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ORIGINAL RESEARCH ARTICLE

Preservation of residual hearing after cochlear implant surgery: Evaluation of residual hearing function in a group of recipients in cochlear implant units

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ABSTRACT

Introduction: Preservation of residual hearing has become increasingly important in cochlear implant surgery. Preserving residual hearing is a positive prognostic indicator for improving hearing abilities. **Objective**: To evaluate the preservation of residual hearing after cochlear implantation in a group of patients from two large cochlear implant centers. **Method**: A quantitative paradigm and exploratory research were adopted in a retrospective data review project. The sample consisted of 50 surgical records and 53 audiological records from 60 observations. The records were selected with purposive sampling and consisted of records from participants aged six to 59 years. In this study, the mean time to postoperative audiograms was 24.7 months (SD = ± 9.0). Data were analyzed using qualitative and inferential statistics, a comparative analysis of pre- and postoperative audiological test results was performed without the aid of a hearing aid. **Results**: The results indicated a high success rate of 92% of preservation of residual hearing, half of the sample of implantees exhibited complete preservation in all frequencies postoperatively. Total hearing loss on all frequencies postoperatively was observed in only 8% of cochlear implants. There was no relationship between preoperative hearing thresholds and postoperative hearing preservation. The two main surgical techniques used in the present study were contour on stylet and the advance off-stylet technique, and most surgeons used a cochleostomy approach. From the findings, it was evident that most cases did not have intraoperative complications. This is a positive prognostic indicator for the preservation of residual hearing. **Conclusion**: The findings suggest improved surgical outcomes of cochlear implantation when compared to previous studies, suggesting a progress in surgical techniques. The surgical skill and experience of the surgeon is evidenced by minimal intraoperative complications and a high rate of successful hearing preservation. This is a positive prognostic indicator for individuals with preoperative residual hearing, since preserved residual hearing enables potential electroacoustic stimulation (EAS), which in turn has auditory benefits of its own.

Keywords: audiologic; cochlear implantation; preservation; hearing; surgical technique

1. Introduction

Cochlear implants have revolutionized the way that rehabilitation of patients with severe to profound hearing loss is approached in the recovery of speech

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understanding[1]. Successful residual hearing conservation after cochlear implantation has benefited patients with high levels of low-frequency residual hearing that were not previously considered for conventional cochlear implantation[1].

Verhaegen et al.[2] have evaluated how the advent of cochlear implantation has allowed individuals with bilateral profound sensorineural hearing loss (for whom the benefits of hearing aids are minimal or nil) to be effectively rehabilitated. Gstoettner et al.[3] noted that in the last two decades cochlear implants have become the standard intervention procedure for individuals with profound sensorineural hearing loss. In their 2009 study, Lenarz et al.[4] stated that cochlear implantation is the "current treatment of choice for patients with profound sensorineural hearing loss".

In the past, only individuals with profound hearing loss without residual hearing were implanted[2], and individuals with residual hearing at low frequencies were excluded due to the intraoperative risks of residual hearing loss[3,5]. However, in the last decade, the inclusion criteria for implantation have been expanded to include individuals with some residual hearing[2,3]. This expansion of inclusion criteria has occurred due to technological advances[6], improvements in surgical techniques[3,4], and less traumatic insertion of the electrode array[4]. Improved outcomes have allowed these patients to perform better after surgery, and cochlear implants have become the primary form of management for bilateral severe-profound hearing loss[5,7,8].

A review of previous literature on traditional measures to ensure hearing preservation shows that comparisons between studies are a complex procedure, indicating the need for caution when comparing findings. This is the case in the present study, in which retrospective record reviews were conducted without any active manipulation of variables. As early as 1997, in a study by Hodges et al.[9] reported the preservation of residual hearing in about 50% of implanted patients. However, the first reports in the literature on the efficacy of cochlear implantation indicated a significant decrease in residual hearing after surgery; most implanted subjects lost residual hearing after implantation[8]. As a result, only subjects with profound hearing loss received implants[8,10]. Adunka et al.[11] reported in their study that residual hearing was maintained postoperatively in most implanted subjects. However, 90% achieved only partial preservation, which led them to conclude that additional efforts were needed to improve surgical protocols with the goal of achieving complete hearing preservation in all cases.

Several authors[2,7,12,13] have reported the importance of hearing preservation with cochlear implantation. Verhaegen et al.[2] and Kiefer et al.[7] have argued that residual hearing is a good prognostic indicator of good cochlear implant performance. These authors have shown that residual hearing after cochlear implant surgery allows for long-lasting and stable performance of speech understanding, as well as improved speech perception.

Preserved hearing has also become beneficial for one of the most significant advances: the introduction of bimodal electroacoustic stimulation (BES). BES involves the amplification of preserved low frequencies by acoustic stimulation in the form of hearing aids, while high-frequency hearing loss is addressed with electrical stimulation in the same ear by means of a cochlear implant[2]. This is used in implant recipients whose residual low-to-medium frequency hearing has been preserved postoperatively and has considerable hearing benefits, hence the importance of studies such as ours, which aimed to explore the preservation of residual hearing function in a group of implant recipients.

2. Objectives of the study

To investigate the preservation of residual hearing function in a group of cochlear implant patients; to describe and perform a comparative analysis of hearing function before and after cochlear implant surgery; to determine to what extent residual hearing has been preserved or lost; to establish whether there

is a relationship between the hearing findings and the surgical technique used, as well as intraoperative complications.

3. Method

3.1. Study design

Within a quantitative paradigm, a retrospective data analysis design was performed[14]. The researcher retrospectively examined existing surgical records as well as pre- and postoperative unaided audiological test results to determine whether residual hearing was preserved. Due to the retrospective nature of the study, no manipulation of variables was employed to influence post-operative outcomes. This includes the type of surgical technique employed.

3.2. Selection of participants

Sampling Strategy

The purposive sampling strategy was used to obtain the participants' records[14].

3.3. Description of the participants

Participant records included audiological test data and cochlear implant surgery records with preoperative residual hearing. Participants included both unilateral and bilateral cochlear implant patients of both genders from two cochlear implant units. Children had to be at least 6 years old (to increase the reliability of the pure-tone test findings) in the preoperative hearing test, and adults older than 59 years (to minimize the influence of presbycusis) in the postoperative tests. The mean time to postoperative audiograms included in the present study was 24.7 months (s.d. = ± 9.0).

A prerequisite of this study was that participants needed to have some preoperative residual hearing at any or all of the following frequency: 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1,000 Hz, 1,500 Hz, 2,000 Hz, 3,000 Hz, 4,000 Hz, 6,000 Hz, and 8,000 Hz.

3.4. Participant sample size

The sample consisted of 50 surgical records and 53 participant audiological records. Although there were 53 participants' audiological files, seven of these individuals were bilaterally implanted, resulting in a sample size of 60 ears.

3.5. Selection criteria

Participant inclusion criteria

The following factors were considered in the inclusion criteria:

- Cochlear implants: Participants received a cochlear implant, unilaterally or bilaterally, at least one month before the post-operative pure-tone test.
- Hearing condition: The participants should have a moderate to profound prone to sensorineural hearing loss, severe to profound sensorineural loss or profound sensorineural loss (i.e. some residual hearing at any of the frequencies—Not a corner audiogram) in both ears and should show some benefit, even minimal, after the use of hearing aids.
- Speech discrimination: As the participants were submitted to cochlear implantation, it was concluded that, preoperatively, the participants obtained < 50% for sentence recognition in the ear to be implanted and < 60% in the non-implanted ear or contralateral or bilaterally for speech discrimination, as this is a criterion for cochlear implantation[15].
- Auditory nerve function: Since the participants had cochlear implants, the researcher could assume that the auditory nerve fibers of the participants were intact so that they could receive electrical stimuli within the cochlea[16].
- Medical condition: It was concluded that the participants' medical conditions and inner ear structures met the requirements for

implantation, as these are eligibility criteria[16].

- Age: One of the inclusion criteria was that the ages of the participants had to range from six to 59 years to ensure the reliability of the results and to exclude presbycusis-related loss.

3.6. Data collection

Audiological data review

The following data were collected from each participant's records: cochlear implant unit (Unit A/Unit B); left/right ear; bilateral/unilateral implant; time (months) between the last preoperative hearing test and surgery; and time (months) between surgery and the first postoperative hearing test.

The hearing thresholds (in dB) of the pure-tone air conduction test were obtained pre- and postoperatively at the following frequency: 125 Hz; 250 Hz; 500 Hz; 750 Hz; 1,000 Hz; 1,500 Hz; 2,000 Hz; 3,000 Hz; 4,000 Hz; 6,000 Hz and 8,000 Hz.

The change: The pre- and post-operative difference between the hearing thresholds (in dB) of the pure-tone test results, at the frequencies above where these frequencies could be measured.

The researcher collected additional data: age; gender; etiology; duration of hearing loss before implantation (in years); implant type; implant manufacturer; electrode type; electrode array insertion; electrode array depth; surgical technique; and intraoperative complications.

The types of cochlear and electrode array implants, the depth of insertion, and the surgical techniques used are summarized in **Table 1**.

Type of cochlear implant

Of those implanted, 50% received the CI24RE implant and 25% the CI512. The Other category (17%) included, among others, the cochlear implant type-Nucleus CI24R with Contour Advance type electrode (n = 5).

Electrode matrix type

The majority of the participants (83%) received the implant of the contour advance type electrode array.

Electrode array insertion depth

Of the participants, 94% underwent complete insertion of the electrode array. Very few patients (an average of 2%) underwent partial insertion of the electrode array.

Table 1. Implant type, electrode type, insertion depth and surgical technique

Implant type	
NF-CI24RE	50%
CN-CI 512	25%
Another	17%
No information	8%
Electrode type	
Contour advanced	83%
Another	8%
No information	8%
Insertion depth	
Complete	93%
Partial	2%
No information	5%
Surgical technique	
Contour on stylet	8%
AOS (advance off-stylet)	67%
Another	20%
No information	5%

n = 60; number of participants, 53.
CN-CI 512, Cochlear Nucleus 5 cochlear implant; NF-CI24RE, Nucleus Freedom cochlear implant with Contour Advance leads or straight leads.

Surgical techniques

The two main surgical techniques used in the present study were contour on stylet and AOS (advance off-stylet), AOS was the most used (67%). The surgical technique used had no negative effect on postoperative hearing threshold levels. The use of AOS or contour on stylet or ''other'' techniques did not alter the postoperative outcome in terms of preservation of residual hearing.

Most surgeons used a cochleostomy approach, with the exception of four cases in which the round window approach was used.

Data analysis

The researcher chose to adopt the approach of James et al.[17] whereby an artificial value is used to

represent the total residual hearing loss. James et al.[17] suggested that this could occur at the maximum output intensity of the audiometer.

The researcher chose to assign an artificial or numerical value to represent the total residual hearing loss at maximum audiometer output plus 5 dB. The researcher also chose to represent the maximum output intensity of the audiometer as 120 dB.

When calculating pre- and post-operative hearing threshold levels, when the hearing threshold level was "no response" (NR), the researcher assigned a value of 125 dB to NR. This value was assigned to replace NR in order to determine residual hearing or lack of hearing pre- or post-operatively.

3.7. Statistical procedures

Data analysis was performed in Statistica software (version 10). The results were evaluated using descriptive and inferential statistics[14]. For inferential statistics, the confidence level of 95% was used throughout the analysis unless otherwise specified.

3.8. Reliability and validity

To minimize the impact of variables on the reliability and validity of the results, the researcher excluded records in which participants were deemed ''unreliable'' during testing or in which there was ''questionable reliability''. In addition, as in the study by Kiefer et al.[7], any ''vibrotactile'' responses reported by the participants were excluded from the calculations. The researcher worked under the assumption that the expert audiologists would have reported any unreliable responses and would have used best practices regarding testing protocols, sound isolation and equipment calibration.

3.9. Ethical considerations

Before the study began, the researcher obtained permission from the University's Human (Medical) Research Ethics Committee (Protocol No. M111037). Subsequently, the researcher obtained permission from all relevant authorities. In addition, the work is in accordance with the Helsinki Declaration of 1975 as revised in 2008.

4. Results and discussions

4.1. Demographic profile

Table 2 represents the demographic profile of the sample in the present study.

As shown in **Table 2**, 60 observations formed the basis of the present study. Most participants (64%) were female, with a mean age of 30.8 years. Seven were bilaterally implanted.

Table 2. Demographic profile of the observers (n = 60)

Variable	General
Number of participants	53
Number of bilateral implants	7
Ears (% of total ears)	60
Ears (% of left ears)	40%
Age at surgery (mean ± 95% confidence interval)	30. 8 ± 3. 6
Gender: % male	36%

The sample size of the present study was considered adequate and had a larger number of observations than some other studies reported in the literature. For example, Gstoettner et al.[3] did a very successful clinical trial with the Med-El Flex EAS array, in which the residual hearing of all recipients was preserved postoperatively, with a sample size of nine recipients, which limited the generalizability of the study. Lenarz et al.[4] did a clinical trial with 24 participants (and 32 observations).

4.2. Hearing function before surgery (pre)

Data could only be recorded for 11 participants at the 125 Hz frequency. In this context, this is an important finding that requires attention from the audi-ological community, since Franks et al.[18] state that the criteria for the test protocol should include the 125 Hz frequency for clinical testing. In addition, the data were limited for all interoitems. It was assumed that this was possibly due to the fact that, according to Franks et al.[18] when performing hearing tests for clinical purposes, the half-octave is only tested ''occasionally''.

Figure 1 represents the preoperative hearing threshold levels at individual frequencies from 125 Hz to 8,000 Hz for all participants. The results indicated that preoperatively, participants in the overall sample had some degree of residual low frequency hearing, with reduced hearing at high frequencies. As frequency increased from 125 Hz to 8,000 Hz, hearing loss also increased. A Generalized Linear Model (GLM) was used to confirm this audiogram configuration, which showed greater residual hearing at the preoperative low frequencies. This was expected and may be explained by the tonotopicity of the cochlea, in which the high frequencies are more susceptible to damage than the lower frequencies[19]. The degree of pre-implantation hearing loss was generally in the low-pitched range, as shown in **Figure 1**.

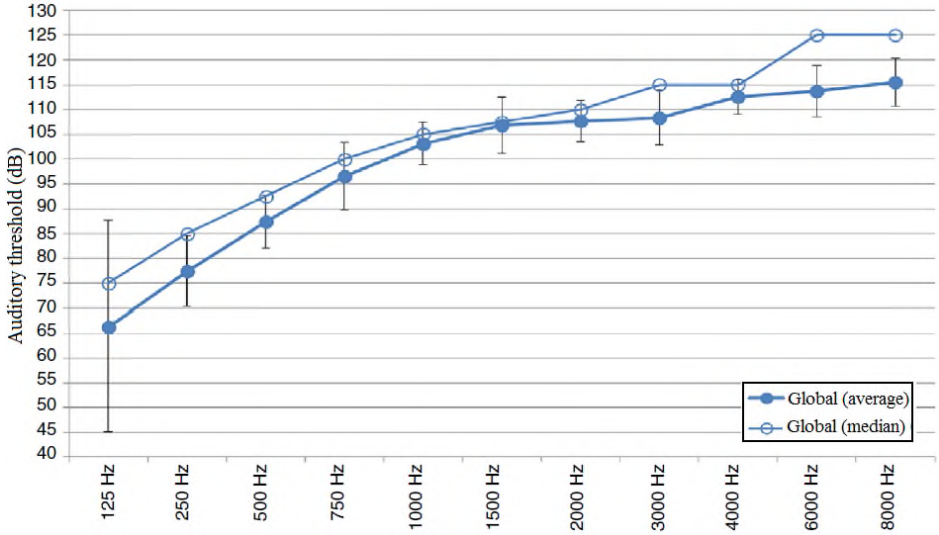

Figure 1. Global hearing threshold levels preoperatively (PRE HTL global).

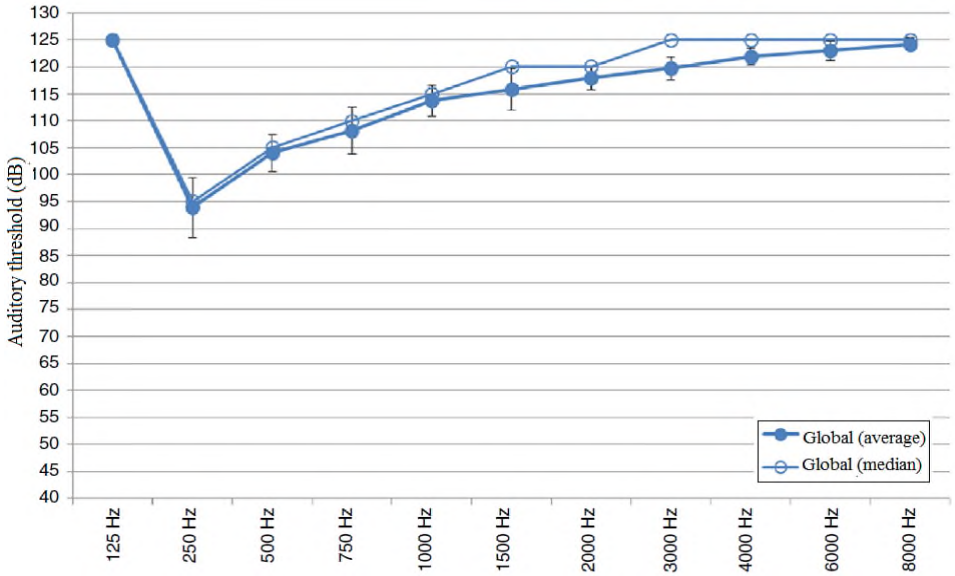

Figure 2. Global postoperative auditory threshold levels (Post HTL Global).

4.3. Hearing function after surgery (post)

As seen in **Figure 2**, the results obtained indicated a high frequency loss in the postoperative period, with some preservation of low frequencies and slight preservation of medium frequencies. At 8,000 Hz there was total hearing loss, while at 250 Hz the hearing threshold level was 95 dB. Although the results indicated some preservation of low and medium frequency hearing (the latter to a lesser degree), it was clear from the results that there was some loss in residual hearing, indicated by the hearing threshold

levels that decreased from the preoperative to the postoperative period.

4.4. Alteration in hearing function

Overall, as described in **Figure 3**, there was a medium loss in residual hearing, particularly in the high frequencies. There was also a loss in the low and mid frequencies, but to a lesser degree than in the high frequencies.

The alteration in residual hearing indicated by hearing loss, minor in the middle and low frequencies, is clinically significant. This preservation of hearing at low and medium frequencies aids speech perception in noise and allows consideration of EAS-electroacoustic stimulation with a hearing aid and a cochlear implant for high frequencies.

It was expected that there would be a decrease in auditory threshold levels at high frequencies due to the placement and insertion of the electrode in the cochlea and due to its tonotopicity. Moreover, high frequencies are more susceptible to damage given their placement in the cochlea, as observed in the present study.

The preoperative and postoperative hearing threshold levels were plotted on the same graph to more clearly describe the change in residual hearing in single lines, as illustrated in **Figures 4** and **Figure 5**. Most cases are above the line, indicating that hearing loss has occurred.

4.5. Preservation of hearing

Classification of altered hearing function

The change in hearing function from preoperative to postoperative auditory threshold levels was classified for each participant, which is in accordance with the schemes in the work of Gstoettner et al.[3] and Balkany et al.[5]. In addition, the researcher chose to include all frequencies in this study in order to obtain more detailed information about the change in residual hearing.

Three frequency combinations were used as inputs to the above classification: Gstoettner et al.[3]: averaged over 125–750 Hz; Balkany et al.[5]: averaged over 250, 500 and 1,000 Hz; All: averaged over all frequencies.

The alteration in hearing function, according to the three classifications, is shown in **Table 3**.

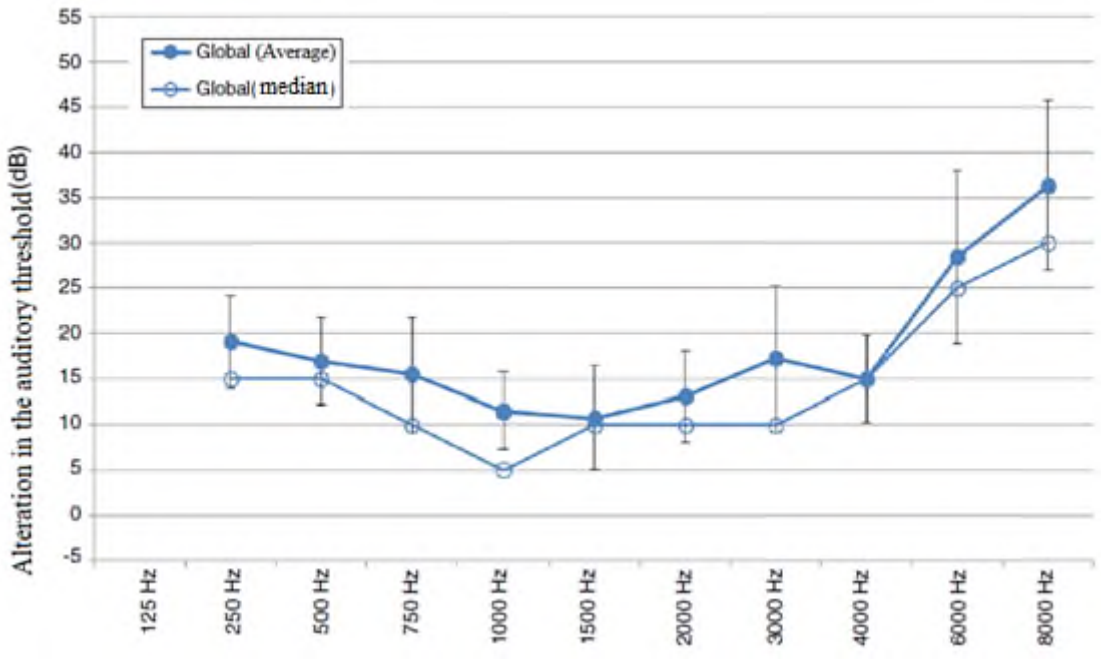

Figure 3. Change in global hearing threshold levels (CH HTL Global).

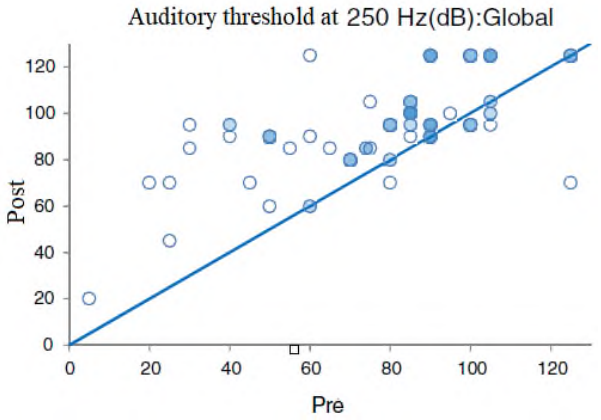

Figure 4. Pre- and post-operative auditory threshold levels at 250 Hz (Pre-Post HLT 250 Hz Global).

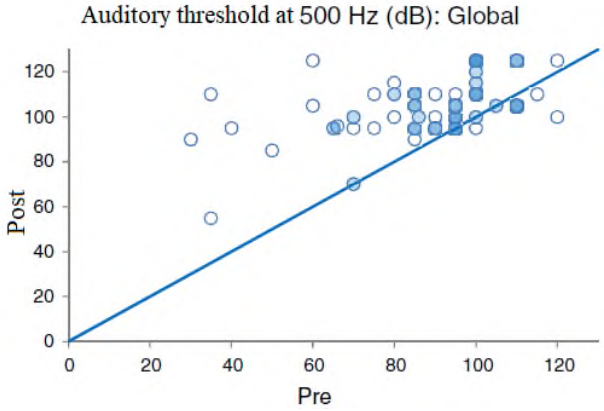

Figure 5. Pre- and post-operative auditory threshold levels at 500 Hz (PR-POST HLT 500 Hz Overall).

Table 3 shows that the vast majority of recipients preserved their hearing, partially or totally. There was no significant difference between the three classifications used. According to the classification by Balkany et al.[5], in general, 92% of the implanted patients presented partial or complete hearing preservation postoperatively. With further analysis, according to **Figure 6**, 50% experienced complete hearing preservation (0 to 10 dB change in auditory threshold levels) and 42% partial hearing preservation (> 10 dB change in auditory threshold levels). A small minority (8%) of cochlear implanted patients experienced total residual hearing loss postoperatively, as evidenced by absent responses on all frequencies postoperatively.

In summary, the current findings indicate that the vast majority of cochlear implanted patients have been able to preserve residual hearing, either partially or totally. These are positive findings that have implications for the clinical and surgical management of cochlear implant patients.

Table 3. Classification of Gstoettner et al.[3], Balkany et al.[5] and the researcher

Classifications	Classification by Gsteottner et al.	Classification by Balkany et al.	Classification of the researcher
Hearing preserved	53 90%	55 92%	55 92%
Total preservation	23 39%	24 40%	30 50%
Preservation partial	30 51%	31 52%	25 42%
Total loss	6 10%	5 8%	5 8%
Totals	59	60	60

Table 4. Surgical complications in the current sample

Intraoperative complications	
Adhesions	3%
Perforation of the basal gyrus	3%
Gusher	5%
Trauma	10%
Other	3%
Not reported	68%
No information	7%

Intraoperative complications

As illustrated in **Table 4**, the major categories for intraoperative complications included adhesions (3%); basal gyrus perforation (3%); Gusher (5%); and trauma (10%). A significant majority (68%) of case records indicated no complications.

The study by Hodges et al.[9] showed that hearing was only preserved in 50% of the implanted patients. In the study by Di Nardo et al.[8] the majority of implanted patients maintained residual hearing. However, despite the use of a non-traumatic surgical approach, 22% had total hearing loss after surgery.

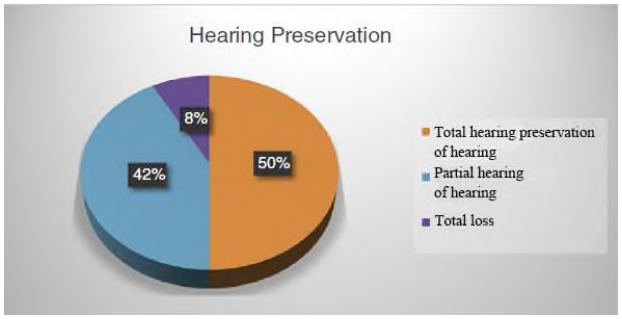

Figure 6. Percentage of hearing preservation in the current sample (n = 60).

Balkany et al.[5] reported findings from the 1980s that indicated preservation of pure-tone thresholds in 33% of the implants postoperatively. In the 1990s, residual hearing loss was observed in approximately half of the patients after surgery. This number increased to a post-operative preservation rate of 89% in 2006 with the use of the Nucleus Freedom Contour Advance lead and the advance off-stylet technique. The findings in the present study show a 92% preservation rate, which implies a better overall hearing conservation result than that presented by most previous studies. Furthermore, the findings in the present study showed a higher rate of partial and complete hearing preservation according to similar classification, 50% and 42% for complete and partial preservation, respectively. This improvement over the past decades can be attributed to a combination of advances in surgical techniques and cochlear implant technology[5].

Verhaegen et al.[2] observed in their study residual postoperative hearing retention in 70% of the implants after using the soft surgery technique with the Nucleus Contour electrode. Although these results indicate an improvement over previous studies, the overall successful preservation rate of 92% found in the present study was considerably higher.

The relationship between postoperative auditory findings and the degree of preoperative hearing loss was also investigated in the present study. There was no significant correlation between preoperative hearing threshold levels and postoperative residual hearing preservation ($p = 0.154$). The degree of preoperative hearing loss did not determine the outcome of postoperative hearing threshold levels. These findings are consistent with those of Cosetti et al.[20] who found no significant relationship between postoperative hearing loss and low-frequency pure-tone averaging. However, these findings are different from those presented by Balkany et al.[5], in which a relationship was found between the degree of preoperative hearing loss and postoperative hearing findings. In their study, patients with a higher degree of preoperative hearing loss tended to have complete residual hearing loss after surgery.

The current findings showed similarities with the findings of Roland et al.[21] regarding surgical techniques, electrode insertion and electrode sets used. In the study by Roland et al.[21] they evaluated the use of Contour Advance electrodes with the AOS technique. The non-traumatic insertion was achieved by precise perimodiolar placement on the tympanic ramp, providing protection to the intracochlear structures[21]. This is consistent with the current findings, in which most surgeons have used the AOS technique, with results showing successful preservation of residual hearing in most cases.

The positive findings in the present study demonstrated that the cochleostomy approach was successful in preserving residual hearing postoperatively. Mangus et al.[22] stated that the round window approach has advantages for residual hearing preservation over the cochleostomy approach, which may result in intracochlear trauma. Briggs et al.[23] observed that both approaches successfully avoided cochlear trauma during surgery, thus preserving residual hearing postoperatively.

Derinsu et al.[24] evaluated the round window approach and found that complete preservation of residual hearing was achieved in 35.48% of patients. With the use of the cochleostomy approach in most cases, the present study found a more positive result than the Derinsu et al.[24] study, with complete preservation achieved in 50% of the patients.

Most cases in the present study did not report intraoperative complications. This is a positive prognostic indicator for the preservation of residual hear-

ing. Intraoperative complications may result in intracochlear damage, which in turn may lead to the loss of residual hearing and thus affect its preservation. According to Clark et al. and Balkany et al. (as cited in Di Nardo et al.[8]), surgical complications affect anatomical structures after implantation. Kiefer et al.[7] have warned that damage to the cochlea may result from acoustic trauma from bone burrowing during cochleostomy surgery.

In the study by Di Nardo et al.[8] observed that the cochlea was not as sensitive to trauma caused by surgery. These researchers maintain that this should lead to positive outcomes regarding the preservation of residual hearing. However, 22% of the implants in Di Nardo's study suffered complete postoperative hearing loss. The present study had a more favorable outcome than the study by Di Nardo et al.[8] in which only 8% lost their hearing completely, illustrating the successful preservation of residual hearing in most cases.

The authors are of the opinion that the positive outcome in this study is due to the experience of the surgeons, along with improved electrode designs, as evidenced by minimal intraoperative complications. Although most implant recipients received a complete insertion of the electrode array, minimal surgical complications occurred, successful hearing preservation was achieved.

5. Conclusions

Preservation of residual hearing after cochlear implantation was successfully achieved in 92% of participants –42% partial and 50% complete, 8% of recipients had complete postoperative hearing loss. Similar results were obtained regardless of the surgical technique used-OA or contour on stylet. Most surgeons used the cochleostomy approach, which proved to be successful. Few intraoperative complications were reported, a positive outcome was obtained, indicative of successful surgical techniques and surgeon experience, as well as improved lead designs. The current findings have clinical significance, and have made EAS a reality.

Current findings indicate that preservation of residual hearing has become the main focus following the increase in the number of people implanted[10], the extension of the criteria for cochlear implantation, the continuous increase in the success rate of cochlear implants over the last two decades[7] and the positive performance indicators of residual hearing[2] preoperatively.

Conflict of interest

The authors declare no conflict of interest.

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