Anatomy-based vs. logarithmic standard frequency allocation in cochlear implants: A comparative study on speech intelligibility and sound quality

Anatomiebasierte vs. logarithmische Standardfrequenzverteilung für das Cochlea-Implantat: Eine vergleichende Studie zu Sprachverständlichkeit und Klangqualität

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Abstract

The here presented prospective, randomized, single-blinded crossover study investigated the effects of anatomy-based versus standard logarithmic frequency allocation on speech intelligibility and sound quality in 77 adult first-time cochlear implant (CI) recipients. Cochlear implant signal processing relies on filter bank configurations that distribute incoming frequencies across electrode contacts, with manufacturers typically employing standardized logarithmic frequency allocations. Recent advances in imaging technology now enable patient-specific optimization based on individual cochlear anatomy. Participants were randomly assigned to be first-fitted with either the manufacturer's standard frequency allocation (STD) or an anatomy-based fitting (ABF). To establish ABF, postoperative cone-beam computed tomography (CBCT) scans were analyzed using Otoplan® software (Cascination, Bern, Switzerland) to determine insertion angles and intracochlear electrode positions, enabling individualized calculation of filter bank center frequencies. After three months, all participants crossed over to the alternative frequency allocation, with both configurations available for direct comparison at the second follow-up visit, and the study concluded with a final assessment at nine months. Speech intelligibility was assessed using the Freiburg monosyllabic word test in quiet and the Oldenburg sentence test in noise. Subjective hearing quality and listening preferences were evaluated through questionnaires. While statistical analyses revealed no significant differences in speech intelligibility between the two frequency allocation methods at the final visit, participants subjectively preferred the anatomy-based allocation, particularly those with single-sided deafness (SSD). These findings suggest that while speech intelligibility remains comparable between standard and individualized frequency allocations, the anatomy-based approach offers perceptual advantages in sound quality without compromising speech reception. However, further research is needed to determine whether these subjective benefits translate into measurable improvements in real-world performance and long-term satisfaction.

Keywords: cochlear implant, anatomy-based fitting, crossover study

Zusammenfassung

Die hier vorgestellte prospektive, randomisierte, einfach verblindete Cross-over-Studie untersuchte die Wirkung einer anatomiebasierten Frequenzverteilung im Vergleich zur logarithmischen Standard-Frequenzverteilung auf die Sprachverständlichkeit und die Klangqualität bei 77 erwachsenen Erstnutzern von Cochlea-Implantaten (CI). Die CI-Signalverarbeitung basiert auf Filterbank-Konfigurationen, welche die eingehenden Signale auf die Elektrodenkontakte verteilen. Hierzu werden typischerweise standardisierte logarithmische Frequenzverteilungen verwendet. Fortschritte in der Bildgebungstechnologie ermöglichen inzwischen eine patientenspezifische Optimierung auf Basis der individuellen Cochlea-Anatomie. Die Studienteilnehmer wurden zum Zeitpunkt der Erstanpassung randomisiert entweder der Standard-Frequenzverteilung (STD) oder der anatomiebasierten Frequenzverteilung (ABF) zugewiesen. Zur Erstellung der ABF-Verteilung wurden postoperative DVT-Computertomographie-Aufnahmen mittels der Otoplan®-Software (Cascination, Bern, Schweiz) analysiert, um Insertionswinkel und intrakochleäre Elektrodenpositionen zu bestimmen. Dies ermöglichte die Berechnung individueller Mittenfrequenzen für die Filterbank. Nach drei Monaten wechselten alle Teilnehmer zur alternativen Frequenzverteilung. Bei der zweiten Untersuchung standen beide Konfigurationen zum direkten Vergleich zur Verfügung, gefolgt von einer abschließenden Evaluation nach 9 Monaten. Sprachverständlichkeitstests umfassten den Freiburger Einsilbertest in Ruhe sowie den Oldenburger Satztest im Störgeräusch. Subjektive Bewertungen der Klangqualität und Hörpräferenzen wurden mittels Fragebögen erhoben. Obwohl statistische Analysen bei der letzten Visite keine signifikanten Unterschiede in der Sprachverständlichkeit zwischen den beiden Frequenzverteilungsmethoden zeigten, gaben die Teilnehmer subjektiv eine Präferenz für ABF an, insbesondere Patienten mit einseitiger Taubheit. Die Ergebnisse deuten darauf hin, dass die anatomiebasierte Frequenzverteilung Vorteile für die Klangqualität bietet, ohne das Sprachverständnis zu beeinträchtigen. Weitere Forschung ist jedoch erforderlich, um zu klären, ob sich diese subjektiven Vorteile in messbare Verbesserungen in Alltagssituationen und der langfristigen Zufriedenheit widerspiegeln.

Schlüsselwörter: Cochlear-Implantat, anatomiebasierte Anpassung, Cross-over-Studie

1 Introduction

Patients with profound hearing loss or deafness can benefit from cochlear implantation (CI) to achieve sustainable improvements in speech understanding. While CIs offer significant advantages, many users experience listening through the device, particularly in the initial phase, as unpleasant and disruptive. Even after acclimatization, CI performance varies widely among individuals and often remains inadequate in real-world listening environments with background noise [1]. One potential factor contributing to this suboptimal sound quality may be the manufacturer-prescribed distribution of center frequencies in the CI audio processor's filter bank, which is uniformly applied across all patients [2]. During initial activation, the processor is typically programmed with a standard frequency allocation without consideration for the individual's cochlear anatomy or precise electrode position. However, cochlear duct length (CDL) varies significantly among patients, resulting in possible deviations of up to two octaves between the electrical frequency bands at a given intracochlear position and the corresponding physiological frequency mapping. This study investigates whether an anatomy-based frequency allocation (ABF), adjusted to the individual electrode positioning, can improve sound quality and speech perception compared to conventional frequency distribution. By incorporating precise imaging-based data on electrode insertion depth and cochlear morphology, this approach aims to provide a more physiologically aligned frequency-to-place mapping, potentially enhancing auditory outcomes for CI recipients.

2 Methods

This study included 77 participants (38 male, 39 female, 85 ears) with a mean age of 58 years. The cohort comprised individuals with varying hearing profiles. 25 patients with single-sided deafness (SSD), 40 bimodal users, 3 unilateral cochlear implant (CI) recipients, and 9 bilateral CI users. Additionally, 9 patients had either received electric-acoustic stimulation (EAS) or were identified as EAS candidates prior to implantation. Participants were implanted with Synchrony 2 devices (MED-EL, Innsbruck, Austria), with electrode array lengths selected based on individual cochlear duct length (CDL) measurements to optimize tonotopic matching. The implanted electrode types included 1 Flex24, 8 Flex26, 40 Flex28, 36 FlexSoft, and 1 Cochlear CI612 (Cochlear Ltd., Macquarie, Australia). For sound processing, participants used either Rondo 3 or Sonnet 2 audio processors. The study employed a randomized crossover block design, in which participants were allocated into two groups using a computerized randomization procedure. At the initial activation of the audio processor, Group 1 received the manufacturer's default logarithmic frequency allocation (STD), while Group 2 was fitted with an anatomy-based frequency (ABF) mapping. After a three-month period, participants crossed over to the alternative frequency allocation for an additional three months. Following this crossover phase, all participants were provided with two dedicated listening programs (STD and ABF) for a final three-month period, during which they could self-select their preferred setting based on subjective and objective performance. At each study visit, most comfortable loudness (MCL) and threshold (THR) levels were systematically adjusted using categorical loudness scaling to ensure optimal fitting prior to conducting any perceptual assessments. Speech perception testing was conducted at each study visit under controlled conditions. Speech intelligibility in quiet was evaluated using the Freiburg Monosyllabic Word Test (FMT) at 65 dB SPL, while speech perception in noise was assessed using the Oldenburg Sentence Test (OLSA), with speech and noise presented from the front (S_0N_0). To evaluate subjective hearing quality, participants completed the Speech, Spatial, and Qualities of Hearing Scale (SSQ) questionnaire. While additional audiological tests and questionnaires were administered at each visit, the present analysis focuses exclusively on speech perception outcomes and subjective sound quality ratings on the last visit.

2.1 Creation of Anatomy-Based Fitting (ABF)

Analysis of pre- and postoperative imaging (CT/CBT) was performed using OTOPLAN 3.0 (CASCINATION AG). This imaging modeled electrode insertion depths and determined individual tonotopic frequency allocation based on cochlear anatomy (Alexiades et al. [3], Escudé et al. [4], Greenwood [5]), as previously detailed by Gooss and Baumann [6]. Because the cochlea has a logarithmic frequency distribution (Greenwood function), the manufacturer's standard fitting (STD) is used to approximate an anatomically-based frequency assignment, particularly in the basal region. Calculated center frequencies were imported into MAESTRO (v9.0.5, MED-EL) within the predefined frequency range (70–8,500 Hz). To align filter banks more precisely with the organ of Corti (OC) tonotopy, we made individual adjustments: the apical lower cutoff of E1 was increased to avoid overlap with non-physiological regions, and electrode 12 was deactivated if it was outside the processor's stimulation range, as described in [7]. MCL/THR settings were verified and adjusted based on subjective loudness responses, following standard clinical protocols.

3 Results

3.1 Hearing quality

Preference questionnaire

Results of the preference questionnaire are shown in Figure 1. During the last follow-up visit after 9 months, the median preference rating for ABF was 2.25 (±0.95), whereas the median rating for STD was 3.0 (±1.2). This difference in favor of ABF was statistically significant ($p=0.017$).
At the end of the study, out of 50 patients, 29 reported a preference for ABF, while 13 preferred STD, and eight patients indicated no preference. Notably, patients with SSD exhibited a strong preference for the ABF frequency distribution. While 17 SSD-patients favored ABF, only two preferred STD. Additionally, two SSD patients had no preference.

SSQ results

Figure 2 presents the results of the third subscale of the SSQ, which assesses hearing quality preferences. The mean quality rating for the STD-preferred group was 4.89 (±1.84), while the mean rating for the ABF-preferred group was 6.0 (±1.95). The difference between the two groups was not statistically significant.

3.2 Speech intelligibility

Figure 3 shows a boxplot of the results of the Freiburg monosyllable test (FMT) in quiet on the study endpoint (9-month interval), shown for all participants ($n=52$). The median speech intelligibility in quiet was 60% (±22%) for the STD-mapping and 60% (±23%) for ABF-mapping. When stratifying results by preference, the ABF-preferred group ($n=36$) had a median speech intelligibility in quiet of 65% (±19%), and 62.5% (±21%) with the STD-setting. In contrast, the STD-preferred group ($n=16$) exhibited a decline in speech intelligibility when using the ABF setting. The median speech intelligibility in quiet for the STD-preferred group with the STD-setting was 55% (±25%) and 37.5% (±26%) with the ABF-setting (Figure 4). The results of the OLSA tests are not presented here and will be the subject of a later publication.

3.3 Dropouts

Switching between frequency allocation strategies frequently resulted in acceptance difficulties, primarily due to altered sound quality perceptions. Most participants described the anatomy-based frequency (ABF) mapping as producing a deeper, occasionally warmer sound compared to standard (STD) configurations. However, individual responses varied significantly. While some users reported minimal perceptual differences and maintained comparable speech recognition performance, others experienced degraded sound quality and corresponding declines

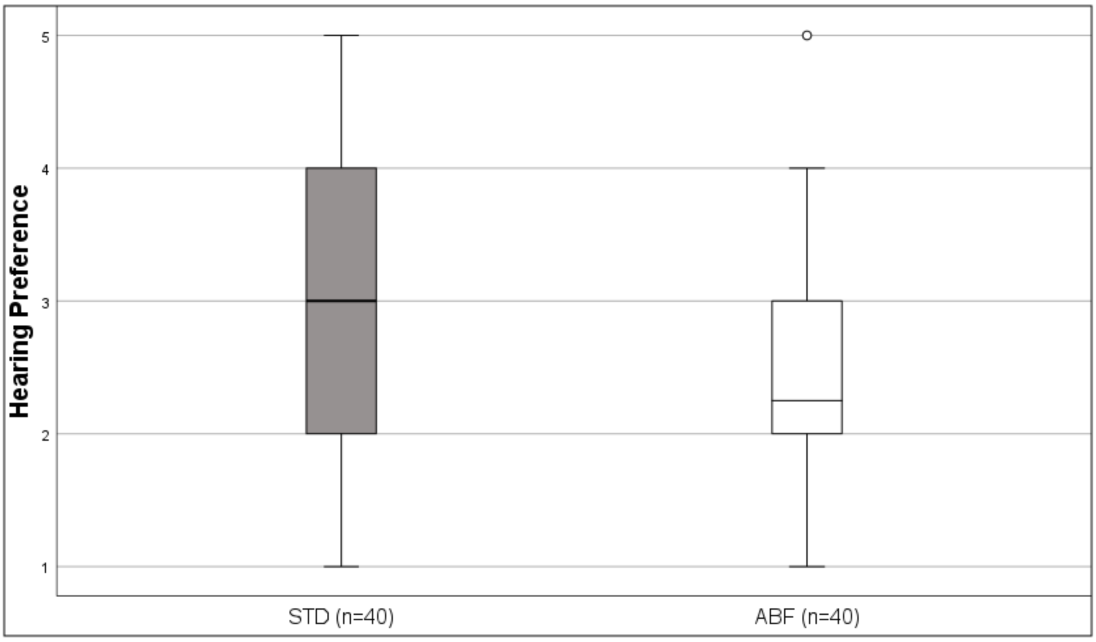

Figure 1: Boxplot, results of the Preference questionnaire in grades (1-very good, 5-bad) on the 3rd visit (9 months). n: number of cases, STD: standard frequency allocation, ABF: anatomy-based frequency allocation

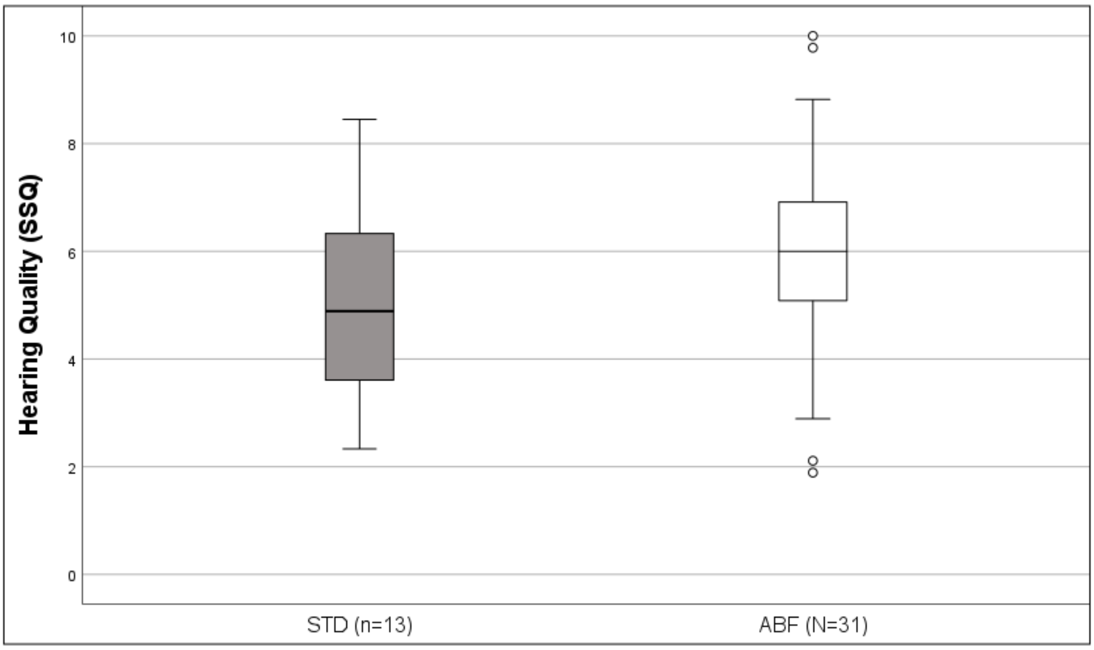

Figure 2: Boxplot, results of the SSQ questionnaire, part "quality" in the 3rd visit (9 months). n: number of cases, STD: standard frequency allocation, ABF: anatomy-based frequency allocation

in speech intelligibility scores. Acceptance difficulties were less pronounced when frequency mappings overlapped substantially between conditions. The most significant challenges occurred during initial transitions, particularly in the first three-month assessment period. A subset of participants reported their own voice as unnaturally low-pitched and acoustically unpleasant when switching from STD to ABF, an effect more commonly observed among female participants, likely due to fundamental frequency characteristics (female f_0≈220 Hz). Considering only voice fundamental frequencies (f_0), a 220 Hz tone is assigned to electrode 2 in the STD-mapping. Switching to the ABF-mapping often shifts the frequency allocation, assigning 220 Hz and lower frequencies to electrode 1 instead. This shift does not affect typical male fundamentals (male f_0≈130 Hz).

Of 23 study cases dropouts, 10 could not adapt to the alternative frequency allocation (6 rejecting ABF, 4 rejecting STD). The immediate perceptual disruption and perceived reduced efficacy following switches may have contributed to long-term non-compliance, particularly evident at the three-month follow-up.

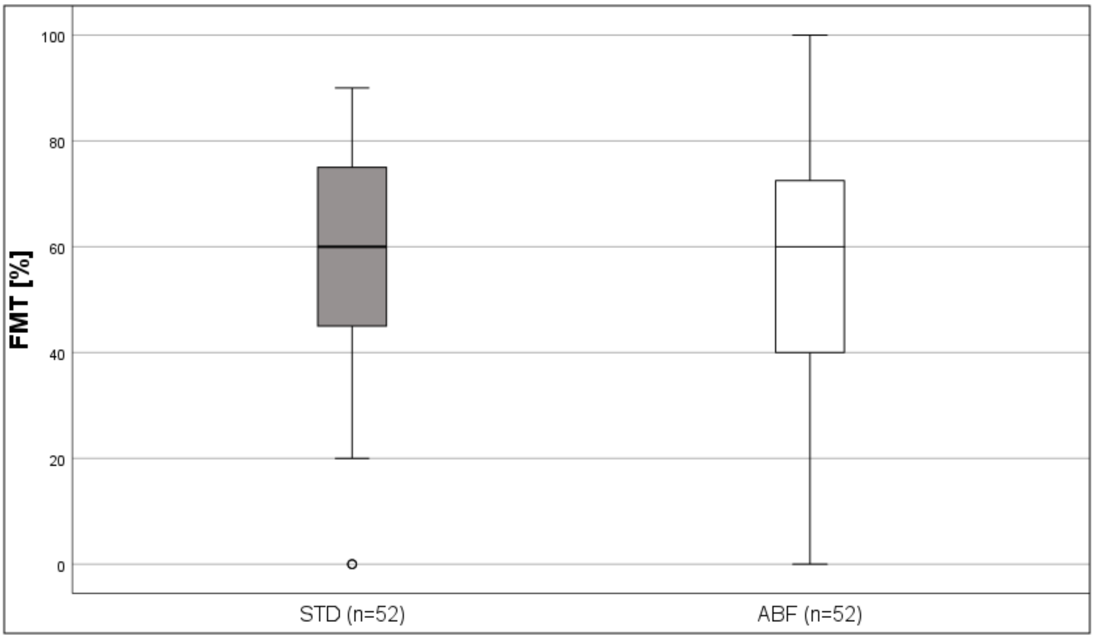

Figure 3: Boxplot, speech intelligibility in quiet (Freiburg monosyllable test) depending on tested frequency allocation (x-axis) and habituated frequency allocation in both settings (9-month interval), percent correct. n: number of ears tested, STD: standard frequency allocation, ABF: anatomy-based frequency allocation

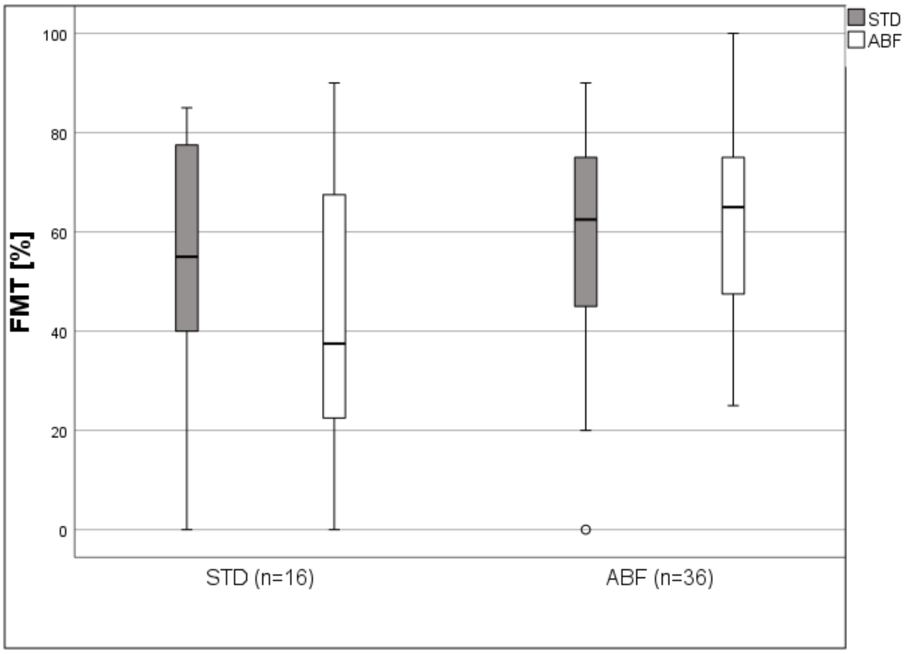

Figure 4: Boxplot, speech intelligibility in quiet (Freiburg monosyllable test) depending on tested frequency allocation (x-axis) and habituated frequency allocation in the preferred setting (9-month interval), percent correct. n: number of ears tested, STD: standard frequency allocation, ABF: anatomy-based frequency allocation

4 Discussion

The results suggest that ABF may improve hearing quality in CI users without compromising speech intelligibility. Especially, in the group of SSD patients, hearing quality perceived with ABF was described as more natural and overall more pleasant, compared to STD. Recently published studies show similar results. Kurz et al. [8] examined 12 SSD patients with ABF and STD and found significantly higher speech intelligibility in noise scores with the ABF as well as benefits in summation and squelch effects. As in our study, no significant improvement in speech intelligibility was observed with the ABF map. Upon the end of the study, all users opted to keep ABF, in accordance with our findings for the SSD group. While speech intelligibility scores outcomes showed no significant differences between the two approaches, the subjective questionnaire suggested potential advantages of individualized frequency mapping, particularly among SSD users. This is encouraging and may indicate that

SSD participants are able to take advantage of the potential benefits of an individualized fitting. Interestingly, the ABF-preferred group demonstrated consistently better performance and greater adaptability when switching between settings (Figure 4). While the STD-preferred group showed a decline in speech intelligibility when switching from STD to ABF, the ABF-preferred group showed no significant difference between the two frequency allocations and had similar results as the STD group in STD frequency allocation. This trend emerged early in the study and persisted across all visits (results of the other visits are not considered here). This indicates a better customization to both frequency allocations, not depending on the usage of the CI alone. The acceptance problem that was observed in some participants when attempting to switch between frequency allocations at the first test interval after 3 months indicates that switching to an alternative frequency allocation can be a challenge, especially at an early stage after implantation. Generally, participants needed time to get used to the change. Fan et al. [9] studied 48 postlingually deaf adults, split into anatomy-based (ABF) and standard frequency allocation groups (24 each), at 6 and 12 months post-implantation. While speech intelligibility in quiet showed no difference, ABF improved speech in noise perception, subjective hearing, and music quality. Unlike ours, their study lacked a crossover design, kept the lowest filter unchanged, and did not deactivate basal electrodes for OC-frequency alignment. Creff et al. [10] tested 26 first time implantees in a 3-month crossover study, reporting better speech-in-noise performance with ABF and absent differences for speech in quiet. Conversely, Lambriks et al. [11] found STD allocation superior across all tests, though their subjects had shorter electrodes (Advanced Bionics), which may not achieve full cochlear coverage — raising questions about ABF's benefit for "midscale" or "SlimJ" electrodes. Kurz et al. [12] described improved speech intelligibility in 10 experienced bilateral patients using ABF, noting that ≥620° insertion angles enhanced ABF acceptance. Regarding the patient cohort of the present study, mostly shallower insertion angles than 620° were observed. Analysis of the effect of insertion angle will be subject to further investigation.

4.1 Limitations

The study population presented here exhibited substantial interindividual variability in key clinical parameters, including etiology and degree of hearing loss, cochlear morphology, and electrode insertion characteristics. While these factors are known to influence cochlear implant outcomes, formal statistical analysis of insertion depth remains pending. During the final three-month evaluation phase, participants were instructed to use both frequency allocation strategies (standard vs. anatomy-based) equally. However, adherence to this protocol varied substantially. Some individuals exclusively favored one frequency allocation throughout this period. This disparity in usage patterns introduces a potential confounding factor, as prolonged exposure to a certain allocation may differentially affect neural adaptation and speech intelligibility. Consequently, observed differences in speech recognition scores could reflect not only the inherent efficacy of the frequency allocation strategies but also usage-dependent training effects or individual preference biases.

5 Conclusion

The results demonstrate an absence of a significant advantage for ABF in terms of speech perception scores in quiet when compared to STD allocation. Because consonants, being spectrally broad rather than sharply frequency-specific, are less dependent on precise electrode placement, shifts in the stimulation site are unlikely to affect their intelligibility. Nevertheless, SSD patients report improved sound quality with ABF and perceive a more natural sound profile that more closely resembles that of the contralateral, normal-hearing ear. Any partial loss of frequency bands resulting from the switch to the ABF setting is likely compensated for by the contralateral ear and thus has only a minimal impact on overall perception.

Notes

Conference presentation

This contribution was presented at the 28th Annual Conference of the German Society of Audiology and published as an abstract [13].

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Ethics statement and informed consent

The experimental protocols and the study design were formally reviewed and approved by the Ethics Committee of the Goethe University Frankfurt (approval number/Geschäftszeichen: GZ 20-940). The study was conducted in strict accordance with the ethical principles outlined in the Declaration of Helsinki. Prior to any testing or data collection, the background and purpose of the screening were explained to all participants, and written informed consent was obtained from each individual.

Competing interests

The authors declare that they have no competing interests.

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