitation of this study is bias due to matching subjects between groups for potential underlying causal factors on outcomes.

INTRODUCTION

The lowering of the audiological criteria for cochlear implantation (CI) in the revised 2019 NICE1,2 guidelines is welcomed. The previous 2009 guidelines required hearing thresholds worse than 90 dBHL at 2 and 4 KHz whereas the new guidelines state thresholds can be equal to or worse than 80 dBHL at any two frequencies of 0.5, 1, 2, 3, 4 KHz. However, the new guidelines have clearly stipulated that the hearing loss must be bilateral. Prior to this revision, children and young people (CYP) with asymmetrical thresholds, either
those with unilateral hearing loss or single-sided deafness (where the better-hearing ear is normal) or bilateral asymmetric hearing loss (where the better-hearing ear is also impaired to some degree) have been considered for unilateral CI when one ear was in audiological criteria, providing it was clear that they were not making anticipated progress in speech, language and education. Currently, unilateral hearing loss occurs in approximately 0.6 per 1000 births. The latest revision will have a significant effect on those CYP with asymmetrical hearing loss (AHL), who will be prevented from benefiting from this life-changing intervention. Children with AHL represent an important cohort of potential CI candidates, who will continue to be prevented from benefiting from CI unless evidence is produced to support implantation and maximise subsequent benefit.

Our increasing understanding of the importance of access to binaural hearing from early childhood contributes to the decision-making around CI candidacy. Children with binaural electrical-only or electro-only acoustic stimulation achieve higher academic outcomes, have better localisation acuity and speech recognition, and have a better social integration in the hearing environment.

Positive outcomes of CI in children with AHL have been reported in the literature together with the importance and benefits of bimodal hearing. Despite these positive outcomes, bimodal hearing comes with some limitations compared with binaural electrical or binaural acoustical hearing in certain audiological domains. Literature concerning this subject in the paediatric population remains scarce, further complicated by the difficulty in assessment and rehabilitation of young children with an AHL.

To aid multidisciplinary CI teams in their decision-making around individual patients, an evolving understanding of audiological performance of children with different hearing modalities on various audiometric domains is essential. Furthermore, the field would benefit from the identification of formal set of tools that are clinically feasible in the paediatric population, including domains such as sound localisation, speech perception, music perception and listening effort.

**Study aim**

The aim of this study is to investigate the hearing performance in complex listening situations in a group of children who have received a unilateral CI and who have moderate-to-severe hearing thresholds in the contralateral ear that are outside the current UK NICE 2019 audiological criteria for CI. The contralateral ear will be aided using a conventional hearing aid (HA). The outcomes from this ‘bimodal’ group will be compared with a group of children who have received bilateral CI and a group of children using bilateral HA, to extend the current knowledge about the different performance levels between bilateral CI, bilateral HA and bimodal hearing in CYP. Accomplishing this would represent an important step towards truly meaningful shared decision-making in those with borderline hearing thresholds.

**Primary objective**

- To meaningfully explore the benefit of bimodal hearing using a CI and HA in children that are out of the current UK NICE 2019 audiological criteria for CI.
- To evaluate compliance to the study protocol test battery, the number of tests fully completed.

**METHODS AND ANALYSIS**

This is a single-site, case–control, observational study with prospective data collection that does not involve any change from standard care. Single measure design with five outcome domains tested for each subject. Participants will be matched between the three groups as far as possible to the same age, hearing thresholds, and duration of HA or cochlear implant use where applicable.

Subjects will be selected from our database of paediatric patients who have undergone CI using either bilateral CI or bimodal (CI+HA) and bilateral HA users at the Royal Manchester Children’s Hospital. If they meet the inclusion/exclusion criteria (see table 1) trained research personnel will obtain informed consent (and assent if appropriate) from the patient/parent (see online supplemental files 1–3).

At the time of enrolment, we will record the demographic information: see table 2.

The research audiologist will prospectively perform all hearing assessments for each participant assigned into the following groups:

- Bimodal (CI and contralateral HA).
- Bilateral CI group.
- Bilateral HA group.

The test order is randomised to limit the effect of fatigue.

The audiological test battery described below has been utilised previously within another study by our group investigating borderline cochlear implant candidacy and more specifically hearing preservation. We are using a very similar auditory test battery/methodology in the current study to help standardise the outcomes obtained.

**Spatial release from masking**

To simulate complex auditory environments with competing sounds, participants will be tested on spatial release from masking. Targeted speech will be presented from the front (0°) with the 4-talker babble masker coming from the front (0°) or the side of the one ear (90° or −90°) followed by the side of the other ear (figure 1). Speech perception will be tested by the McCormick automated toy test for children younger than 7 years of age and the Bamford-Kowal-Bench sentence test for children older than 7 years of age (depending on child’s cognitive abilities) with a starting signal level of 60 dBSPL. To measure speech-reception thresholds (SRTs), the competing noise will be fixed at 60dBSL throughout the test.
Complex pitch direction discrimination test
The pitch direction test is implemented using a two-alternative, forced-choice test with one-up, one-down adaptive tracking. On each presentation, a tone at the alternative, forced-reversal at 0 is automatically added by the test algorithm when the user answers correctly at 1 semitone. Adaptive tracking is performed simultaneously with samples from the reference F0 and a higher-pitched tone determined by the adaptive interval size are played in random order. The minimum tested interval is 1 semitone (approximately 6% F0 difference), and the maximum is 12 semitones or 1 octave (100% increase in F0). To create an accurate psychometric function, a reversal at 0 is automatically added by the test algorithm when the user answers correctly at 1 semitone. Adaptive tracking is performed simultaneously with samples from 3 base frequencies (262 Hz (C4), 330 Hz (E4) and 391 Hz (G4)) interleaved in random order, until 3 trials of 8 reversals for each base frequency are completed. The threshold values for each base frequency are calculated separately by using the mean of the last six reversals for each trial and averaging the results from the three trials into a final threshold for discrimination of synthetic complex pitch direction change. The duration of the test varies according to the responses of the participant (figure 2).

Melodic identification test
Stimuli: A melody clip (total of 12), for example, Old MacDonald or Twinkle Twinkle Little Star tune is randomly presented (each melody is presented 3 times). Stimuli are presented from the front (0°) loudspeaker 1 m away. Each tone has a 500 ms duration and is presented at a tempo of 60 beats per minute. The amplitude of each note in the melody is randomly varied by ±4 dB, and five different versions of each melody are prerecorded. One version is randomly chosen each time the melody is presented, and all melodies are truncated at 8 s to prevent song length providing a potential cue. To eliminate rhythm cues for melody recognition, the melodies are created by repeating all longer notes in an eighth-note pattern, yielding isochronous melodies. The final score is reported as a percentage of correct response on the melodies with which the listener is familiar (figure 2).

Perception of prosodic stress in speech
To determine the subject’s ability to pick up on prosodic features of speech, an in-house test was developed by our lead speech and language therapist consisting of a voice recording of ten sentences. One sentence at a time is played and the participant has to circle/underline the stressed word in the sentence on a sheet of paper with the sentences written down. The stressed word is often described to the participant as the important word in the sentence. Participants have to be literate to complete the test, although further applications are considered with pictures replacing written words. An initial pilot study revealed normal hearing subjects outperformed bilateral CI subjects, with both outperforming unilateral CI participants (figure 2).

**Table 1** Inclusion/exclusion criteria

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
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<tbody>
<tr>
<td>Aged greater than/equal to 6 years old and less than 18 years old.</td>
<td>Aged greater than/equal to 18 years old.</td>
</tr>
<tr>
<td>Bilateral CI user OR bimodal (CI and contralateral HA) user with hearing thresholds better than 80 dBHL pure tone average across frequencies 0.5, 1.0, 2.0, 4.0 KHz OR bilateral HA user with hearing thresholds better than 80 dBHL pure tone average across frequencies 0.5, 1.0, 2.0, 4.0 KHz and symmetrical hearing loss with a difference of no more than 10 dBHL in the pure tone averages between the right and left ears.</td>
<td>Not a bilateral CI user OR bimodal (CI and contralateral HA) user with hearing thresholds better than 80 dBHL pure tone average across frequencies 0.5, 1.0, 2.0, 4.0 KHz OR bilateral HA user with hearing thresholds better than 80 dBHL pure tone average across frequencies 0.5, 1.0, 2.0, 4.0 KHz and symmetrical hearing loss with a difference of no more than 10 dBHL in the pure tone averages between the right and left ears.</td>
</tr>
<tr>
<td>Minimum duration of CI or HA use of 12 months.</td>
<td>Have used CI for less than 12 months.</td>
</tr>
<tr>
<td>English as native language.</td>
<td>Minimum duration of CI or HA use of 12 months.</td>
</tr>
<tr>
<td>A parent/guardian/carer/participant (as appropriate) has given their consent to take part in the study.</td>
<td>English as native language.</td>
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</table>

CI, cochlear implantation; HA, hearing aid.

**Table 2** Demographic information form

<table>
<thead>
<tr>
<th>Age of participant</th>
<th>Gender of participant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Two cochlear implants</td>
</tr>
<tr>
<td>Does the participant wear: (please tick one option)</td>
<td>Two cochlear implants</td>
</tr>
<tr>
<td></td>
<td>One cochlear implant and one hearing aid on the other ear</td>
</tr>
</tbody>
</table>

| Date of cochlear implant surgery (or year if precise date is not available) when received hearing aids |}

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Threshold equalising noise test
Cochlear dead regions can be diagnosed using threshold equalising noise test (TEN)\(^{20}\) by measuring masked threshold of a pure tone presented in the background of a spectrally shaped masker. The masker level is held constant and the signal level is adjusted to obtain the masked thresholds. TEN level is set to the highest acceptable level \(-5\) dB. Testing is only done at thresholds of 500 Hz, 750 Hz and 1000 Hz, given that higher frequencies are not of relevance with regards to low-frequency hearing preservation (125 Hz and 250 Hz are not part of the TEN test software). If for a specified frequency the masked threshold is \(10\) dB or more above TEN level, and the difference between masked and absolute threshold is \(\geq10\) dB, the result indicates presence of a death region at this frequency. The duration of the test is approximately 30 min. The TEN test is also validated for use with children as young as 8 years old. The inclusion for the study is 6 years old, therefore, those below this age within our population will not complete the test.

Statistical analysis plan
In the absence of previous information to power the study, sample size was determined on pragmatic grounds. Tests are exploratory and for hypothesis generating purposes. Therefore, the standard criterion of \(p<0.05\) will be used rather than corrected for multiple test effect.

Appropriate descriptive analysis of participants’ demographics and baselines will be provided. The number (%) of participants completed each part of the tests will be reported. Numeric outcome measures will be summarised for each test condition using mean/median (SD/IQR) depending on the distribution. Binary outcomes will be summarised by count (%).

Outcome domain 1: spatial release from masking: #
SRT score in control and intervention condition (numeric).
Analysis of variance (ANOVA) with three levels (hearing modality: CI only vs CI+HA (bimodal) vs HA only; with the outcome being mean SRT).

Outcome domain 2: complex pitch direction discrimination test
Interval size in control and intervention condition (numeric 0–12).
ANOVA (hearing modality: CI only vs CI+HA (bimodal) versus HA only. This will be completed for each base frequency: 262 Hz (C4 or middle C), 330 Hz (E4) and 391 Hz (G4)) with the outcome being mean percent score correct.
For outcome domains 1 and 2, if data not normally distributed, we will use Kruskal-Wallis test.

Outcome domain 3: melodic identification test
Correct response score in control and intervention condition (numeric/percentage 0–100).
T-test or equivalent non-parametric test.

Outcome domain 4: prosodic features in speech
Number of words correct in control and intervention condition (numeric/percentage 0–100).
T-test or equivalent non-parametric test.

Outcome domain 5: dead region testing descriptive statistics for presence or absence of dead region
Cochlear dead regions present or not in control and intervention condition (binary yes/no).
Fisher’s exact test.
A follow-up t-test will be performed to investigate differences in mean found by ANOVA.

Inference criteria: Number and percentage of participant completing the test and its 95% CI will be calculated. Reasons for incomplete test will be summarised.

Data exclusion: Outliers, that is, defined by standard box plot IQR multiplied by 1.5 will be included in the analysis. This was chosen as the data are exploratory and CI outcomes can be highly variable especially in the paediatric population.

Missing data: Due to differences in cognitive development, children might not be able to participate in a test despite meeting the age criterion. Furthermore, the T-N test has been shown to be validated upwards from 8 years of age, therefore, those below this age within our population will not complete the test and excluded from analysis. Therefore, sample size between tests might vary. If a patient cannot participate in the test, they will be excluded from analysis for that particular subtest.

The data generated by the study will be analysed at Manchester University National Health Service (NHS) Foundation Trust and the analysis will be performed by researchers employed by Manchester University NHS Foundation Trust.

Patient and public involvement
The Cochlear Implanted Children’s Support group (CICS, website: www.cicsgroup.org.uk) was consulted in the design of study documentation, review of the PIS.

Study results will be disseminated via the CICS social media channels and mailing lists.

Methodological summary
There is a paucity of evidence on what constitutes the best listening device modality for CYP with bilateral moderate-profound SNHL especially for those with AHL. Maintenance of binaural stimulation is essential for localisation and understanding spatially separated speech in noise, which has been suggested to be a marker for sequential CI. Furthermore, the level of available residual hearing is thought to contribute to music perception. Therefore, for our study we have chosen a ‘real-life’ test battery including spatial separated speech, music and speech stress/intonation.

Data storage and security
Data will be stored on Manchester University NHS Foundation Trust’s network drives with firewalls and security measures in place. Hard copy records will be stored in a locked cabinet in a secure location. Access to records and data will be limited to study personnel who are also part of the clinical care team. Study data will be deidentified and a master linking log with identifiers will be kept and stored separately from the data.

Ethics and dissemination
This study has been reviewed within the funding organisation (Cochlear Research and Development), by an independent and relevant peer reviewer/committee. Favourable comments and approval of the protocol were given from the peer-review process. A favourable opinion has also been granted by the Health Research Authority and NHS Research Ethics Committee (REC) for the study and all the supporting documents including this protocol, information sheets, informed consent forms and other relevant documents (22/EM/0104).

Study results will be disseminated via the CICS Group via, for example, newsletters, social media, as deemed appropriate by the charity and mailing lists. A summary of study results will be provided to all participants who have consented to be contacted regarding the study results. Aim for publication of the final study results in medical literature and presentation on medical conferences.

There is also an intention to share an anonymous final data set with external researchers, however, this will only occur if the correct data sharing agreement is in place.

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Contributors
The study concept and design were conceived by IB, SS, KK, JL, MO, AR and MS. IB is the chief investigator who secured funding together with SS and MO. MS will conduct recruitment, screening and data collection. The statistical analysis plan was authored by AR and will be performed by AR. IB, SS, MO and MS prepared the first draft of the manuscript. All authors provided edits and critiqued the manuscript for intellectual content.

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