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Applicability and clinical considerations of the Contralateral Routing of Signal System (CROS): systematic review

Aplicabilidade e considerações clínicas do Sistema Contralateral *Routing of Signal* (CROS): revisão sistemática

Aplicabilidad y consideraciones clínicas del sistema de enrutamiento de señal contralateral (CROS): revisión sistemática

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Abstract

Introduction: The system Contralateral Routing of Signal (CROS) is an option of auditory intervention in order to improve the monaural perception and minimize the difficulties of unilateral hearing loss. **Objective:** to analyze and describe the target users, the adaptation time and the control use of CROS system, the evaluations utilized to measure its benefits, as well as its effectiveness and limitations. **Method:** This study was conducted according to the PRISMA guidelines. The bibliographic research was through the scientific data online banks in the health area, PubMed and Scopus, using the keywords "Unilateral hearing loss", "Hearing aid", "CROS" and "Contralateral Routing of Signal". The results of the research were limited to experimental scientific articles, which address directly the CROS system, published in English, Portuguese or Spanish. **Results:** Eleven studies were selected to review. The age

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VOCN: study conception, methodology, data collection and analysis, manuscript drafting, final manuscript revision.
LBU: methodology, data analysis and collection, manuscript drafting, final manuscript revision.
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of CROS users ranged from nine to 84 years and male sex prevalence. There was great diversity in the evaluations being carried out. The performance's evaluation date varied between less than 30 days and more than six months after the adaptation. Such assessments were performed using non-standardized questionnaires and objective evaluations with controlled stimuli. The use of CROS provides benefits in sound localization, head shadow effect and speech intelligibility, but it is not effective in noisy situations. **Conclusion:** CROS should be the first option in unilateral hearing loss rehabilitation for being a non-invasive, easy adaption, handling dispositive and with good benefits to the client.

Keywords: Unilateral hearing loss; Hearing; Rehabilitation; Hearing Aids.

Resumo

Introdução: O Sistema Contralateral *Routing of Signal* (CROS) é uma opção de intervenção auditiva com propósito de melhorar a percepção monoaural e minimizar as dificuldades da perda auditiva unilateral. **Objetivo:** analisar e descrever o público-alvo, o tempo de adaptação, o controle de uso do Sistema CROS, as avaliações utilizadas para medir os seus benefícios, sua efetividade e limitações. **Método:** Este estudo foi conduzido de acordo com as diretrizes PRISMA. A pesquisa bibliográfica foi realizada através dos bancos de dados científicos online na área da saúde, PubMed e Scopus, foram utilizadas as palavras-chave "*Unilateral hearing loss*", "*Hearing aid*", "*CROS*" e "*Contralateral Routing of Signal*". Os resultados da pesquisa limitaram-se a artigos científicos experimentais, que abordavam diretamente o sistema CROS, publicados em inglês, português ou espanhol. **Resultados:** Onze artigos foram selecionados para a revisão do texto completo. Quanto aos usuários do CROS, a faixa etária variou entre nove a 84 anos; prevalência do sexo masculino. Observou-se grande diversidade nas avaliações, sendo realizadas com tempo de uso inferior a 30 dias e superior a seis meses, após adaptação do CROS. Tal avaliação era realizada por meio de questionários não padronizados e avaliações objetivas com estímulos controlados. O uso do CROS proporcionou benefícios na localização sonora, efeito sombra da cabeça e inteligibilidade de fala, porém não mostrou eficácia em situações ruidosas. **Conclusão:** Por ser um dispositivo, não invasivo, de fácil adaptação e manuseio que traz benefícios imediatos, o CROS deve ser a primeira opção na reabilitação da perda auditiva unilateral.

Palavras-chave: Perda auditiva unilateral; Audição; Reabilitação; Auxiliares de audição.

Resumen

Introducción: El Sistema Contralateral Routing of Signal (CROS) es una opción de intervención auditiva con el propósito de mejorar la percepción monoaural y minimizar las dificultades de la pérdida auditiva unilateral. **Objetivo:** analizar y describir el público objetivo, el tiempo de adaptación, el control del uso del Sistema CROS, las evaluaciones utilizadas para medir sus beneficios, su efectividad y limitaciones. **Metodo:** Este estudio se realizó de acuerdo con las pautas PRISMA. La búsqueda bibliográfica se realizó a través de bases de datos científicas online del área de salud, PubMed y Scopus, utilizando las palabras clave "Unilateral hearing loss", "Hearing aid", "CROS" y "Contralateral Routing of Signal". Los resultados de la investigación se limitaron a artículos científicos experimentales, que abordaron directamente el sistema CROS, publicados en inglés, portugués o español. **Resultados:** Se seleccionaron once artículos para revisión de texto completo. En cuanto a los usuarios de CROS, la edad osciló entre los nueve y los 84 años; prevalencia masculina. Hub gran diversidad en las evaluaciones, realizadas con tiempos de uso de menos de 30 días y más de seis meses tras la adaptación del CROS. Dicha evaluación se realizó mediante cuestionarios no estandarizados y evaluaciones objetivas con estímulos controlados. El uso de CROS proporcionó beneficios en la localización del sonido, el efecto de sombra de la cabeza y la inteligibilidad del habla, pero no fue efectivo en situaciones ruidosas. **Conclusión:** Al tratarse de un dispositivo no invasivo, de fácil adaptación y manejo que aporta beneficios inmediatos, CROS debería ser la primera opción en la rehabilitación de la hipoacusia unilateral.

Palabras clave: Pérdida Auditiva Unilateral; Audición; Rehabilitación; Audífonos.

Introduction

The impact of hearing loss on individuals' lives is an important subject that must be addressed as it extends far beyond the ability to understand auditory information and also affects the way people engage with their environment and culture.[1] In cases of unilateral hearing loss, these difficulties occur in specific situations, interfering with directional hearing, speech comprehension in the presence of multiple speakers, and the exclusion of noise, which in turn can affect academic performance and the emotional and social well-being of children and adults.[2,3-5]

Though unilateral hearing loss may appear to be a mild condition, it can be caused by a variety of factors, including otological disease, degeneration, trauma, and congenital anomalies.[2] However, studies show that approximately 56% of cases of postlingual unilateral hearing loss are idiopathic.[3] Unilateral hearing loss has been investigated by several studies due to its high prevalence in the general population and its association with more serious adverse consequences than previously thought.[6-10]

Auditory rehabilitation through sound amplification is considered a challenge for speech pathologists who treat unilateral hearing loss since its benefits are limited, especially in cases of more significant losses, where the level of amplification required may generate discomfort and interfere with the performance of the unaffected ear.[11] It was the need to improve monaural perception and minimize these difficulties that prompted the development of the Contralateral Routing of Signal (CROS) system. The CROS is a non-surgical intervention for unilateral hearing loss first introduced in 1965 by Harford and Barry.[11,26]

The CROS system works by routing the signals that arrive at the hearing-impaired ear to the ear with normal hearing. Currently, signal routing is performed through wireless signals that transmit the sound that arrives at a microphone placed in the impaired ear to a receptor positioned on the ear with normal hearing.[4,12,13] As it does not require surgery and is relatively inexpensive compared to other hearing rehabilitation methods, such as BAHA, the CROS is more easily accepted by individuals with hearing loss.[13,14] This system allows for the perception of sounds on both sides of the head, improving spatial equilibrium as well as speech comprehension in the presence of noise.[13]

In recent years, CROS hearing aids have undergone significant advances which have resolved many of their early acoustic limitations.[15] Some researchers have shown that in older models, the auricular mold placed in the ear allowed for little ventilation and caused a feeling of obstruction of the outer ear canal. Current CROS hearing aids no longer cause sensations of occlusion. This is because they are open-fit hearing aids (with only a RIC or slim tube receiver to be used in the ear canal), which have improved aesthetics and tolerability of use as they allow for minimal obstruction of the natural acoustics of the ear canal.[13-16]

In Brazil, the CROS system was implemented in the *Sistema Único de Saúde* (SUS) in 2012,[17] becoming available at no cost to patients who met the criteria for its use. However, further research is necessary to determine the applicability and limitations of the CROS. In light of these observations, this study aimed to analyze and describe the target population, the length of the adaptation period and control of the use of the CROS system, and the assessment methods used to determine its benefits, effectiveness, and limitations.

Method

This was a cross-sectional qualitative literature review that aimed to combine, analyze and summarize the results of experimental studies on the topic of interest. The search procedures and eligibility criteria were selected according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[18]

This study was guided by the following research questions: How is the target population distributed with regard to sex and age? How long are the acclimatization and effective/daily use periods required for adaptation to the CROS, and how long should researchers wait to conduct performance assessments? What assessment methods are used to determine the benefits and performance of the CROS? How effective is the CROS system and what are its limitations?

All articles were independently selected by two reviewers and screened based on inclusion criteria. Disagreements were settled by a third reviewer who analyzed the articles and made a final decision on inclusion.

The method used in this study will be described in the following section and divided into literature search, screening, eligibility, and article inclusion.

a) Literature search

This first stage aimed to retrieve studies on the use of the CROS system. In order to ensure reliability, two researchers independently searched the PubMed and Scopus databases in November 2019 and again in September 2020.

The databases were searched using the following keywords: *unilateral hearing loss* and *hearing aid.* The terms *CROS* and *Contralateral Routing of Signal* were also used to narrow the scope of the search. The keywords were combined using the Boolean operator *OR*. Search terms were selected based on the frequency with which they were cited in articles pertaining to the topic of study. The search was limited to title and abstract in both databases.

The association between the constructs was investigated in each database by combining searches with the Boolean operator AND. The search was limited to articles in English, Spanish and Portuguese. The results were not filtered by participant age, date of publication, or full-text availability.

b) Screening

The second stage aimed to carry out a preliminary screening of studies retrieved in the original search to identify eligible articles for full-text analysis. Data extracted from the articles retrieved were entered into a spreadsheet. Duplicate articles were immediately removed. Search results were then refined based on information from the titles, abstracts, and keywords of each article.

Reasons for exclusion included the following: (1) publication language other than English, Spanish, or Portuguese; (2) no direct connection to the topic of study; (3) literature reviews or letters to the reader.

The articles were independently selected by two researchers. Articles whose titles and abstracts were judged to be relevant according to previously described criteria were then retrieved in full. Agreement rates were evaluated between the two researchers Disagreements were settled by a third reviewer who analyzed the abstracts and determined whether they should be included or excluded based on the aforementioned criteria.

C) Eligibility

The third stage involved the selection of full-text articles for inclusion in the review.

The following inclusion criteria were applied: (1) experimental scientific studies; (2) articles that had the CROS system as the main subject of study. Reasons for exclusion included the following: (1) no full-text availability; (2) no direct discussion of the CROS system; (3) studies comparing the CROS system to other technologies.

D) Inclusion

After study selection, relevant data were extracted from each article, coded, and entered into a table containing the following categories: (1) target population; (2) length of adaptation period and control of use; (3) assessments; (4) effectiveness and limitations.

Results

The initial search conducted in the identification stage retrieved a total of 139 abstracts (PubMed = 26; Scopus = 113). The independent search procedures used by each of the two researchers resulted in a similarity of 100% between findings. During screening, 24 duplicate articles and 41 that did not meet inclusion criteria were excluded from this review. A total of 74 articles were thus selected for full-text analysis. The researchers agreed in their assessment of 56 articles (75%) but disagreed with regards to the remaining 18 (25%). The third researcher opted for the inclusion of eight of these studies and the exclusion of the other 10, resulting in the selection of 64 for full-text analysis.

The application of exclusion criteria led to the removal of nine articles with no full text available, six that were not experimental studies, 37 that focused on other technologies, and one whose results were inconclusive. The final sample for this review, therefore, contained 11 articles. The article selection process is illustrated in the PRISMA flow diagram in Figure 1.

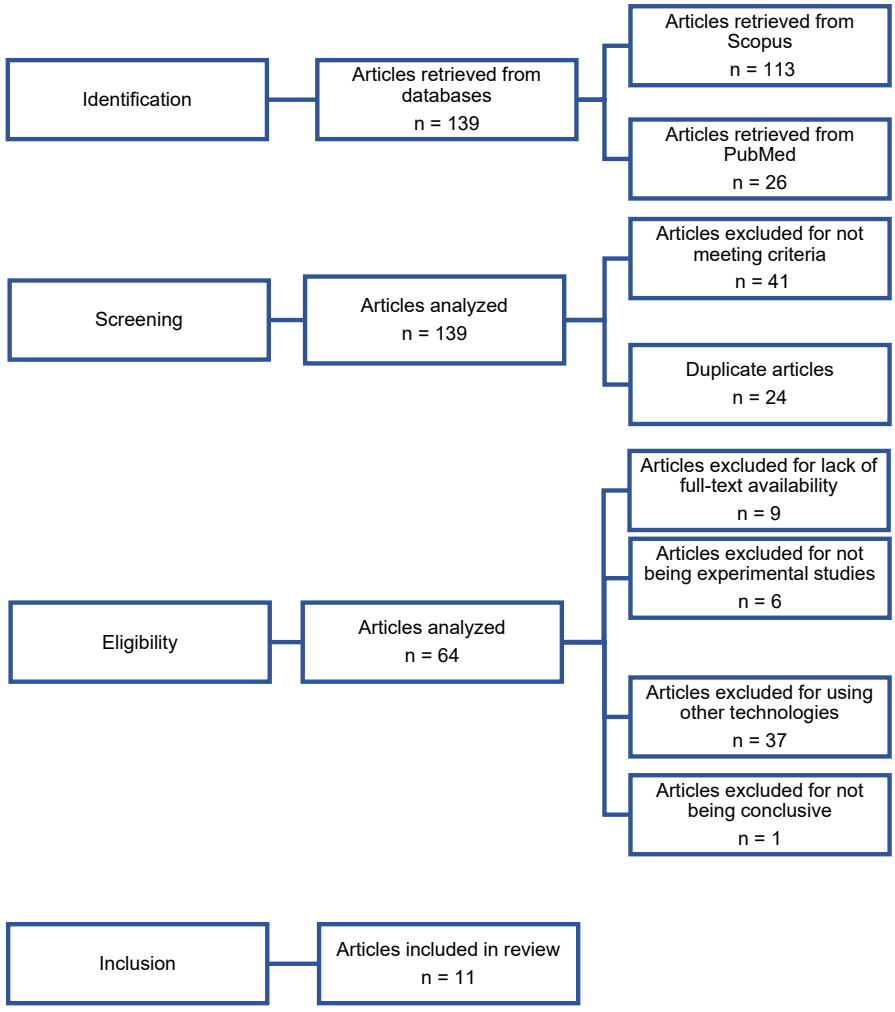

Figure 1. Flowchart of study design.

The differences between the results of the studies reviewed will be analyzed below, in the following categories: (1) target population; (2) length of adaptation period and control of use; (3) assessments; (4) effectiveness and limitations.

1) Target population

The age of individuals in the articles reviewed ranged from nine to 84 years. One article did not provide this information,[24] another included a single nine-year-old child,[21] and all remaining studies had samples that ranged in age from 15 to 84 years.

Most participants across all samples were male. One study included a single female participant[4] and two others did not provide this information.[20,24]

2) Length of adaptation period and control of use

The length of the adaptation period differed between studies. However, when making this comparison, it is important to consider the different populations evaluated by each article. Three studies conducted performance assessments less than 30 days after fitting,[13,21,26] and three did so 90 days after it.[4,22,25] Of the three studies that evaluated patients over three months after this fitting,[14,19,23] two involved participants that had been using CROS devices for periods ranging from six months to seven years,[14,23] and an additional two studies did not provide this information.[20,24]

Most studies did not discuss the monitoring of CROS use at home. The studies that did so reported that the duration of use was estimated through patient reports rather than using any technological methods, such as data logging, to collect this information. Three articles reported that patients used the device for eight to 12 hours a day.[4,14,23] In one study, participants used the device for 50% or less of the time stipulated by the researchers (4 hours).[19]

3) Performance Assessment Instruments

The articles used different methods to assess the performance of the CROS system. Most used unstandardized questionnaires created by the researchers themselves. Chart 1 describes the assessment methods used by the articles reviewed as well as their aim, format, and procedures.

Chart 1. Assessments used to determine the effectiveness of the CROS system.

Assessment	Objective	Format	Method of administration	Study
Korean version of the Hearing Handicap Inventory for the Elderly (K-HHIE)[27]	To provide a quantitative assessment of discomfort in patients with hearing loss and estimate the level of improvement with hearing aid use.	25 questions with social/situational and emotional subscales.	Patient-administered.	Ryu et al. (2015)[13]
Korean version of the International Outcome Inventory for Hearing Aids (K-IOI-HA)[28]	To determine the subjective outcome of hearing aid use.	7 questions about compliance with daily use, benefits, residual activity, satisfaction, participation restrictions, impact on others and quality of life.	Patient-administered.	
Korean version of the Speech, Spatial, and Qualities of Hearing Scale (K-SSQ)[29]	To assess the subjective effects of hearing loss on daily life.	The questionnaire focuses on binaural hearing and addresses three domains: speech perception, spatial hearing and other qualities of hearing.	Patient-administered.	
Korean Version of the Hearing in Noise Test (HINT)[30]	To assess discomfort in noisy environments.	24 lists of 10 sentences containing 4814 phonemes.	Sound booth with an audiometric system to emit sentences under silent (background noise below 25 dB) and noisy conditions (65 dB).	
Sound Localization Test	To assess sound localization skills.	A two-second broadband click was emitted at 75 dB NPS from each loudspeaker in random order for a total of 32 times.	Six loudspeakers were positioned at ear level, 1m from the center of the subject's head, at 45° intervals save for the 0° and 180° positions throughout the test. The stimuli were emitted at 0°, 90° and 27° azimuth angles.	
Questionnaire developed by the researchers.	To investigate patients' use of the CROS.	Questions regarding hearing loss, sound perception in several situations, directional hearing, sound quality and device maintenance and operation.	Questions were e-mailed to patients 2 to 36 months after fitting.	Busk
Visual Analog Scale (VAS)	To quantify the degree of pain, tinnitus and difficulty experienced by the individual.	Scale with positive and negative expressions and a scale ranging from 0 to 10 where 0 indicates no discomfort/difficulty and 10 indicates extreme discomfort/difficulty.	Participants answered by drawing a mark on the 10cm line where scores near 1 were indicative of a negative experience while scores near 10 indicate a positive experience.	Linnebjerg and Wetke (2014)[19]

Assessment	Objective	Format	Method of administration	Study
Brazilian version of the Hearing Handicap Inventory for Adults (HHIA)[31]	To assess the benefits of hearing aid use or intervention programs for individuals with hearing loss.	25 items, 13 regarding emotional issues and 12 assessing social and situational topics.	Questions were answered by patients before and 3 months after fitting.	Mondelli et al. (2013)[4]
Sound Localization Questionnaire[32]	To analyze the benefits of hearing aids on localization during everyday activities in individuals with hearing loss fitted with hearing aids.	14 questions regarding everyday activities to be answered on a 4-point scale.	Patient-administered.	
Brazilian version of the Hearing in Noise Test (HINT)[33]	To assess discomfort in noisy environments.	24 lists of 10 sentences containing 27 phonemes occurring a total of 4064 times.	Sound booth with an audiometric system to emit speech and noise from the front: 0°; speech from the front and noise from the left 90°; speech from the front and noise from the right: 90°.	
Probe microphone measurement	To examine the individual sound amplification device.	Two reference microphones.	A probe microphone is inserted into the preserved ear - the one that receives the CROS transmission.	
Threshold Tone and Speech Audiometry	To determine the minimum intensity at which the individual can respond to sound stimuli.	Pure tone thresholds, speech thresholds and speech discrimination.	Sound booth with an audiometer; patient positioned in an acoustic field between two loudspeakers placed at a 45º azimuth angle, 1 meter from the preserved ear.	Gelfand (1979)[14] Lundborg, Swärd and Lindström (1976)[20] Tooning (1972)[22] Aufricht (1972)[23] Lotterman and Kasten, (1971)[24] Harford and Dodds (1966)[25] Harford and Barry (1965)[26]
Questionnaire developed by the researchers.	To determine the percentage of time during which patients actually wore their hearing aids.	41 situations in which patients should indicate how many hours a day they wore their device and whether it helped; including the ability to localize sound with and without the hearing aid; and whether speech was clearer and more pleasant to hear with the aid as opposed to without it. Specific complaints about the device and their use.	Patient-administered.	Gelfand (1979)[14]
Questionnaire developed by the researchers.	To elucidate the patient's hearing ability in six distinct situations: At home with their family; at home with guests; in meetings; at work; during work breaks; with the telephone held to the unaffected ear.	Answer the question: "Can you hear speech from your affected ear in these 6 situations?"	Patient-administered questionnaire.	Lundborg, Swärd and Lindström (1976)[20]
Sound field audiometry	To demonstrate the objective benefits of CROS hearing aids.	Compare the results of sound field audiometry under two conditions: with the patient facing a loudspeaker vs. with the affected ear facing the loudspeaker.	First, the patient sat facing the loudspeaker at a distance of approximately 1 meter. Then, sitting at the same distance, they turned their ear with hearing loss toward the loudspeaker.	Navarro and Vogelson (1974)[21]

Assessment	Objective	Format	Method of administration	Study
Speech Reception Threshold[34]	To assess intelligibility based on a coordinate system.	Coordinate system created by the author to provide a more precise assessment of intelligibility based on the azimuth of the sound source.	Loudspeaker placed at four different locations on a horizontal plane: 0º azimuth at the front, 90º to the right, 180º behind, and 270º on the left side of the patient.	Tonning (1972)[22]
Questionnaire developed by the researchers.	To investigate CROS use.	10 questions on preferences, length of use, better and worse situations, whether patients hear better with or without the CROS, complaints, etc.	Patient-administered.	Aufricht (1972)[23]
"CNC word lists" [35]	To assess speech discrimination in noise.	*The CNC words were recorded on a magnetic tape with cafeteria noise as a competing signal on the second track. Speech Direct-Noise Indirect, Speech Direct-Noise Overhead, Speech Indirect-Noise Direct, Speech Indirect-Noise Overhead, Speech from the Front-Noise Overhead.*	Stimuli emitted using a dual-channel tape recorder through a speech audiometer with attendant booster amplifiers on to two of the three loudspeakers. Subject was seated in the center of the room equidistant from two loudspeakers. A third loudspeaker was mounted on the ceiling directly above the subject.	Lotterman and Kasten, (1971)[24]
Dirks and Carhart (1962)[36] Questionnaire	To estimate the efficiency of the CROS system in several listening situations.	21 listening situations such as: whispering voices, restaurant with/ without noise, group conversations, television, parties, etc.	Patient-administered questionnaire.	Harford and Barry (1965)[26]
Speech discrimination tests	To evaluate speech discrimination in hearing aid users.	Hearing and speech discrimination were evaluated in 21 situations involving faint voices, whispers, situations where the subject was alone, noisy situations, among other factors.	All sound field speech discrimination tests were conducted with the emission of stimuli at 70 dB SPL from loudspeakers placed at approximately 2 meters from the subject at a 45° azimuth from the affected ear.	

4) Effectiveness and limitations

Most of the studies reviewed found that the CROS system was effective and had several benefits on the everyday lives of individuals with monaural hearing, although one study found the CROS system to be ineffective.[14] It must be noted, however, that the study in question was performed over 20 years ago. The studies also revealed some limitations of the CROS system, as described in Chart 2.

Chart 2. Effectiveness and limitations of the CROS.

Article	Effectiveness and limitations
Ryu et al. (2015)[13]	Satisfaction and improvements in lateral and spatial localization, social issues and emotional aspects. The younger participant group showed better recognition. Continuous improvement only reported after two to four weeks of CROS use. No benefits observed when noise was emitted toward the impaired ear. No significant differences between genders.
Busk Linnebjerg and Wetke (2014)[19]	Overall, the devices were efficient and users were satisfied, finding it easy to operate. No differences were observed between age groups and genders. The CROS was used most frequently in social situations, though participants found the sound quality to be best in quiet settings. Most users still felt they had better hearing in the unaffected ear.
Mondelli et al. (2013)[4]	Improvement in social and emotional issues, handicap, localization ability, head shadow effect and speech discrimination.
Gelfand (1979)[14]	Significant improvement in speech discrimination with the hearing aid. Patients did not notice a difference in their own voice. No significant differences were observed depending on patient occupation. Improved localization. There were complaints about the acoustic signal, especially in noisy environments, yet the hearing aid was most used in communicative situations.
Lundborg, Swärd and Lindström (1976)[20]	Significant improvement when the stimulus was presented to the unaffected ear. However, patients still experienced difficulties when stimuli were presented to the affected ear. In response to the situations listed in the questionnaire, most participants reported some difficulties at home with their family, and major difficulties when at home with guests, in meetings, and in work breaks. Responses to questions about work ranged from 'some' to 'major' difficulties.
Navarro and Vogelson, (1974)[21]	Behavioral improvement according to the mother. Significant improvement in speech recognition and discrimination. Parents and teachers also reported improvements in reading, spelling and social skills.
Tonning (1972)[22]	Demonstrated that a standard set-up regarding stimulus distance and position is ideal since both factors are known to improve or worsen speech comprehension, especially in learning age children. Concluded that stimuli should always be emitted from the side with better hearing.
Aufricht, 1972[23]	85% of participants used the device and reported benefits in social, leisure, and work sistuations. The other 15% used the device but did not notice any changes, reporting that the sound quality was not good.
Lotterman and Kasten (1971)[24]	Improved intelligibility in favorable use conditions, but decreased intelligibility in complex situations such as noisy environments.
Harford and Dodds (1966)[25]	Effective in 66% of cases, improving the comprehension of speech as well as social/emotional situations. None of the patients who purchased CROS devices had any complaints. The authors concluded that the device made it more convenient for users to engage in conversation. Findings did not vary greatly across age groups, although researchers believed that adults may be able to analyze their difficulties and benefits more clearly.
Harford and Barry (1965)[26]	Improvement in the head shadow effect. However, this improvement was significantly greater when the stimulus was presented on the side with better hearing. Major benefits in the following situations: talking to a group in a quiet room; watching TV in silence; watching TV with other people; dinner conversations on the side of the affected ear; speaking toward the side of the affected ear during meetings. In most cases, there was also adequate comprehension of the following: speech in noise; whispered speech; conversation in a restaurant; speech on the side of the affected ear while driving.

Discussion

The full-text analysis of the articles reviewed provided answers to some of the questions that guided this study. However, the findings were quite diverse and publication dates varied significantly between articles.

What is the target population?

The rehabilitation of individuals with unilateral hearing loss constitutes a major challenge for speech pathologists.[14] It is extremely difficult to predict the successful outcome of CROS use since not all individuals with unilateral hearing loss are eligible for this intervention. Two important factors must be considered when selecting candidates for CROS use: everyday activities and the hearing level of the unaffected ear. Individuals with greater hearing demands are more likely to be successful users of CROS hearing aids.[26] Therefore, individuals fitted with the device must be evaluated in acoustically controlled environments, undergo a testing period, and attend specific follow-up appointments.[14, 26]

The CROS technology can be used by children as long as they have the maturity and ability to control the physical location and position of their heads in the acoustic environment. In other words, the child must be able to reposition themselves to enhance auditory organization in difficult listening conditions.[12] In school-age children, significant improvements in speech recognition and discrimination, as well as reading, spelling and social skills, were reported with CROS use.[21]

The study by Mondelli et al.[4] showed that the CROS system met the needs of a 19-year-old patient who had difficulty understanding their teachers in classroom settings, communicating in noisy environments, and performing sound localization. Ryu and colleagues[13] reported that the short-term benefits of CROS use were greater in younger individuals as a result of brain plasticity. Harford and Barry[26] noted that patient age at the onset of hearing loss does not interfere with the successful outcome of CROS use.

Findings did not vary greatly across age groups, although researchers believed that adults may be able to analyze their difficulties and benefits more clearly.[25] On a similar note, no significant differences were seen between positive and negative outcomes of CROS use across genders.[13]

How long are the acclimatization and effective/daily use periods required for adaptation to the CROS, and how long should researchers wait to conduct performance assessments?

The length of time from fitting to performance assessment varied between studies. In one investigation[13] improvements in performance were observed in the first two weeks after fitting. However, slight improvements were also observed between two and four weeks of CROS use. The authors noted that four weeks may be too short a period for adaptation, which may explain the small magnitude of change observed from weeks 2 to 4.

The study by Navarro and Vogelson[21] reported clear behavioral improvements in CROS users after 3 weeks of adaptation. Another investigation found that after three months of use, patients who purchased CROS hearing aids had no complaints about the device.[4,25] Regarding the effective/daily use of the hearing aid, patients who used CROS devices for 10 to 12 hours a day reported significant benefits.[4]

Studies mentioned that younger individuals adapted better and used the CROS for longer.[13,19] Younger patients used CROS devices for over 4 hours a day in situations that demanded significant effort for comprehension, such as classroom settings. Older individuals used the device for less than 4 hours a day.[19] The study also reported an association between the number of hours of daily CROS use and the benefits perceived by users. However, in the Gelfand[14] study, no significant differences were observed in the performance assessments or communicative use of the CROS device between participants who used it for 50% of the specified time (4 hours) and those who used it for shorter periods.

Though the studies present conflicting findings on the association between number of hours and benefits of CROS use, this variable must be observed in clinical practice and considered in longitudinal data collection during the adaptation period. This can be done through simple questionnaires regarding hours of daily use or more technical methods such as data logging in the device itself.[45]

What assessment methods are used to determine the benefits and performance of the CROS?

The most frequently used methods to assess the benefits of CROS use were Pure Tone and Free-Field Speech Audiometry, conducted before and after patients were fitted with the device, and subjective questionnaires developed by the researchers themselves.[14,20,22-26] Sound Localization Tests were also used by researchers.[4,13,22]

The control stimulus used in the assessments was a pure tone, in the presence or absence of speech or white noise as a competing stimulus, to determine if there were any improvements in individuals with and without the CROS device.[14,20,22-23]

Over the years, researchers have used a variety of assessment methods and scales to determine the benefits of CROS use. More recent studies have used the Brazilian and Korean versions of the Hearing in Noise Test.[4,13] In a Brazilian study, an adapted version of the Hearing Handicap Inventory for Adults[31] was used to determine the benefits of intervention programs for patients with hearing loss.

The study by Ryu et al.[13] made the most extensive use of questionnaires for the subjective assessment of hearing loss, intervention methods, and discomfort in patients with hearing loss. It used

the Korean versions of the Hearing Handicap Inventory for the Elderly (K-HHIE), the International Outcome Inventory for Hearing Aids (K-IOI-HA), and the Speech, Spatial, and Qualities of Hearing Scale (K-SSQ).

There is no standard method in the literature to evaluate the performance, use, and benefit of hearing rehabilitation interventions and no specific instruments for the assessment of CROS. However, Van de Heyning and colleagues[44] have described what variables should be assessed, how this should be done, and the frequency with which these assessments should be performed in cases of unilateral hearing loss.

According to this article, the following procedures should be performed during the adaptation process: (1) speech in noise testing; (2) sound localization tests; (3) questionnaires to investigate quality of life and frequency of device use; and (4) questionnaires that assess the impact of tinnitus before and after treatment, if applicable.[44] These procedures should be conducted at the time of hearing aid fitting, after the 3-week trial period, and at 1, 3, 6, and 12 months of follow-up.

What are the applications and limitations of the CROS system?

The articles reviewed demonstrate that in most cases, the CROS has more benefits than limitations. The main advantage of its application is that the re-routing of acoustic signals from the impaired to the unaffected ear allows individuals to regain access to sounds emitted on the affected side. This allows the listener to be continuously involved in communication regardless of the location of the speaker.[15]

Additionally, a significant benefit of the CROS is its ability to reduce the negative effects of the head shadow, improving speech perception in noise when said speech is presented to the ear with hearing loss.[4,21,25,26,37-39] The aforementioned factors were observed in the studies reviewed.

The design and ease of use of CROS devices must also be considered. The stigma associated with the use of hearing aids is still a major concern that must be addressed when selecting such a device. Reductions in the visibility of hearing aids increase the likelihood of device use by 29 to 38%.[40] As a result, aesthetic improvements of the CROS in recent years have had a positive impact on its acceptability.

Additionally, as they only re-route an acoustic signal, CROS devices do not require complex programming or adaptation strategies. The adaptation process is therefore quick and involves minimal adjustments, which leads many users to report immediate subjective benefits to sound localization and intelligibility in both silent and noisy environments.[13,15]

The extent to which the CROS device meets an individual's communication needs is better reflected by their pattern of use than their opinion regarding the intervention. According to Gelfand,[14] if a patient continues to use the CROS device, they must be doing so because they experience substantial communicative improvement, regardless of their subjective interpretation of this improvement.[14]

However, some studies noted that the use of the CROS was hindered by acoustic limitations that resulted in user complaints about low sound quality and discomfort.[41,42] Though this device allows users to listen to sounds produced on both sides of the head, all auditory input is still processed through a monaural system; in other words, binaural hearing is not restored and individuals may still have difficulty in complex auditory tasks such as binaural summation and interaural time estimation.[15]

The CROS is indicated for situations involving competitive listening since the main complaints of patients with unilateral hearing loss pertain to speech comprehension in noisy situations, which require significant listening effort to compensate for impairments in directional listening.[4,14,19,20,23-25] If the noise is emitted near the affected ear, it reaches the CROS receiver and is transferred to the side with preserved hearing, promoting a demonstration of interest from the listener and improving speech comprehension.[38,43]

In 1965, researchers[26] reported that the CROS would not improve sound localization in noisy situations due to the inherent difficulty of distinguishing between speech sounds and noise in unilateral listening. Therefore, individuals with unilateral hearing loss who use CROS hearing aids generally do so in specific situations rather than continuously.[14]

Social and emotional benefits associated with the CROS system were also reported by the studies reviewed.[4,13,21,23] Additionally, the fact that patients demonstrated improved auditory performance whether or not the sound stimuli were presented

on the same side as the hearing aid, led to positive evaluations from patients, who also experienced improvements when exposed to stimuli near the preserved ear.[13,20,22,26]

Conclusion

Despite the wide variability in findings, we were able to conclude that the CROS system is suitable for all age groups; that most of its users are men; and that the device improves sound localization, enhances the head shadow effect, and improves speech intelligibility. However, the device did not seem to be effective under noisy conditions.

In conclusion, the CROS is a non-invasive device that is easily adaptable and manageable, resulting in immediate benefits to users. There is, however, a need for specific protocols to assess the performance of individuals fitted with CROS devices as well as more studies in the Brazilian population to analyze the applicability of this method in public health settings.

References

1. Silman S, Iório MCM, Mizhahi MM, Parra VM. Próteses auditivas: um estudo sobre seu benefício na qualidade de vida de indivíduos portadores de perda auditiva neurossensorial. Distúrb. comun. 2004; 16(2): 153-65.

2. Zhang Y et al. Detection of Unilateral Hearing Loss by Stationary Wavelet Entropy. CNS Neurol Disord Drug Targets. 2017; 16(2): 122-8. DOI: 10.2174/1871527315666161026115046.

3. Usami S et al. Etiology of single-sided deafness and asymmetrical hearing loss. Acta Oto-Laryngol. 2017; 137(565): S2- 7. DOI: 10.1080/00016489.2017.1300321.

4. Mondelli MFCG, Hoshii LA, Garcia TM, de Souza Jacob RT. Unilateral hearing loss: CROS fitting. Braz. J. Otorhinolaryngol., 2013; 79(4), 523. DOI: 10.5935/1808-8694.20130093.

5. Almeida K, Santos TMM. Seleção e adaptação de próteses auditivas em crianças. In: Almeida K, Iorio MCM. Próteses auditivas: fundamentos teóricos e aplicações clínicas. 2ª ed. São Paulo: Lovise; 2003. p.357-80.

6. Costa LD, Santos SN, Costa MJ. Perda auditiva unilateral e o uso de prótese auditiva: reconhecimento de fala, benefício, autopercepção do desempenho funcional e satisfação. Rev. CEFAC. 2019; 21(1), e13918. DOI: 10.1590/1982-0216/201921113918.

7. Firszt JB, Reeder RM, Holden LK, Dwyer NY, Cadieux JH. Results in individuals with asymmetric hearing loss using a cochlear implant and a hearing aid. In: Semantic Scholar; 2015 [base de dados na internet]; [cited 2020 Set 15]. Available from: https://www.semanticscholar.org/paper/Results-in-Individuals-with-Asymmetric-Hearing-Loss-Firszt-h./f97f0e89f3eda1bdbf3c5e47 a0 9f778905e63453.

8. Lee DH, Noh H. Prediction of the use of conventional hearing aids in Korean adults with unilateral hearing impairment. Int. J. Audiol. 2015; 54(9): 6139. DOI: 10.3109/14992027.2015.1023902.

9. Krishnan LA, Hyfte SV. Management of unilateral hearing loss. Int. J. Pediatric. Otorhinolaryngol. 2016; 88: 63-73. DOI: 10.1016/j.ijporl.2016.06.048.

10. Mondelli MFCG, Santos MM, José MR. Speech perception in noise in unilateral hearing loss. Braz. J. Otorhinolaryngol. 2016; 82(4): 427-32. DOI: 10.1016/j.bjorl.2015.08.019.

11. Snapp HA, Hoffer ME, Liu X, Rajguru SM. Effectiveness in Rehabilitation of Current Wireless CROS Technology in Experienced Bone-Anchored Implant Users. Otol Neurotol. 2017; 38(10): 1397-1404. DOI: 10.1097/MAO.0000000000001614.

12. Tharpe A, Sladen D, Murphy JD, Boney S. Minimal Hearing Loss in Children: Minimal But Not Inconsequential. Semin Hear. 2009; 30: 80-93. DOI: 10.1055/S-0029-1215437.

13. Ryu N et al. Clinical effectiveness of wireless CROS (contralateral routing of offside signals) hearing aids. Eur Arch Otorhinolaryngol. 2015; 272(9): 2213-9. DOI: 10.1007/s00405-014-3133-0.

14. Gelfand SA. Usage of CROS hearing aids by unilaterally deaf patients. Arch Otolaryngol. 1979; 105(6): 328-332. DOI: 10.1001/archotol.1979.00790180026005.

15. Snapp H. Nonsurgical Management of Single-Sided Deafness: Contralateral Routing of Signal. J Neurol Surg B Skull Base. 2019; 80(2): 132-138. DOI: 10.1055/s-0039-1677687.

16. Kiessling J, Brenner B, Jespersen CT, Groth J, Jensen OD. Occlusion effect of earmolds with different venting systems. J Am Acad Audiol. 2005; 16(04): 237–249. DOI: 10.3766/jaaa.16.4.5.

17. BRASIL, 2012. Instrutivos de reabilitação auditiva, física, intelectual e visual. [cited 2020 Set 15]. Available from: https://www.gov.br/saude/pt-br.

18. Moher D, Liberati A, Tetzlaff J, Altman D, Group P. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. J. Clin. Epidemiol. 2009; 62: 1006-1012. DOI: 10.1371/journal.pmed.1000097.

19. Busk Linnebjerg L, Wetke R. The benefits of CROS aids for individuals with unilateral sensorineural hearing loss. Hear. Balance Commun. 2014; 12:1, 36-40. DOI: 10.3109/21695717.2013.794593.

20. Lundborg T, Swärd I, Lindström B. Experience with Classic Cros Hearing Aids in Unilateral Deafness. Scand Audiol. 1976; 5: 1,17-23. DOI: 10.3109/01050397609043091.

21. Navarro MR, Vogelson DO. An objective assessment of a CROS hearing aid. Arch Otolaryngol. 1974; 100(1): 58-59. DOI: 10.1001/archotol.1974.00780040062012.

22. Tonning FM. Directional Audiometry: V. The Influence of Azimuth on the Perception of Speech in Patients with Monaural Hearing Loss treated with Hearing Aids (CROS), Acta Oto-Laryngol. 1972; 74: 1-6,37-44. DOI: 10.3109/00016487209128420.

23. Aufricht H. A follow-up study of the CROS hearing aid. J Speech Hear Disord. 1972; 37(1): 113-117. DOI: 10.1044/jshd.3701.113.

24. Lotterman SH, Kasten RN. Examination of the CROS type hearing aid. J Speech Hear Res. 1971; 14(2): 416-420. DOI: 10.1044/jshr.1402.416.

25. Harford E, Dodds E. The clinical application of CROS. A hearing aid for unilateral deafness. Arch Otolaryngol. 1966; 83(5): 455-464. DOI: 10.1001/archotol.1966.00760020457010.

26. Harford E, Barry J. A rehabilitative approach to the problem of unilateral hearing impairment: the contralateral routing of signals CROS. J Speech Hear Disord. 1965; 30: 121-138. DOI: 10.1044/jshd.3002.121.

27. Park SN et al. Standardization for a Korean version of hearing handicap inventory for the elderly. Korean J Otorhinolaryngol-Head Neck Surg. 2011; 54: 828–834. DOI: 10.3342/KJORL-HNS.2011.54.12.828.

28. Chu H et al. Standardization for a Korean adaptation of the international outcome inventory for hearing aids: study of validity and reliability. Korean J Otolaryngol-Head Neck Surg. 2012; 55:20–25. DOI: 10.3342/KJORL-HNS.2012.55.1.20.

29. Moon IJ et al. Sound localization performance improves after canaloplasty in unilateral congenital aural atresia patients. Otol Neurotol. 2014; 35: 639–644. DOI: 10.1097/MAO.0000000000000271.

30. Moon SK et al. The Korean hearing in noise test. Int J Audiol. 2008; 47: 375–376. DOI: 10.1080/14992020701882457.

31. Aiello CP, Lima II, Ferrari DV. Validity and reliability of the hearing handicap inventory for adults. Braz. J. Otorhinolaryngol. (Impr.). 2011; 77, 4, 432-438. DOI: 10.1590/S1808-86942011000400005.

32. Mondelli MFCG, Jacob RTS, Ribeiro JP, Felici MGFM, Sanches RCP. Unilateral Hearing Loss: The Benefit of Auditory Localization after Adaptation of Hearing Aids Individual. Int Arch Otorhinolaryngol. 2010; 14(3): 309-15.

33. Bevilacqua MC, Banhara MR, Da Costa EA, Vignoly AB, Alvarenga KF. The Brazilian Portuguese hearing in noise test. Int J Audiol. 2008; 47(6): 364-5. DOI: 10.1080/14992020701870205.

34. Tonning FM. Directional audiometry. II The influence of azimuth on the perception of speech. Acta Otolaryng. 1971, 352. DOI: 10.3109/00016487109122493.

35. Peterson GE, Lehiste I. Revised CNC Lists for Auditory Tests. J. Speech Lang. Hear. Res. 1962; 27(1), 62. DOI: 10.1044/jshd.2701.62.

36. Dirks D, Carhart R. A survey of reactions from users of binaural and monaural hearing aids. J. Speech Hearing Dis.1962; 311-322. DOI: 10.1044/jshd.2704.311.

37. Finbow J, Bance M, Aiken S, Gulliver M, Verge J, Caissie R. A Comparison Between Wireless CROS and Bone-anchored Hearing Devices for Single-sided Deafness: A Pilot Study. Otol Neurotol. 2015; 36(5): 819-25. DOI: 10.1097/MAO.0000000000000762.

38. Snapp H A, Hoffer M E, Liu X, Rajguru S M. Effectiveness in rehabilitation of current wireless CROS technology in experienced bone-anchored implant users. Otol Neurotol. 2017a; 38(10): 1397-1404. DOI: 10.1097/MAO.0000000000001614.

39. Snapp H A, Holt F D, Liu X, Rajguru S M. Comparison of speech-in-noise and localization benefits in unilateral hearing loss subjects using contralateral routing of signal hearing aids or bone-anchored implants. Otol Neurotol. 2017b; 38(01): 11–18. DOI: 10.1097/MAO.0000000000001269.

40. Kochkin S. MarkeTrak VIII: The key influencing factors in hearing aid purchase intent. Hear Rev. 2012; 19(03): 12–25.

41. Williams VA, McArdle RA, Chisolm TH. Subjective and objective outcomes from new BiCROS technology in a veteran sample. J Am Acad Audiol. 2012; 23(10): 789–806. DOI: 10.3766/jaaa.23.10.5.

42. Ericson H1 SI, Högset O, Devert G, Ekström L. Contralateral routing of signals in unilateral hearing impairment. A better method of fitting. Scand Audiol. 1988; 17: 111–6. DOI: 10.3109/01050398809070699.

43. Taal CH, van Barneveld DC, Soede W, Briaire JJ, Frijns JH. Benefit of contralateral routing of signals for unilateral cochlear implant users. J Acoust Soc Am. 2016; 140(01): 393. DOI: 10.1121/1.4955307

44. Van de Heyning P, Távora-Vieira D, Mertens G, et al. Towards a Unified Testing Framework for Single-Sided Deafness Studies: A Consensus Paper. Audiol Neurotol. 2016; 21(6): 391-398. DOI: 10.1159/000455058.