frontiers | Frontiers in Audiology and Otology

TYPE Conceptual Analysis
PUBLISHED 29 August 2023
DOI 10.3389/fauot.2023.1242196

OPEN ACCESS

EDITED BY
Jorge Humberto Ferreira Martins,
Polytechnic Institute of Porto, Portugal

REVIEWED BY
Cristina Caroça,
CUF Infante Santo Hospital, Portugal
Antonio Vasco Oliveira,
Polytechnic Institute of Porto, Portugal

*CORRESPONDENCE
Roulla Katiri
✉ roulla.katiri@nhs.net

RECEIVED 18 June 2023
ACCEPTED 07 August 2023
PUBLISHED 29 August 2023

CITATION
Katiri R, Peters JPM, Fackrell K and Hoare DJ (2023) Device-based interventions that seek to restore bilateral and binaural hearing in adults with single-sided deafness: a conceptual analysis. *Front. Audiol. Otol.* 1:1242196.
doi: 10.3389/fauot.2023.1242196

Device-based interventions that seek to restore bilateral and binaural hearing in adults with single-sided deafness: a conceptual analysis

Roulla Katiri [1,2,3,4]*, Jeroen P. M. Peters [5,6], Kathryn Fackrell [1,2,7] and Derek J. Hoare [1,2,8]

[1]Hearing Sciences, Mental Health and Clinical Neurosciences, School of Medicine, University of Nottingham, Nottingham, United Kingdom, [2]National Institute for Health Research Nottingham Biomedical Research Centre, Nottingham, United Kingdom, [3]Department of Audiology, Mater Misericordiae University Hospital, Dublin, Ireland, [4]Audiology Department, University Hospitals Sussex NHS Foundation Trust, Brighton, United Kingdom, [5]Department of Otorhinolaryngology and Head and Neck Surgery, University Medical Center Utrecht, Utrecht, Netherlands, [6]UMC Utrecht Brain Center, University Medical Center Utrecht, Utrecht, Netherlands, [7]Wessex Institute, University of Southampton, Southampton, United Kingdom, [8]Nottingham University Hospitals NHS Trust, Queen's Medical Centre, Nottingham, United Kingdom

Single-sided deafness (SSD) is defined by severe-to-profound sensorineural hearing loss in one ear only. This article outlines the etiologies and associated functional, psychological, social, and other consequences of SSD in adulthood. The available hearing aids and auditory implants for SSD are described, alongside an overview of the methods adopted by clinicians and researchers to define and measure their benefits and harms. Current concepts and issues to consider in the field of rerouting and restoring device-based interventions are explored. A contemporary overview of the current challenges in outcome measurement of all available interventions in the field is also provided, and cost effectiveness of SSD interventions is discussed briefly. This article therefore proves a comprehensive summary of the current knowledge on interventions and outcome measurement for SSD for those interested or actively working in the field, and recommendations for future trials. These include recommendations on the timescale of measurements, long-term benefits (or harms), cost utility, and the use of the internationally agreed core outcome domain set for all future clinical trials of device-based interventions for SSD.

KEYWORDS

CROS hearing aid, bone conduction device, cochlear implant, single-sided deafness (SSD), unilateral hearing loss, hearing interventions, auditory implant

Introduction

Single-sided deafness (SSD) arises when there is normal or near-normal hearing in one ear and a severe-to-profound sensorineural hearing impairment in the other ear (Van de Heyning et al., 2017). SSD is defined by a specific audiological classification: the mean pure tone average at frequencies of 0.5, 1, 2, and 4 kHz should be $\geq$70 dB HL on the poorer ear, and $\leq$30 dB HL on the better ear, with an interaural threshold gap of $\geq$40 dB HL. This definition is in line with a previous definition published in a proceedings paper which aimed to differentiate between SSD and asymmetric hearing loss (AHL) (Vincent et al., 2015). With regards to terminology, SSD is sometimes used interchangeably with unilateral hearing loss which may incorporate conductive (middle ear related), or mixed (both middle and inner ear related) hearing losses (BSA, 2018). Developing a consensus around the definition allowed us to differentiate between SSD and AHL when comparing data.

This conceptual analysis aims to provide a narrative overview of SSD. The functional and psychological impact are discussed first, followed by the impact on wellbeing and quality of life (QoL). Finally, novel challenges in choice of device-based treatments faced by patients diagnosed with SSD, healthcare professionals, and clinical researchers working in the field are discussed.

Etiology

SSD can be (i) congenital or perinatal, (ii) of sudden acquired causes, or (iii) progressive. The most common causes of SSD in adulthood are sudden and idiopathic.

Congenital or perinatal causes

Cochlear nerve deficiency is one of the most common causes of pediatric SSD (Usami et al., 2017), followed by inner ear malformation (Acke et al., 2021). The causes can also be genetic, secondary to family history, syndromic (Widen et al., 2000; Fitzpatrick et al., 2017), or due to *in-utero* or post-natal infections such as cytomegalovirus or meningitis (Ghogomu et al., 2014; Huttunen et al., 2019; Dewyer et al., 2022). Perinatal causes include sudden idiopathic sensorineural hearing loss, or head trauma.

Sudden acquired causes

In adulthood, SSD can be of sudden causes secondary to conditions like Ménière's disease (Wu et al., 2019), follow viral infections such as labyrinthitis, be idiopathic (Chandrasekhar et al., 2019; Mirian and Ovesen, 2020; Simani et al., 2022), or due to autoimmune systemic diseases (McCabe, 1979; Rossini et al., 2017; Li et al., 2018). Sudden onset SSD can be caused by temporal bone fracture(s) following head trauma, or be iatrogenic following otological surgery (Bird and Bergin, 2018; Deep et al., 2021). More recently, case reports of sudden onset SSD following COrona VIrus Disease (COVID-19) (Koumpa et al., 2020; Asfour et al., 2021; Pokharel et al., 2021), or attributed to immunization for COVID-19 with SARS-CoV-2 mRNA vaccines (Ekobena et al., 2022) have been documented.

Progressive causes

SSD can be progressive, for example, in cases of cholesteatoma (Usami et al., 2017), cerebellopontine angle tumor(s), neurofibromatosis (Jia et al., 2020), or vestibular schwannoma (Daniels et al., 2000; Staecker et al., 2000; Douglas et al., 2007). Other progressive causes including ototoxicity, vascular conditions, demyelinating conditions, Lyme disease, otosyphilis, and human immunodeficiency virus have been proposed (Timon and Walsh, 1989; Peltomaa et al., 2000; Lee and Baloh, 2005; García-Berrocal et al., 2006; Chau et al., 2010; Schreiber et al., 2010).

Although the causal relationship between these causes and unilateral sensorineural hearing loss is difficult to verify, these causes should be outruled in cases of SSD in adulthood (Lawrence and Thevasagayam, 2015; Chandrasekhar et al., 2019; Twigg et al., 2020).

Prevalence and incidence of SSD

It has been suggested that SSD affects between 12 and 27 individuals in every 100,000 of the general population (Kitterick et al., 2014). More recently, it has been estimated that 10.4–25.4 individuals per 100,000 are at risk for SSD (Sprinzl and Wolf-Magele, 2016); 5–20 per 100,000 due to sudden sensorineural hearing loss (SSNHL) (Plaza et al., 2011). A more recent study containing information for more than 60 million unique patients estimated the prevalence of SSNHL in the USA to be 27 per 100,000 (Alexander and Harris, 2013). The NHANES epidemiologic study in the USA estimated the prevalence of SSD in adults to be 0.14% (Kay-Rivest et al., 2021); and to be higher in females (0.17%) vs. males (0.11%). The NHANES data also demonstrated that the prevalence of SSD was higher in individuals aged 60–79 years (prevalence of 0.25%) than in younger individuals (0.11% in ages 20–39 years, and 0.11% in ages 40–59 years).

The incidence of SSD in the UK has been estimated at 7,500 new adult cases per year (Baguley et al., 2006). Extrapolating to the 2023 population in the UK of ∼67 million (www.ons.gov.uk), the incidence of SSD is ∼9,000 new cases per year. Baguley et al. (2006) calculated that the highest incidence of SSD per 100,000 of the adult population per year was due to SSNHL, followed by Ménière's disease, with vestibular schwannoma being the lowest.

Associated otologic features

Tinnitus

SSD can be associated with tinnitus, defined as "the conscious awareness of a tonal or composite noise for which there is no

Abbreviations: ABI, Auditory Brainstem Implant; AHL, Asymmetric hearing loss; BCD, Bone conduction device; BSA, British Society of Audiology; CI, Cochlear implant; CINGLE, Cochlear Implantation for siNGLE-sided deafness; CNC, Consonant-Nucleus-Consonant; COVID-19, COrona VIrus Disease; CROS, Contralateral Routing of Signals; CROSSSD, Core Rehabilitation Outcome Set for Single-Sided Deafness; ENT, Ear, Nose, Throat; fMRI, functional Magnetic Resonance Imaging; HADS, Hyperacusis questionnaire; HHIA, Hearing Handicap Inventory for Adults; HINT, Hearing in Noise Test; HRQoL, Health-related quality of life; HUI, Health Utilities Index; ICER, Incremental Cost-Effectiveness Ratio; ILD, Interaural level difference; ITD, Interaural time difference; MEI, Middle Ear Implant; NHANES, National Health and Nutrition Examination Survey; NICE, National Institute for Health and Care Excellence; OlSa, Oldenburg Sentence Test; QALY, Quality-Adjusted Life Year; QoL, Quality of Life; SF-36, 36-Item Short Form Survey Instrument; SSD, Single-sided deafness; SSNHL, Sudden sensorineural hearing loss; SSQ, Speech, Spatial and Qualities hearing scale; TFI, Tinnitus Functional Index; THI, Tinnitus Handicap Inventory; US(A), United States (of America); VAS, Visual Analogue Scale.

identifiable corresponding external acoustic source" and/or tinnitus disorder, which arises when tinnitus is "associated with emotional distress, cognitive dysfunction, and/or autonomic arousal, leading to behavioral changes and functional disability" (De Ridder et al., 2021). It is estimated that ~80% of patients with sudden idiopathic sensorineural loss have tinnitus (Nosrati-Zarenoe et al., 2007; Schreiber et al., 2010; Levy et al., 2020). One hypothesis states that it can be due to reduced or absent auditory input that can lead to changes in neural activity (Eggermont and Roberts, 2012). Studies that used the Tinnitus Handicap Inventory (THI) (Newman et al., 1996) and the Hearing Handicap Inventory for Adults (HHIA) (Newman et al., 1991) to investigate the prevalence of tinnitus in those with idiopathic SSD showed that two thirds of patients reported intrusive tinnitus as per THI scores (Chiossoine-Kerdel et al., 2000). Visual Analog Scales (VAS) indicating the loudness of the tinnitus, and distress evoked by the tinnitus showed correlations between tinnitus loudness, distress, and hearing handicap (Chiossoine-Kerdel et al., 2000). Of those diagnosed with SSD secondary to Ménière's disease 78.6% report tinnitus (Young et al., 2022). In a retrospective study including 22 individuals with a vestibular schwannoma, tinnitus burden was measured using the THI (West et al., 2022). The authors highlighted that the methods adopted to date for evaluation of tinnitus may be a limitation due to participants being inadequately instructed to distinguish between the ears or situations (e.g., when wearing a hearing device or not). Tinnitus is also experienced by those who sustain SSD due to endolymphatic hydrops, labyrinthitis, trauma, iatrogenic causes, herpes zoster oticus, otosclerosis, cholesteatoma, or cerebrovascular accident (Van de Heyning et al., 2008; Buechner et al., 2010; Arndt et al., 2011a; Mertens et al., 2016; Ramos Macías et al., 2018).

Hyperacusis

Alongside the experience of tinnitus, some people with SSD also experience hyperacusis, which has been attributed to excessive gain increase in the central auditory pathway (Ramos Macías et al., 2018). Hyperacusis is a chronic disorder of loudness perception (Tyler et al., 2014) that involves reduced tolerance or increased sensitivity to regular noises (Baguley and Hoare, 2018; Fackrell et al., 2019; Adams et al., 2021). Hyperacusis is sometimes used interchangeably with loudness recruitment, which is a common symptom of peripheral hearing loss, defined as an abnormally fast growth of loudness perception of sound intensity (Shi et al., 2022). Hyperacusis in SSD has been linked to reduced median scores on the sub-scales of the Khalfa et al. (2002) hyperacusis questionnaire (HQ) (Mertens et al., 2016). The HQ however focuses on the psychological and social aspects of hearing, rather than on hyperacusis itself (Mertens et al., 2016). The Sound Hypersensitivity Questionnaire (SHQ) (Herráiz et al., 2006) was used in a Spanish multi-center study (Ramos Macías et al., 2018) to measure the impact of loud sounds and noise on the QoL in patients with SSD. It has 15 questions reported in four grades (Grade I: mild 1–10, Grade II: moderate 11–17, Grade III: severe 18–25, and Grade IV: very severe: 26–45) for three subscales of behaviors, cognitive reactions, and emotional reactions. Patients with SSSD score on average "severe" degree (Grade III) of incapacity (Ramos Macías et al., 2018).

Aural fullness

SSD due to sudden causes has been associated with aural fullness, which is described as "ear pressure," "sense of fullness," or "clogging sensation" (Westerlaken et al., 2003; Sakata and Kato, 2006; Park et al., 2012). Aural fullness in sudden onset SSD has no relationship to gender and age at the time of first assessment, however it is more common in low-frequency hearing loss audiograms (Sakata et al., 2008). In those diagnosed with Ménière's disease, 57.1% report unilateral aural fullness (Young et al., 2022), which is attributed to pressure imbalances between the round and oval windows in the inner ear (Sakata et al., 2008).

Vestibular dysfunction

The vestibular system can also be involved in 30–40% of cases with sudden unilateral loss (Nakashima and Yanagita, 1993; Schreiber et al., 2010; Shih et al., 2017). In Ménière's disease, individuals experience acute vestibular dysfunction (Thai-Van et al., 2001; Wu et al., 2019). In cases of SSD due to vestibulocochlear cranial nerve involvement individuals can experience instability while moving their head, imbalance, or vertigo (Nicoucar et al., 2006; Greene and Al-Dhahir, 2022).

Cortical changes in SSD

Studies have reported central auditory system re-organization in cases of unilateral deafness (Legris et al., 2018; Alzaher et al., 2021). These studies however, pool together data from individuals with various degrees of hearing loss that fall into the highly AHL category, as opposed to an SSD cohort explicitly. In adults, brain reorganization is detectable 5 weeks after onset of SSD (Suzuki et al., 2002), and functional magnetic resonance imaging (fMRI) studies have demonstrated that reorganization plateaus after 1 year (Bilecen et al., 2000). Magnetoencephalography studies of brain activation during performance of auditory syllable sequence reproduction tasks demonstrate that in adult-onset SSD there is both functional and structural alterations to the dorsal temporal and frontal-parietal areas of the brain (Shang et al., 2018). SSD also leads to physiological lateralization of auditory cortical activity, which has an impact on auditory spatial abilities (Karoui et al., 2022). An asymmetry of neuronal activity of the inferior colliculus and primary auditory cortex has been demonstrated using ^{18}F-FDG PET imaging studies (Speck et al., 2020, 2022). AHL loss has a significant impact on glucose metabolism of the auditory pathway, which in turn can negatively influence audiological performance (e.g., speech recognition in noise) following cochlear implantation (Speck et al., 2022). Speck et al. (2022) enrolled nine participants with either AHL or SSD, with heterogeneous etiology, disease onset, and duration of deafness, so they suggest larger longitudinal studies to be able to confirm their hypothesis.

Impact of SSD

The disabling effects of SSD (speech, spatial, qualities domains), and impact of these effects on the degree of handicap experienced by the hearing impaired individual, vary considerably (Gatehouse and Noble, 2004; Noble and Gatehouse, 2004).

Why we need two ears

Good hearing in both ears (binaural hearing) helps us deal with everyday listening tasks (Dwyer et al., 2014; Snapp and Ausili, 2020). Auditory processing of speech in complex environments gives listeners with binaural hearing a benefit of 4–10 dB in processing speech (Hawley et al., 2004) in comparison to monaural (hearing with one ear only). This is known as binaural loudness summation, i.e., sounds presented to two healthy ears is perceived louder than the same level of sound presented to one healthy ear only (Avan et al., 2015). The squelch effect is another ability of a healthy auditory system, which allows listeners to combine signal(s) and competing noise information retrieved from both ears to improve speech perception in noise. Benefits of binaural hearing include understanding speech in noisy or reverberant environments and locating where sounds such as the telephone or car traffic are coming from (Levitt and Rabiner, 1967; Hawley et al., 2004; Snapp, 2019; Snapp and Ausili, 2020; Gallun, 2021).

Sound localization in the horizontal (azimuth) plane relies mainly on interaural time differences (ITDs) and interaural level differences (ILDs) (Agterberg et al., 2012; Rothpletz et al., 2012; Pedley and Kitterick, 2017). In other words, the auditory system helps us judge our positioning in space by dynamically calculating our interaction with signals that are constantly changing in terms of pitch (frequency spectrum), level (intensity), and time (latency) (Akeroyd, 2006; Arndt et al., 2011a; Snapp and Ausili, 2020). The integration of acoustic information from both ears is essential for spatial awareness (Güldner et al., 2013; Karoui et al., 2022), for example, determining where sounds are coming from (Douglas et al., 2007; Pedley and Kitterick, 2017; Snapp, 2019).

Although there can be a degree of adaptation in certain monaural listeners (Slattery and Middlebrooks, 1994; Rothpletz et al., 2012), and possible long-term compensation for loss of binaural cues (Liu et al., 2018; Alzaher et al., 2021), localization abilities can be severely impaired in those hearing monaurally (Wazen et al., 2005; Agterberg et al., 2012; Hoth et al., 2016; Pedley and Kitterick, 2017; Snapp, 2019). A further complication for monaural listeners is introduced by the head shadow effect, where the head acts as an acoustic barrier to signals that travel from one side of the head to the other, which can lead to significantly impaired speech understanding (Akeroyd, 2006; Pedley and Kitterick, 2017; Snapp, 2019). In cases of SSD, speech originating from the poor-hearing side of the head is reduced in intensity by 6.4 dB by the time it reaches the normal-hearing ear; it therefore arrives distorted due to loss of high-frequency information from the speech spectrum (McLeod et al., 2008).

Functional difficulties experienced by adults with SSD

Due to the challenges arising from monaural access to sound, individuals with SSD have difficulties dealing with everyday tasks such as speech recognition (Lieu et al., 2010; Dwyer et al., 2014) and impaired ability to understand speech in the presence of background noise (Welsh et al., 2004; Rothpletz et al., 2012; Firszt et al., 2017; Vannson et al., 2017; Peters et al., 2021; Kitoh et al., 2022). It is estimated that there is a reduction in speech understanding by approximately 3 dB in SNR in cases of SSD (McLeod et al., 2008). Speech understanding is reduced due to reduced signal loudness detected by the monaural listener.

Different features of the conversation context, for example the complexity of the acoustic environment, the type or loudness of the background noise, or the number of people in a group can influence speech perception and impact on individuals' need to modify their communication strategies (Hadley et al., 2021). Adults with unilateral hearing loss are more likely to report a higher level of communication difficulties than normal-hearing adults (Dwyer et al., 2014; Choi et al., 2021). SSD can also impact music appreciation. Music can sound unnatural, unpleasant and indistinct, lack perceptual qualities such as stereo sound, and be confounded by distortion effects and tinnitus (Meehan et al., 2017).

Moreover, SSD is associated to increased listening effort when compared to normally hearing individuals (Dwyer et al., 2014; Lopez et al., 2021). Listening effort is defined as the mental exertion required to attend to and understand an auditory message (McGarrigle et al., 2014). Hearing impaired listeners may experience increased listening effort in challenging listening situations than normally hearing individuals, even if they use hearing aids (Alhanbali et al., 2017). The constant effort applied by a listener with SSD to adjust to their listening environment is fatiguing, and can be unsustainable for many (Snapp, 2019). The real-world impact of increased fatigue is dependent on personal factors and lifestyle (Holman et al., 2019), and can influence social activity level (Holman et al., 2021a). Fatigue could arise due to decreased audibility of sounds, and in part, increased requirement for listening effort (McGarrigle et al., 2014). Other factors such as related challenges in auditory processing, and increased listening effort required in demanding listening environments have been proposed (Hornsby et al., 2016; Ohlenforst et al., 2017; Peelle, 2018). Associations to work, social, or physical activity levels, and wellbeing are also relevant and have implications on daily-life fatigue in people with hearing loss (Holman et al., 2021b). Objective measures of pupil dilation as an indicator of listening effort during listening tasks demonstrate that the individual's motivation is a factor that can influence objective measures of fatigue (Wang et al., 2018). Qualitative studies interviewing people with hearing loss identified factors such as lifestyle, personality, situational control, the relationship with those in conversation and the attribution of blame are key to individual emotional experiences (Holman et al., 2022).

Psychological impact of SSD

The psychological impact of SSD in adulthood has been well-documented in the literature, including worry about losing the hearing in the other ear, embarrassment related to the social stigma attached to hearing loss, and reduced confidence and belief in one's own abilities to participate (Sano et al., 2013b; Lucas et al., 2018; Choi et al., 2021). Individuals with unilateral hearing loss are at a disadvantage in social and emotional situations. They report being upset, anxious, frustrated and isolated due to their hearing handicap secondary to monaural listening (Araújo et al., 2010; Sano et al., 2013a; Lucas et al., 2018). It has also been reported that SSNHL is associated with anxiety and depression (Arslan et al., 2018). Furthermore, increased stress levels related to the need to find an optimal position in social settings, that will help with speech perception and participation, have been reported in interview studies (Lucas et al., 2018). Those who acquired SSD secondary to a vestibular disorder (e.g., labyrinthitis, Ménière's disease) could be at risk of chronic anxiety which could precede depressive states (Hilber, 2022). Analysis from the 2008 National Health Interview Survey, which included ~18 million people with vestibular vertigo in the USA, suggested that cognitive impairment (memory loss, difficulty concentrating, confusion) and psychiatric diagnoses (depression, anxiety, panic disorder) are comorbidities in those with vestibular deficiencies (Bigelow et al., 2016), which can also be linked to difficulties remembering in 32% of individuals. In addition, individuals diagnosed with SSD report decreased self-esteem when in places with background noise, which can leave them feeling frustrated and isolated (Lucas et al., 2018). They also report increased stress levels and exhaustion related to their constant attempts to maximize their abilities to hear and participate in complex social situations (Wie et al., 2010; Kuppler et al., 2013). Associated feelings of frustration, annoyance, helplessness, embarrassment, and depressive symptoms have been reported in multiple studies (Giolas and Wark, 1967; Gatehouse and Noble, 2004; Wie et al., 2010; Sano et al., 2013b; Lucas et al., 2018; Choi et al., 2021).

Impact of SSD on wellbeing

QoL is defined as "a patient's general wellbeing, including mental status, stress levels, sexual function, and self-perceived health status" (Farlex Partner Medical Dictionary, 2012). Population based studies evaluated the risks of adverse hearing and wellbeing outcomes (including self-reports on depression, health rating, satisfaction with health, happiness and loneliness), in 113,804 UK Biobank participants aged 40–69 years who self-reported unilateral hearing loss (Pierzycki et al., 2020). Participants with unilateral hearing impairment are significantly more likely to report poor health, dissatisfaction with health, and loneliness than those with normal hearing (Dawes et al., 2014; Pierzycki et al., 2020). The multi-dimensional burden of SSD on overall health is indicated by reductions in health-related QoL in individuals with a diagnosis of SSD, despite use of hearing-assistive devices for SSD (Arndt et al., 2011a; Kitterick et al., 2015; Vannson et al., 2015; Pierzycki et al., 2020). One study reports that the impact of SSD on QoL can exceed that reported by listeners with bilateral hearing loss (Sano et al., 2013a). This Japanese study included 167 adult participants with idiopathic SSNHL and 134 participants with bilateral hearing loss to act as controls. They measured health-related QoL with the Japanese version of the Short-Form Health Survey (SF-36) (Fukuhara et al., 1998). The term "health-related quality of life" (HRQoL) narrows QoL to aspects relevant to health (de Wit and Hajos, 2013). This study concluded that there was reduced mental functioning in those with idiopathic SSNHL, compared to averages in the Japanese population, which was similar to their participants with bilateral hearing loss. The psychosocial impact has also been documented, with annoying tinnitus and remaining vertigo after SSNHL to be the strongest predictors of negative effects on QoL (Baguley et al., 2006; Carlsson et al., 2011). QoL can be affected in those who have vestibular schwannomas surgically removed, as indicated by lower scores yielded on the SF-36 survey instrument (Ware and Sherbourne, 1992), in all categories, but more significantly in physical ability, social functioning, emotional status and vitality (Nicoucar et al., 2006).

Social consequences of SSD

Individuals with SSD report feeling excluded in conversations with multiple speakers, have reduced wellbeing in social settings, and a preference to avoid social gatherings in which they thought significant background noise would be present (Wie et al., 2010; Chang et al., 2020). Qualitative studies indicate that coping strategies of individuals with SSD include withdrawal from within a situation and in some cases, from the social situation completely (Lucas et al., 2018). The impact of SSD on communication can also affect intimate relationships (Hétu et al., 1993; Lucas et al., 2018). SSD can impact individual's vocational activities such as business negotiations, customer service, and meetings, contribute to absences or days away from work, and early retirement (McLeod et al., 2008; Härkönen et al., 2015; Marx et al., 2019; Snapp, 2019). These studies disagree with Colletti et al. (1988) who found no difference between monaurally and binaurally hearing individuals on educational, social, and employment achievement. Their participants however were aged 30–55 years, and had SSD since childhood (Colletti et al., 1988), rather than acquired in adulthood like the other studies. However, longitudinal studies in the USA with older adults with age-related hearing loss report that hearing loss may be associated with reduced engagement in physical and mental activities (Goman et al., 2021; Kuo et al., 2021). They also report higher odds of those with hearing loss reporting loneliness than those reporting excellent hearing, after adjusting for comorbidity index, functional and cognitive ability, self-reported health, and demographic characteristics (Huang et al., 2021). It is well-documented in recent literature that hearing impairment can impair social engagement, alter social roles, and impede the formation and maintenance of relationships (Barker et al., 2017; Vas et al., 2017; Heffernan et al., 2022).

Treatment options for SSD

The aim of SSD device-based treatments is to address the functional difficulties imposed and in turn improve everyday listening and communication. Devices are categorized as either rerouting or restoring.

Rerouting devices for SSD ("bilateral hearing")

The most commonly used treatment options for SSD enable access to sounds on both sides of the head (bilateral hearing) by rerouting sounds from the impaired ear to the hearing ear.

Contralateral routing of signals hearing aid

Rerouting interventions include the CROS hearing aid (Leterme et al., 2015; Ryu et al., 2015; Snapp et al., 2017; Choi et al., 2021). The CROS system (Figure 1) is made of two parts: a wireless microphone which is mounted onto the poor-hearing ear and is paired wirelessly to a hearing aid that is worn on the better-hearing ear. The Snapp (2019) review lists several advantages of the CROS device including sound awareness on the poor-hearing side, improvement of the SNR for sounds directed to the poor-hearing ear in noisy environments, and ease of use. Limitations of this technology include that binaural input is still impaired, poor sound localization in the horizontal plane due to disruption of the available monaural level and spectral cues (Pedley and Kitterick, 2017), and impairments related to hearing in noise, especially if the interfering noise is amplified in the better-hearing ear (Snapp, 2019).

Bone conduction devices

An alternative widely used rerouting intervention for SSD is the BCD which can be implanted on the poor-hearing side. BCDs were first implanted in the 1970s (Tjellström and Granström, 1994) and since then many variations have been developed (Håkansson et al., 2019; Iwasaki, 2022; Maier et al., 2022). A BCD fitting requires surgical implantation of a transcutaneous abutment (Figure 2), or a more recently used device with a subcutaneous magnet (Figure 3) into the skull bone behind the ear. It delivers sounds into the skull by means of sound vibrations, which transfer sound transcranially from the poor-hearing side to the contralateral side. Benefits of the BCD for SSD include overcoming the negative consequences of the head-shadow effect (Niparko et al., 2003; Snik et al., 2004), improvement in hearing speech in noise when noise is presented on the better hearing ear side (Hol et al., 2005), and improvement in QoL (Leterme et al., 2015).

A review of four controlled trials that attempted to determine the benefit of BCD vs. CROS vs. the unaided condition concluded that there is a paucity of evidence to support the efficacy of BCD in the treatment of acquired SSD (Baguley et al., 2006). However, they suggested that speech discrimination in noise and subjective questionnaire measures of auditory abilities showed an advantage for BCD over CROS and the unaided condition. A systematic review comparing the clinical outcomes of the CROS and BCD devices concluded that there is no difference between the two treatment options regarding speech perception in noise and localization, and a moderate improvement in subjective speech communication when using either a CROS or a BCD (Peters et al., 2015a). Other studies also concluded that the BCD does not improve nor deteriorate the localization abilities of individuals with SSD (Wazen et al., 2005; Lin et al., 2006; Agterberg et al., 2019). A study that included 44 individuals with SSD assessed the subjective benefits of BCD with four questionnaires, with a median of 50 months follow-up period (Desmet et al., 2014). Their findings suggest that the majority of individuals (86%) use their processors, and report an overall improvement; however, device use reduces at long-term follow-up, especially in noisy situations.

The subcutaneous magnet version of the BCD system (Figure 3) was compared to the percutaneous (Figure 2) on a prospective study evaluating the long-term audiological and clinical outcomes (Kruyt et al., 2020). The findings suggested that the percutaneous system provided statistically significant or near-significant improvement compared with the unaided condition in all audiometric tests throughout the 24-month follow-up, except for speech recognition in noise at the 24-month visit. However, the statistically significant clinical improvements recorded with questionnaires at 6 months were no longer present at 24 months. Another study that included five individuals with SSD and compared the percutaneous vs. subcutaneous devices during the first 6 months post implantation found an improvement in sound, speech understanding, and QoL in those implanted with the percutaneous device, but limited improvement in localization abilities, and there were no adverse effects noted (Kong et al., 2021).

Active bone conduction implant systems

Active bone conduction implant systems, like the MED-EL BoneBridge^{TM} (Figure 4) have been used to alleviate the impact of SSD in adults (Bianchin et al., 2015; Zernotti and Sarasty, 2015; Sprinzl and Wolf-Magele, 2016; Schmerber et al., 2017; Ratuszniak et al., 2022). The BoneBridge^{TM} consists of an external audio processor and an implantable bone conduction implant which lies completely under the skin on the poor-hearing side. The bone conduction implant is composed of an active electromagnetic bone conduction floating mass transducer, an electrical demodulator, and a receiver coil. Sound vibrations delivered through the skull are transmitted directly to the inner ear. The Cochlear^{TM} Carina, another active bone conduction implant, has not been reported as an intervention for SSD (Katiri et al., 2021).

A longitudinal, 5-year follow-up economic analysis of the BoneBridge^{TM} compared to the percutaneous BCD (Figure 2) demonstrated that the BoneBridge^{TM} is a good alternative option with reduced skin complications reported due to the lack of a percutaneous abutment. However, a drawback of this device is the attenuation of high frequency auditory output by the skin (Amin et al., 2021). Another study that evaluated the post-operative pain following BoneBridge^{TM} implantation concluded that pain scores were similar to those experienced by individuals with other transcutaneous auditory implants (Lassaletta et al., 2016). Structured interviews conducted with 20 adult participants with SSD by Ratuszniak et al. (2022) demonstrated that the BoneBridge^{TM} device provided less subjective satisfaction in those with SSD vs. other types of hearing loss (conductive or mixed). Their interviews included questions on (i) satisfaction of the effect achieved, (ii) sound quality of the device, and (iii) change in hearing (improvement or deterioration).

Adhesive BCD

An adhesive BCD, the ADHEAR (Figure 5) by MED-EL, has also been used to alleviate the functional effects of SSD (Mertens et al., 2018; Moteki et al., 2020). The device comprises a removable, single use adhesive adapter and an audio processor that are worn behind the poor-hearing ear. The adhesive adapter secures the audio processor and provides sufficient contact force

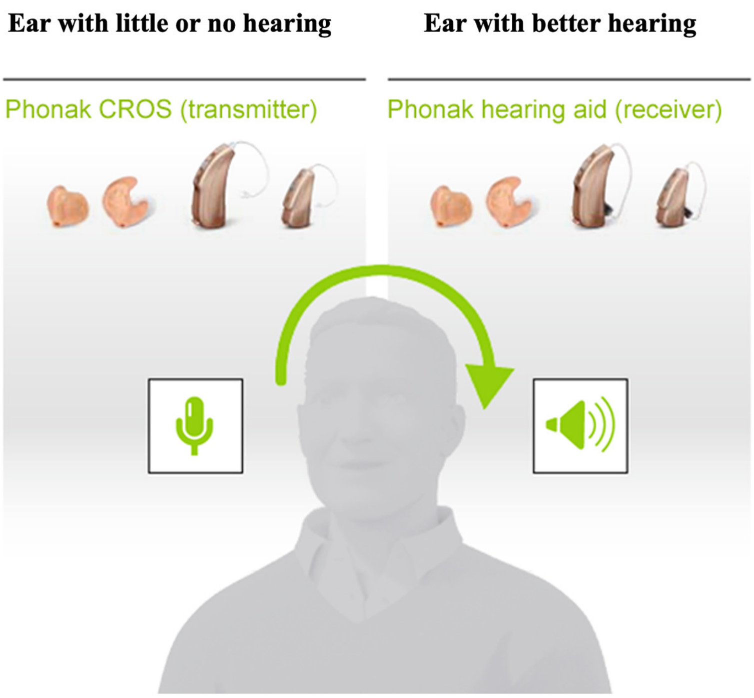

FIGURE 1
Schematic representation of the Phonak Contralateral Routing of Signals (CROS) hearing aid. Retrieved from www.phonakpro.com and used with permission, © 2023 Sonova AG.

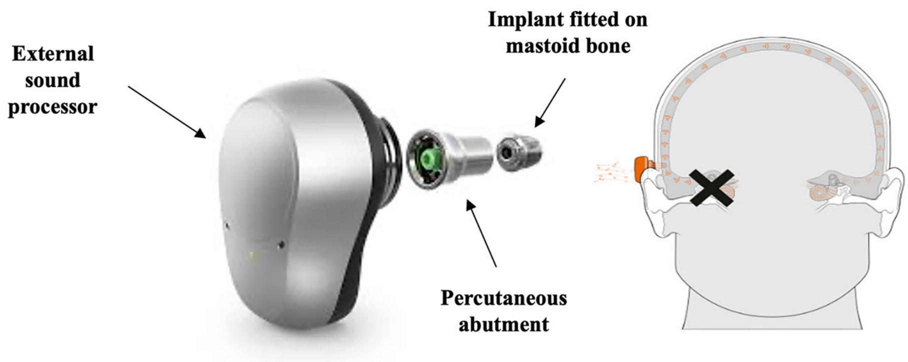

FIGURE 2
Schematic representation of the Oticon Medical™ percutaneous bone conduction device (BCD). Retrieved from www.oticonmedical.com and used with permission from Oticon Medical™.

to provide good physical contact between the vibrating portion of the hearing aid and the user's skull (Mertens et al., 2018). A study aiming to obtain preliminary results regarding the use of ADHEAR in individuals with various types of hearing loss found no improvement in speech perception or sound localization, despite functional hearing gains in their three participants with SSD (Moteki et al., 2020). The speech perception findings mirror the Mertens et al. (2018) conclusions, although they did observe slight improvement in sound localization when wearing the ADHEAR with the omnidirectional microphone program enabled, when compared to the CROS device in 17 participants with SSD. However, due to the large variation in outcomes and limited statistical power no firm conclusions were made.

Dental implant

Another rerouting device, the SoundBite™ dental implant (Figure 6) by Sonitus Medical, has been tested in the past (Popelka et al., 2010; Miller et al., 2011; Murray et al., 2011; Gurgel and Shelton, 2013; Moore and Popelka, 2013; Luo et al., 2020), but is currently only used in China (BusinessWire, 2022). The SoundBite™ is a removable in-the-mouth device that is fixed onto the teeth, and directly coupled to the skull. A behind-the-ear hearing aid picks up signals and transmits them to the in-the-mouth device. The SoundBite™ is directly fixed onto the dental bones, and it generates vibration that passes through the skull to the cochlea. A study that recruited nine Chinese individuals with SSD aged 24–61 years assessed speech recognition in quiet

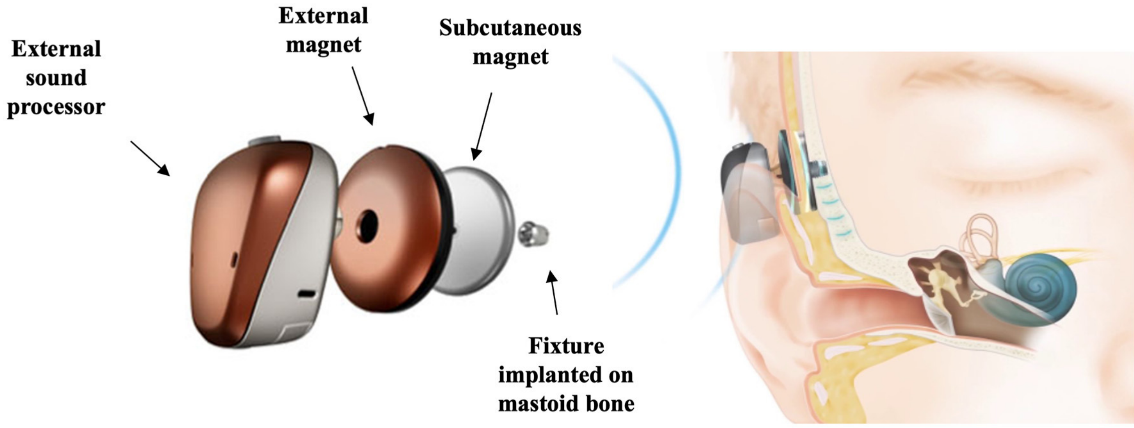

FIGURE 3
Schematic representation of the Cochlear™ Baha® 6 Max Attract system, a subcutaneous bone conduction device (BCD). Images courtesy of Cochlear Bone Anchored Solutions AB, © 2023.

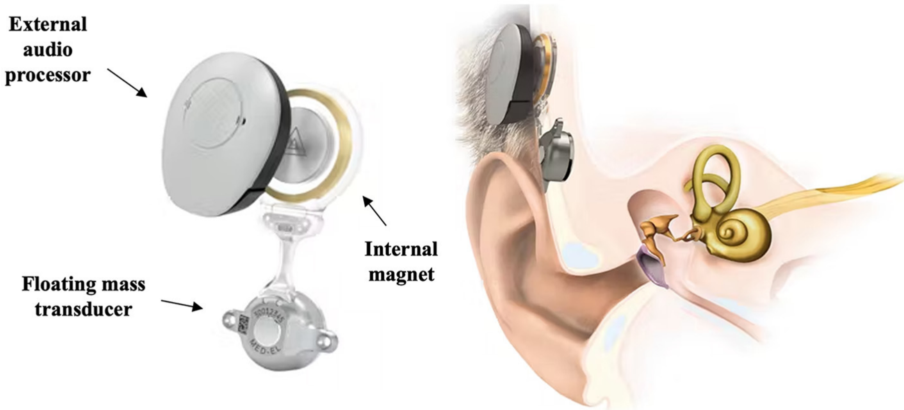

FIGURE 4
Schematic representation of the MED-EL BoneBridge™ bone conduction implant. Retrieved from www.medel.com and used with permission from MED-EL.

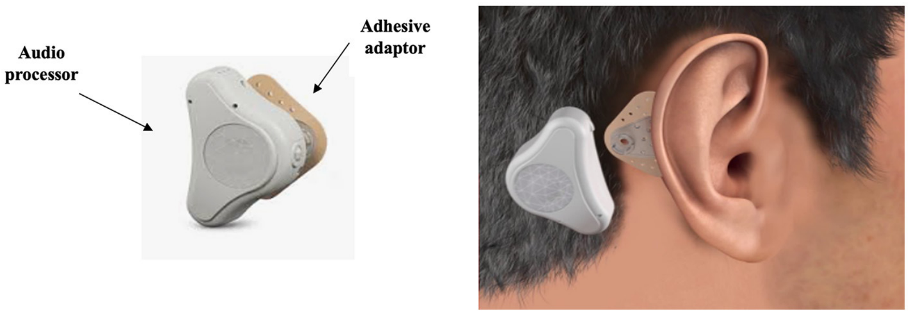

FIGURE 5
Schematic representation of the ADHEAR by MED-EL bone conduction device (BCD). Retrieved from www.medel.com and used with permission from MED-EL.

and noise, and QoL when using the SoundBite™ compared to no intervention (Luo et al., 2020). The findings suggest an improvement in QoL and speech perception benefits in quiet and noise (when noise was presented on the better-hearing ear).

Restoring devices for SSD ("binaural hearing")

Auditory input to the poor-hearing ear can be restored (binaural hearing) by delivering information about sounds directly to the auditory pathway on the side of the impaired ear.

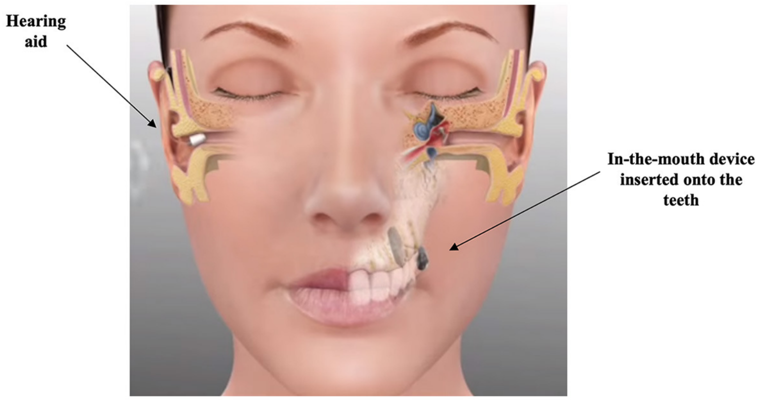

FIGURE 6
Schematic representation of the SoundBite™ dental implant. Reproduced with permission from SoundBite hearing (SoundBite Hearing, 2013).

Middle ear implants

Binaural hearing can be achieved using auditory prostheses like a MEI, such as the MED-EL Vibrant SoundBridge™ (Figure 7). The device consists of an externally worn audio processor and an implant surgically positioned under the skin. The audio processor is held to the implant by magnetic attraction. The audio processor microphones pick up sound waves and the audio processor converts sounds into electrical signals, which are transmitted through the skin to the implant. A small part of the device, the floating mass transducer, converts the signals into mechanical vibrations which in turn stimulates the inner ear (Laske et al., 2015; Gerdes et al., 2016; Schmerber et al., 2017). Schmerber et al. (2017) included 12 individuals with SSD in their study aiming to validate the safety and efficacy of the Vibrant SoundBridge™ to find an improvement in speech-in-noise performance when the speech was presented on the poor-hearing side with the device on. The findings are in agreement with Laske et al. (2015) who also found improvements when the speech signal was presented on the poor-hearing side with the device on.

More recently, the Cochlear™ Osia® system (Figure 8) has been used for SSD (Rauch et al., 2021; Willenborg et al., 2022). The Osia® system is an active bone conduction hearing implant system that has a transcutaneous connection between an external processor and an implant. The vibrator (actuator) is piezoelectricity based and is connected directly to a titanium implant anchored and osseointegrated to the skull bone (Arndt et al., 2021; Hwa et al., 2022). Piezoelectricity is the ability of certain materials to generate an electric charge in response to applied mechanical stress (vibrations), or reversibly to generate vibrations in response to an external electric charge (Goycoolea et al., 2020). A multi-center study including five individuals with SSD investigated the clinical performance, safety, and patient-reported outcomes of the Osia® system (Briggs et al., 2022). They demonstrated a statistically significant and clinically relevant improvement in speech recognition in quiet and noisy situations compared to an unaided situation, and a subjective improvement in hearing benefit when compared to pre-operative scores.

Cochlear implant

Cochlear implantation as an intervention for SSD was first piloted to assess the effect of electrical stimulation via a CI in individuals with SSD and incapacitating ipsilateral tinnitus (Van de Heyning et al., 2008). Since then has been utilized by several clinical teams, mainly in Europe, North America and Australia (Härkönen et al., 2015; Távora-Vieira et al., 2015; Arndt et al., 2017; Marx et al., 2019; Poncet-Wallet et al., 2020; Peters et al., 2021). A CI can deliver information about sounds directly to the auditory pathway, electrically stimulating the impaired ear (Figure 9), thus creating a sensation of binaural hearing (Arndt et al., 2011a). Auditory cortical plasticity studies have suggested that cochlear implantation in asymmetrical hearing loss enables reconstruction of the cortical mechanisms of spatial selectivity needed for sound localization (Karoui et al., 2022).

A systematic review of the literature up to 2015, analyzed the influence of cochlear implantation in a total of 137 individuals with SSD with regards to sound localization, speech perception, tinnitus, and QoL (Cabral Junior et al., 2016). Despite the variation in participant characteristics, onset and duration of SSD, and the diversity of outcomes reported, the authors conclude that cochlear implantation enhances sound localization, speech perception, and contributes to improvement in tinnitus. Another systematic review incorporating nine studies reporting on 112 participants assessed the clinical outcomes of cochlear implantation for SSD or AHL (van Zon et al., 2015). Due to large clinical heterogeneity in the reported measures, especially speech perception in noise, and high risk of bias, a meta-analysis was not conducted. A more recent systematic review included 50 studies totalling 674 adults with SSD aged 19–93 years, with an average duration of deafness ranging from 0.8 to 68 years (Oh et al., 2023). This review aimed to analyse the impact of CI on speech perception in quiet and noise, tinnitus control, sound localization, and QoL. Similar to Cabral Junior et al. (2016) the authors concluded that CI in individuals with SSD provides significant improvement in speech perception, tinnitus control, localization, and QoL. Oh et al. (2023) also highlighted a large variability in participant characteristics (e.g., etiology, onset, duration), numbers recruited in studies (e.g., ranged from 3 to 70 participants), choice and reporting of

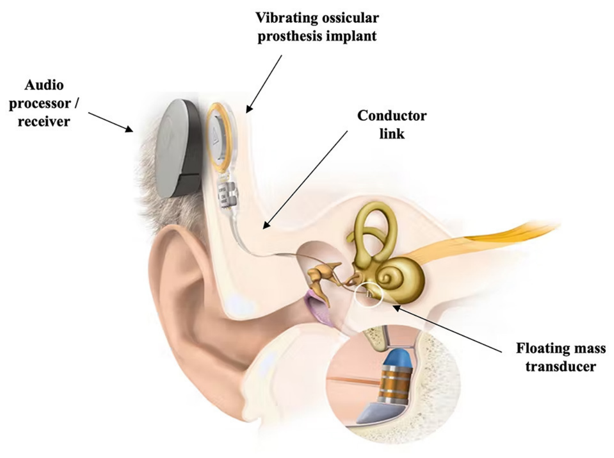

FIGURE 7
Schematic representation of the MED-EL Vibrant SoundBridge™ middle ear implant. Retrieved from www.medel.com and used with permission from MED-EL.

outcome measures (e.g., speech testing configurations, reporting parameters), follow-up time (e.g., ranged from 6 months to 3.5 years) across studies. Of note, a recently reported retrospective case series with 66 adults with SSD that were implanted with a CI report that duration of deafness was not associated with significant differences in speech recognition performance (Lindquist et al., 2022). They measured speech recognition with the Consonant-Nucleus-Consonant (CNC) words and the AzBio sentences in quiet. A systematic review including 31 studies, which aimed to provide a comprehensive overview of the short- and long-term effects of cochlear implantation on disabling tinnitus in adults with SSD, reported an improvement in tinnitus suppression scores despite variability in patient characteristics (Idriss et al., 2022).

Short-term outcomes of CI for SSD were compared to those for BCD, CROS aid, and no intervention in a Dutch randomized controlled trial (Cochlear Implantation for siNGLE-sided deafness, CINGLE-trial) involving 120 participants (Peters et al., 2015b, 2021). Peters et al. reported an improvement in speech perception in noise in various signal-to-noise configurations in their CI group. On the other hand speech perception in noise improved or deteriorated for the BCDs and CROS groups depending on the configuration. There was an improvement in sound localization, the tinnitus questionnaire (Goebel and Hiller, 1994; Meeus et al., 2007) scores, a reduction on tinnitus burden detected on the THI (Newman et al., 1996). In general, all treatment options improved disease-specific QoL on most subscales of the patient reported outcome measures that were used (Peters et al., 2021).

A French multi-center prospective study aimed to assess the efficiency of CI in SSD, compared to that of CROS and BCD trials, using a cost-utility analysis (Marx et al., 2019). Initial findings indicate that approximately half of 104 participants opted for a CROS aid, but over one third of participants with SSD were dissatisfied with the CROS and BCD devices, and those that opted for CI experienced more severe handicap and had a poorer QoL than the other groups (Marx et al., 2021b). There was no significant difference between participants that opted for CROS, BCD, CI, or no intervention in terms of etiology of deafness, deafness duration, side of deafness, hearing thresholds in the better ear, or tinnitus severity. When the outcomes of the 51 participants that opted for a CI were considered with regards to generic and auditory-specific QoL, there was significant improvements noted, especially in participants with SSD and associated severe tinnitus (Marx et al., 2021a). The authors acknowledge the small participant number and the short-term follow-up, restricted to 6 months post implantation. A recent study including 20 participants with SSD implanted with CI demonstrated that localization abilities improve with long-term use, with more consistent responses in sound source localization performance at their 5-year visit (Thompson et al., 2022).

A systematic review by Kitterick et al. (2015) included 23 studies examining the impact of hearing-assistive devices on HRQoL in adults with SSD as measured using generic and disease-specific instruments. The average effect size of CROS aids was small and BCD devices was medium, whereas CI had a large effect with a caveat that it included within-subject comparisons of HRQoL before and after implantation.

Auditory brainstem implant

Finally, ABI has also been used as an intervention for SSD, but sporadically (Mueller et al., 2000). The ABI (Figure 10) was specifically designed to bypass both the cochlea and the cochlear nerve to directly stimulate the cochlear nucleus in the brainstem (van den Berge et al., 2019). Therefore, ABIs are suitable in cases of destruction of the cochlear nerve (Schwartz et al., 2008). When compared to no intervention, an ABI can provide a degree of improvement in sound recognition and speech perception to patients who are not CI candidates (Ontario Health, 2020a).

Cost effectiveness of interventions

Hearing aid and auditory implant cost-effectiveness studies have become increasingly important (Theriou et al., 2019; Neve et al., 2021; Caspers et al., 2022). The device purchasing cost varies from a few hundred pounds for the rerouting hearing aid solutions to ∼£20,000 for the restoring implants. A formal cost-effectiveness analysis for BCD devices in a prospective case-control study of 70 pathways found that there was limited data for cost effectiveness calculations for BCD devices (Monksfield et al., 2011). They presented total costs from initial evaluation, surgery, ongoing annual evaluation and maintenance, and processor upgrades after 5 years to the newest model for an estimated life expectancy of the individual patient (Monksfield et al., 2011). The Health Utilities Index (HUI) questionnaire (Horsman et al., 2003) was used in conjunction with life expectancy estimations to derive Quality-Adjusted Life Year (QALY) and Incremental Cost-Effectiveness Ratio (ICER) ratios. There is limited QoL data available for patients living with an osseointegrated implant. As a result, the cost-effectiveness of the osseointegrated implant, compared to conventional hearing aid devices remains unclear (Crowson and Tucci, 2016).

Amin et al. (2021) performed a retrospective case series analysis with a longitudinal economic analysis. They concluded that the mean total cost per patient of the MED-EL middle ear

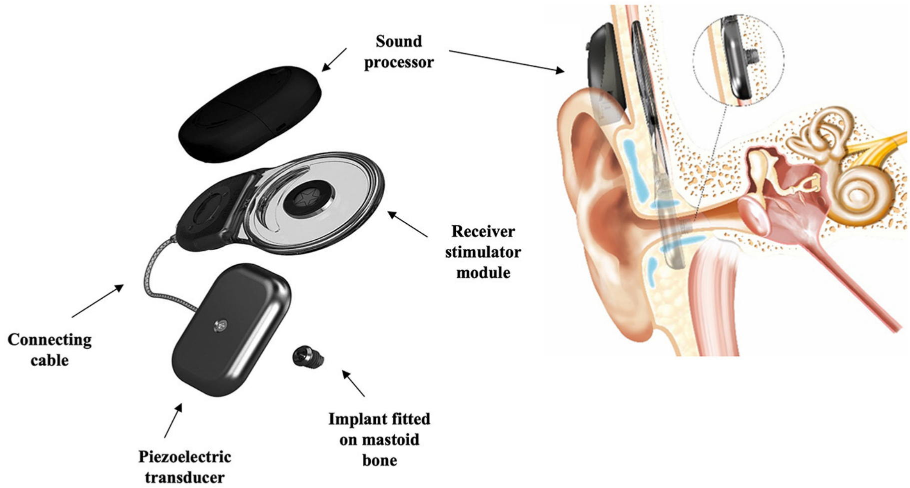

FIGURE 8
Schematic representation of the Cochlear^{TM} Osia® system, an active bone conduction hearing implant. Images courtesy of Cochlear Bone Anchored Solutions AB, © 2023.

implant was significantly higher than percutaneous BCD at 1-year post-implantation. However, by 5-years post-implantation this difference was no longer statistically significant. Unfortunately, cost-effectiveness evaluations were limited by the lack of usable data on QoL and device usage (Caspers et al., 2022). Based on evidence of moderate quality, cochlear implantation and BCD improve functional and patient-important outcomes in adults and children with SSD (Ontario Health, 2020b). The Ontario health technology assessment report highlighted that among people with SSD, cochlear implantation may be more cost-effective than no intervention, whereas BCDs are unlikely to be although are acceptable to patients who cannot use CI.

Outcome measurement for SSD interventions

Existing literature has highlighted inconsistencies in what benefits and risks (side-effects) are measured when evaluating hearing aid(s) and auditory implant interventions for SSD (Kitterick et al., 2016). The challenge of synthesizing evidence for ENT and audiological interventions from trials, and the importance of utilizing valid measurement instruments that effectively measure the intended audiological outcomes has been highlighted in the case of SSD (Hall et al., 2019). Choosing the appropriate intervention for adults with SSD presents a clinical dilemma (Sin Wai and Chua Wei De, 2021; Underdown and Pryce, 2022).

Researchers investigating SSD intervention outcomes have measured a plethora of outcomes, such as speech understanding in quiet, or speech understanding in the presence of noise (Niparko et al., 2003; Firszt et al., 2012). When assessing speech outcomes in the presence of noise, various configurations are used. For example, Niparko et al. (2003) chose the conditions of (i) noise-front, (ii) noise-to-normal-ear, and (iii) noise-to-deaf-ear to compare BCD and CROS devices, using the Hearing in Noise Test (HINT) (Nilsson et al., 1994) that includes noise filtered to match the long-term average spectrum of sentences. In another example, Arndt et al. (2017) compared speech outcomes in noise with CROS, a BCD device, and CI in three conditions; (i) speech and noise from the front, (ii) speech from the hearing side/noise from the deaf side, and (iii) speech from the deaf side/noise from the hearing side, using the adaptive Oldenburger Sentence Test (OlSa) (Arndt et al., 2011a,b). Härkönen et al. (2015) compared CI outcomes in SSD using a speech-in-noise test that included phonetically balanced bisyllabic Finnish words at a level of 65 dB SPL from the loudspeaker at 0° of azimuth, and unmodulated artificial noise presented from four loudspeakers. Finally, a study assessing the masked speech recognition in 16 participants with SSD and a CI suggest a revised test battery to the Van de Heyning et al. (2017) recommendations to ensure binaural hearing abilities are captured (Anderson et al., 2022). Anderson et al. suggest presentation of the target from the front speaker and the masker co-located with the target, 90° toward the implanted-ear, and 90° toward the normally-hearing-ear, to incorporate real-world situations when the listener often faces the speaker of interest. This selection of studies demonstrates the diversity of test configurations chosen by researchers in the field to demonstrate the benefits and harms of SSD interventions.

The question of what outcome domains are important and relevant to individuals with SSD when deciding whether an intervention works has yet to be addressed. One attempt to harmonize evaluation of SSD interventions was made in 2017; it was based on two discussions among professional experts in CI (Van de Heyning et al., 2017) and was intended for adoption in clinical practice. Recommendations for a minimum set of outcome measures were made including daily device use, pure tone audiometry, free-field testing of speech perception in noise, and sound localization. Recommended instruments were the Speech, Spatial, and Qualities of hearing (SSQ) questionnaire (Noble et al., 2013), the HUI (Horsman et al., 2003) and, if applicable, the Tinnitus Functional Index (TFI) (Meikle et al., 2012). This consensus work by Van de Heyning et al. (2017) focussed on

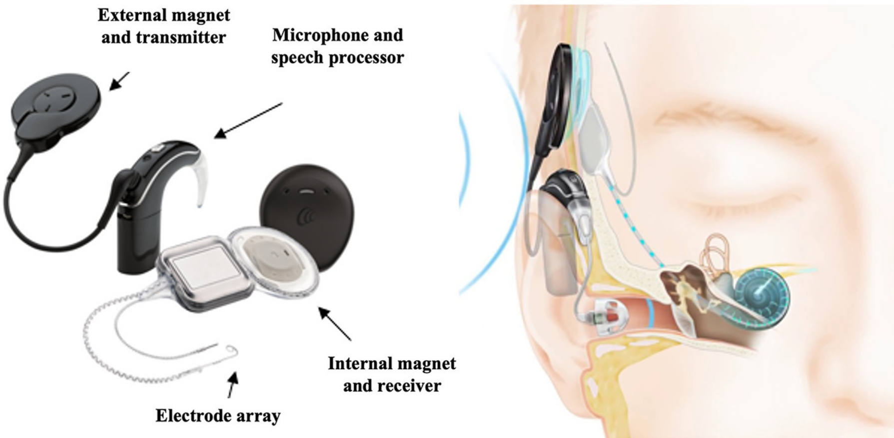

FIGURE 9
Schematic representation of a cochlear implant device. Images courtesy of Cochlear Limited, © 2023.

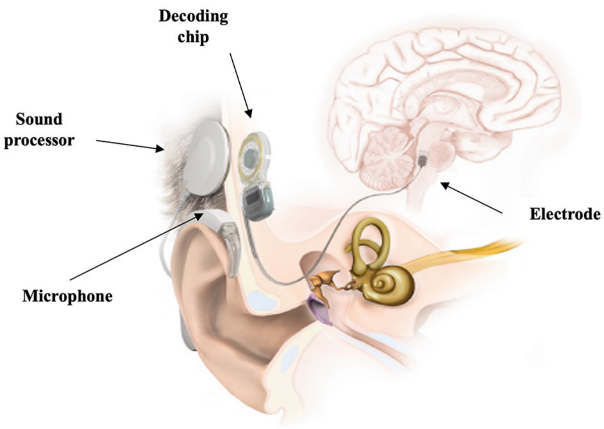

FIGURE 10
Schematic representation of an auditory brainstem implant. Retrieved from www.medel.com and used with permission from MED-EL.

CI as a treatment for SSD and so the expert panels comprised professionals from CI centers. Furthermore, the recommendations included measurement instruments that were readily available in the hearing clinic (e.g., pure tone audiometry, standard audiometric and validated sentence test, binaural effect measures), and there was lack of patient involvement in decision-making. Therefore, it is unclear whether the recommended measures assess outcome domains that are most important or meaningful to patients (e.g., impact on individual's wellbeing, social identity) (Lucas et al., 2018; Underdown and Pryce, 2022). There has been no rigorous scrutiny of outcome reporting for rerouting or restoring interventions, no systematic patient involvement, and no specific consideration of what should be used in clinical trials. Consequently, investigators adopt markedly different methods when assessing the clinical benefit of rerouting and restoring interventions for SSD.

A systematic review and meta-analysis on the use of hearing instruments for SSD in adults has demonstrated ambiguity in the absolute benefit and efficacy of the SSD treatment options (Kitterick et al., 2016). For example, the meta-analysis showed that there was a statistically significant benefit (mean benefit: 2.5 dB) to speech perception in noise for devices that reroute speech signals from the poor-hearing ear to the better-hearing ear using either air or bone conduction. However, rerouting devices also significantly degrade speech understanding (mean deficit: 3.1 dB) when noise gets rerouted from the poor-hearing ear to the better-hearing ear. In relation to sound localization, there was inconsistency in the outcomes chosen by clinical researchers, precluding the synthesis of evidence across studies. Finally, HRQoL was measured in two studies (out of 27 included in the review), and the findings were inconclusive. In summary, Kitterick et al. (2016) concluded that inconsistent measurement of outcomes and observational biases amounted to a low quality of evidence. Kitterick et al. (2016) also concluded that outcome selection was biased toward assessing functional impairments for which measures are readily available and widely used, such as tests of speech perception in noise, with limited measurement of domains that are meaningful to patients such as HRQoL (Lucas et al., 2018). Another systematic review of outcomes of CI in patients with SSD focused on assessing (i) sound localization, (ii) speech perception, (iii) tinnitus, and (iv) QoL outcomes (Cabral Junior et al., 2016). The authors discovered a large variation in choice of outcomes in the included studies, and highlighted the need for high quality studies. Encouragingly, Mertens et al. (2022) have recently developed a consensus classification system for the reporting of sound localization testing results in the field of cochlear implantation. This builds on the Van de Heyning et al. (2017) recommendations, and application of this classification system will allow multi-center studies comparisons and improved meta-analysis in this field (Mertens et al., 2022).

Difficulties that SSD imposes can also affect the individual's psychological and social wellbeing (Carlsson et al., 2011; Sano et al., 2013a; Lucas et al., 2018), and therefore outcomes that assess the impact on an individual's overall health and wellbeing are also relevant and potentially as important (Kitterick et al., 2015). With respect to HRQoL, there is inconsistency in the choice of measurement instruments in trials assessing the benefits of SSD interventions (Kitterick et al., 2016). The authors highlight the need for consist use of patient-reported outcome measures that are sensitive to the impact of devices used by those with SSD, such as the HUI (Horsman et al., 2003). Often, it is unknown what plays a role in decision making and identifying better candidates for specific SSD interventions (Kosaner and Urban, 2014). Qualitative studies demonstrate that patients express uncertainty about choice of treatment options for SSD mainly due to a lack of clarity about their benefit (Underdown and Pryce, 2022), and they seek clinical advice when they need to make a decision. However, due to the varied evidence for different treatment options, clinicians may not know which option is ideal and for whom (Hall et al., 2019).

To address the inconsistency and diversity of outcome measure use in the field of SSD research, the Core Rehabilitation Outcome Set for Single Sided Deafness (CROSSSD) initiative set out to develop a core outcome set for SSD interventions (Katiri et al., 2020, 2022). The CROSSSD initiative developed an international consensus by including opinions of both healthcare users and professionals working in the field. Including a variety of stakeholders in core outcome set development, including the general public, can help demonstrate the impact of interventions on patients' lives (Dodd et al., 2023). The recommended CROSSSD study core outcome set included three outcome domains: *spatial orientation*, *group conversations in noisy social situations*, and *impact on social situations*. Adoption of the CROSSSD core outcome domain set will promote consistent assessment and reporting of outcomes that are meaningful and important to all relevant stakeholders. This consistency will in turn enable comparison of outcomes reported across clinical trials comparing SSD interventions in adults and reduce research waste (Chalmers and Glasziou, 2009; Tunis et al., 2016).The next step entails determining how these outcomes should be measured (Prinsen et al., 2014, 2018; Mokkink et al., 2016). It is important to choose measurement instruments that are comprehensive and sensitive to treatment-related change (Prinsen et al., 2016) as well as inclusive and equitable to ensure they incorporate the diversity of all patients being assessed with the condition of interest (Calvert et al., 2022). Strides are being made to identify available instruments to measure the three outcome domains in the core outcome domain set (Katiri et al., 2022).

Conclusion

SSD in adulthood is most commonly attributed to sudden and idiopathic causes. Although the prevalence and incidence is small, SSD can lead to significant functional, psychological, wellbeing, and social consequences for the individual. A variety of rerouting and restoring interventions have been utilized to date, aiming to alleviate the functional impact of SSD. Outcome measurement in the field of SSD has progressed significantly since the definition and clinical recommendations. Adopting the recently recommended algorithms for measuring sound localization will help with accurate comparison and evidence synthesis for the various SSD treatments. Finally, adoption of the internationally agreed core outcome domain set recommended by the CROSSSD initiative will ensure future clinical trials in the field report on outcomes consistently, and that outcomes that are relevant to both patients and healthcare professionals are reported. Future studies should consider the timescale of measurements, long-term benefits (or harms), and cost utility.

Author contributions

RK was the project administrator who conducted the analysis and drafted the manuscript. RK, KF, and DH were responsible for data curation, visualization, and resource management. KF and DH provided feedback and reviewed previous versions of the manuscript in their role as the PhD supervision team for RK. JP reviewed previous versions of the manuscript as an external examiner for RK's PhD thesis. KF, DH, and JP reviewed the manuscript and provided feedback prior to submission. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by the National Institute for Health Research (NIHR) Nottingham Biomedical Research Centre (BRC), funding reference number BRC-1215-20003. KF was funded by the NIHR and Postdoctoral Fellowship PDF-2018-11-ST2-003. The funding bodies have no role in the study design and implementation, writing the report, or decision to submit the report for publication.

Acknowledgments

The authors would like to acknowledge the contributions of Professor Deborah A. Hall (Heriot-Watt University Malaysia, Putrajaya, Malaysia) and Professor Pádraig T. Kitterick (National Acoustic Laboratories, Sydney, Australia) for their input in designing and conducting a systematic review of outcome domains and instruments used in designs of clinical trials for interventions for single-sided deafness as part of the Core Rehabilitation Outcome Set for Single-Sided Deafness (CROSSSD) study group. Sections of this manuscript were taken from RK's PhD thesis submitted to the University of Nottingham, School of Medicine, in March 2023, which is under embargo until 31st of December 2024.

Conflict of interest

DH declares receiving a grant from Cochlear Europe Ltd outside of the submitted work.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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