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Research paper

A review on the applications of signal processing techniques for mitigating dementia-related hearing implications through a wide-band equalizer

Abigail Copiaco [1], Abeer El Khouly [1], Nidhal Abdulaziz [1] *, Obada Al Khatib [1], Halim Khelalfa [1], Mohamed Fareq Abdulmalek [1], Flevy Lasrado [2]

[1] Faculty of Engineering and Information Sciences (FEIS), University of Wollongong in Dubai
[2] Faculty of Business (FOB), University of Wollongong in Dubai
**Corresponding author E-mail: nidhalabdulaziz@uowdubai.ac.ae*

Abstract

Dementia is a progressive cognitive ailment that affects its patients' daily regime and independence. Over the years, the number of people experiencing dementia is continuously rising, signifying the apparent need for progress within the field. Studies have explored the possible connection between hearing impairment and dementia. In order to minimize the effects of this hearing impairment, existing works have focused on invasive processes in order to bring the hearing curve, referred to as audiogram, back to the normal curve of hearing. However, considering the fact that dementia involves aged individuals, invasive processes are deemed risky for their overall health and well-being, besides their high costs and complexity. Therefore, in this paper, we explore and compare non-invasive processes, which are based on signal processing techniques, in order to design a hearing equalization filter that is translatable to a wearable and mobile device, in order to eliminate the risks of invasive chip embedding.

Keywords: *Audiogram; Dementia; Hearing Equalization; Signal Processing.*

1. Introduction

Dementia is a clinical syndrome in which there is a decline in both memory and in other cognitive abilities, such as the deterioration in judgment or the general processing of information. It affects memory, thinking, orientation, comprehension, calculation, learning capacity, and language. Nonetheless, consciousness is not affected [1-7]. Dementia is an acquired brain syndrome that is of a chronic or progressive nature and characterized by impairment in two or more cognitive domains, such as memory, executive functions, attention, language, social cognition and judgment [1], [4], [6]. Being continuously studied over the past few decades, several studies had suggested a link between dementia and a possible decline in an individual's hearing and visual impairment [8]. Such decline in an individual's significant sensations is argued to be the root cause of the deterioration of the patient's independence and ability to perform daily tasks.

To conduct the research, hearing tests for people with dementia needs to be collected. The hearing test is usually obtained as an audiogram. The audiogram is a graph that indicates the hearing capability of a person, and presents the quietest sounds a person can hear [9]. It is used to describe the hearing capability of a person for frequencies ranging from low frequencies to high frequencies [10]. Hearing loss varies from low or mild hearing loss to moderate hearing loss and severe hearing loss. To amend this, a device can be used to improve the hearing loss. This can be in the form of hearing aids. However, common widely available hearing aids simply attempt to amplify the signals for the individuals with hearing loss. In this research, we aim to assess methodologies that will lead us in designing a device that will equalize the audiogram at different frequencies, as opposed to mere amplification.

The aimed hearing equalizer is classified as a form of assistive technology (AT), which is defined as "any item, piece of equipment, product or system, whether acquired commercially, off-the-shelf, modified or customized, that is used to increase, maintain or improve functional capabilities of individuals with cognitive, physical or communication disabilities."[12]. Majority of existing AT targeting dementia include smart homes, home care safety solutions, and electronic tracking using smart techniques [13]. Although several assistive listening devices currently exist for improving hearing in specific environments, such as noisy or crowded environments, they are not specifically purposed for dementia, and are often not adaptive to various environments [14]. Similarly, majority of these devices consider a bandwidth of up to 8 kHz [14]. Our work aims at considering a wide-band frequency, inclusive of up to 16 kHz. Management of hearing problems will support the social interaction of people with dementia, will lead to social enhancement and contribute to healthier brain aging [8].

In this paper, several signal processing techniques are explored and deliberated along the application of equalizing the hearing curve in order to aid patients from the hearing impairment associated with Dementia. The paper is organized such that the second section aims to discuss and strengthen the connection between hearing impairment and dementia. Subsequently, the next section is directed to emphasize the positive effects of engineering interventions with regards to aiding hearing impairment. The fourth section then explores various related work for the same application. The fifth section is then focused on discussing audiograms and equalization, as well as assessing different signal processing techniques applied to the equalization of the audiogram and hearing curves. Finally, the concluding section emphasizes and compares the existing methodologies, as well as the future work.

2. Hearing loss and dementia

The first step in exploring the relation between hearing loss and dementia is to show the impact of hearing loss on cognitive measures and domains. Over the last decade, various studies and surveys involving the association of hearing impairment with dementia had been conducted, several of which are summarized in the succeeding paragraphs.

A research study was conducted in 2011 on 347 participants of ages 55 years and above from Baltimore in Maryland in the US [8]. Several tests, inclusive of memory, executive function and attention, processing, psychomotor speed tests, and audiometry were administered. The statistical analysis to the results show that a greater hearing loss was significantly associated with lower scores on tests of memory and executive function [8]. A study comparing individuals with normal hearing to those individuals with a mild, moderate, and severe hearing impairment, respectively, had a twofold, threefold, and fivefold increased risk of incident all-cause dementia over more than 10 years of follow-up [15].

Similarly, a recent study in 2018 among 37,898 (mean age 72.5 ± 4.6 years) older Australians living in the metropolitan region of Perth, Western Australia, investigated the association between hearing loss and incidental dementia [16]. The study had found a significant association between hearing loss and incident dementia in the cohort of older men that participated in the study. The hazard of dementia increased by 69% in men, with a self-reported hearing impairment, as opposed to those with normal hearing, age and medical conditions. However, this study has two limitations which affects generalizing the findings: the sample was only men, and the review is limited to studies that were published in English [16].

In the analysis for 14 earlier studies, the researchers found an average increased risk of dementia of 49% for individuals with a hearing loss [17]. Figuratively, with a sample of 3,777 individuals aged 65 or older that had undergone observation for up to 25 years, around 1,289 had reported hearing problems, while 2,290 had reported no trouble. The population-based study involving 25 years of follow-up consists of assessing the relationship between hearing status and the occurrence of four major adverse events: death, dementia, depression, and disability. At each follow-up visit, tests and scales of cognitive performances, cognitive complaints, and functional abilities, were administered to participants. This study evidenced a significant association between self-reported hearing problems and an increased risk of dementia. Similarly, it shows that those who use hearing aids have around the same cognitive level as those with no hearing loss [18]. Thus, it can be inferred that not only hearing loss can accelerate cognitive decline, but it can also constitute as a risk factor for the development of dementia in older adults [2], [17], [19], [20]. Therefore, improving the hearing ability would reduce the negative mental effects of hearing loss. In turn, it would increase the ability to participate in cognitively stimulating activities such as social activities, thereby slowing the progress of cognitive decline [17]. One of the studies states [16]: "hearing loss is common and its risk increases with age, leading to a number of unwanted social and health consequences and reduced quality of life for the individual concerned". Whilst direct causality remains uncertain, the link between hearing and dementia seems plausible, and efforts to reduce its impact should continue to be explored. The study recommends to design a randomized controlled trials targeting older people with hearing loss who are at risk of cognitive impairment. These trials are needed to determine if the link between hearing loss and cognitive impairment is causal and can be reversed with appropriate interference [16].

On the other hand; A study with a sample of 666 older adults with hearing impairment seen at baseline, and followed up 5 years later, had found that there was no direct evidence that hearing aids promote cognitive function, mental health, or social engagement [21]. Although the association between hearing loss and cognitive decline appears robust, the mechanism remains unresolved and their intersection in the auditory brain remains poorly understood [2], [22].

There are several theories as to how hearing loss is linked with dementia. One is that it causes people to become withdrawn and socially isolated. Untreated hearing loss decreases the ability to participate in cognitively stimulating activities such as social activities, and thereby accelerates cognitive decline. Social interaction stimulates the brain and increases connections between brain cells which is essential for coping with dementia. It might also be interpreted that the lack of stimulus to the brain cells causes the loss of brain cells [22]. Another theory is that hearing loss physically damages part of the brain, leading to dementia [22]. One study using brain scans showed the auditory cortex, the area that processes sounds in the brain, was smaller in patients with hearing loss than in those with normal hearing [23]. Other works suggest that hearing loss damages a part of the brain that processes language, an area which is known to shrink in patients with dementia. Shrinkage or loss of brain cells is a hallmark of Alzheimer's [22]. A neuroimaging study demonstrated that individuals with hearing impairment have accelerated rates of a whole brain atrophy as well as specific volume declines in some brain regions that are important for language processing and semantic memory, and are also involved in the early stages of mild cognitive impairment [24], [25]. There is also an evidence of potential health impact of hearing loss in developing dementia [24]. Hence, the benefits of early screening and management of hearing loss are likely significant and without risk [23]. Although scientists have not yet proven whether treating hearing loss will prevent dementia, they believe it is likely to help [22]. Though hearing impairment is not generally regarded as basic feature of dementia [2], it can sometimes go undetected in patients with dementia, which may lead to the overestimation of cognitive compromise [2].

Several studies also suggest that the type of hearing issues experienced by dementia patients varies according to the type of dementia that they are experiencing. Patients with semantic dementia commonly report tinnitus [25], while hallucinations of 'muffled' sounds or voices are often reported by patients with Lewy body dementia [2]. Persistent musical hallucinations are relatively commonly reported in patients with Lewy body disease and are less frequent in other types of dementia [27]. Alzheimer's disease commonly report difficulty following conversations and other sounds against background noise, which contribute to avoid social situations of busy auditory environments, also many patients with frontotemporal dementia exhibit sound aversion [2].

2.1. Types of dementia reporting hearing problems

2.1.1. Semantic dementia (SD)

Progressive loss of semantic knowledge, referred to as semantic dementia (SD) which falls under the broader umbrella of frontotemporal dementia, is characterized by hallmark asymmetrical atrophy of the anterior temporal pole [28].

2.1.2. Dementia with lewy bodies (DLB)

Most experts estimate that dementia with Lewy bodies is the third most common cause of dementia after Alzheimer's disease and vascular dementia, accounting for 10 to 25 percent of cases [3,7], but some states, it may account for only 10-15 percent of all cases of dementia [6].
The hallmark brain abnormalities linked to DLB is Alpha-synuclein protein, the chief component of Lewy bodies (named after the German doctor who first identified them), is found widely in the brain [5-7]. Appearance of Lewy bodies is linked to low levels of important chemicals that carry messages between nerve cells and a loss of connections between nerve cells, which eventually die [6].

2.1.3. Alzheimer's disease (AD)

Alzheimer's disease is the most common cause of dementia [3], [6], [7]. Experts think between 60% to 80% of people with dementia have this disease [5], [7]. The hallmark pathologies of Alzheimer's, proteins build up in the brain to form structures called 'plaques' and 'tangles'. This leads to the loss of connections between nerve cells, and eventually to the damage and death of nerve cells and loss of brain tissue [6], [7].

2.1.4. Frontotemporal dementia (FTD)

The word 'frontotemporal' refers to the lobes of the brain that are damaged in this type of dementia. The frontal lobes of the brain, found behind the forehead and the temporal lobes – on either side of the brain [6]. Frontotemporal dementia occurs when nerve cells in the frontal and/or temporal lobes of the brain die [3], and the pathways that connect the lobes change. Some of the chemical messengers that transmit signals between nerve cells are also lost. Over time, more nerve cells die, the brain tissue in the frontal and temporal lobes shrinks [6].
Frontotemporal dementia is a significant cause of dementia in younger people – that is, those ages between 45 – 65 [6,7]. Frontotemporal dementia is probably the third most common type of dementia in this age group and some studies even place it second most common. It affects men and women roughly equally [6].

3. Importance of engineering interventions

Many world health organizations recognize dementia as a public health priority, due to the heavy burden that it causes on the patient's family and the nation's finance. Reportedly, 60% of dementia patients are living in low- and middle-income countries [3]. In May 2017, the World Health Assembly declared to start the Global action plan on the public health response to dementia 2017-2025 [3]. At 2017, 35 million people worldwide have dementia, with an expected increase to 115 million by 2050 [2]. World Health Organization (WHO) estimates around 50 million people have dementia in 2018 and the total number of people with dementia is projected to reach 82 million in 2030 and 152 in 2050. Thus, there are nearly 10 million new cases annually, implying one new case for every 3.2 seconds [2], [3].
The global cost of dementia has increased from 604 billion dollars in 2010 to 818 billion dollars in 2015, implying an increase of 35.4% [2], [6]. With these shocking numbers, it can be deduced that dementia indeed has a major impact on the nation's health care resources, and is considered to be heavy burden on the patient's family and the nation's finance. This strengthens the importance in making interventions aimed at preventing the progression of dementia. The novel strategies brought about by various engineering solutions are then needed to introduce a better life both for the caregivers, and the patients suffering from Dementia.

4. Existing work

Having identified the link between disruptions in hearing ability to the cognitive deterioration, which eventually leads to ailments such as Dementia, this section explores an overview of the various existing solutions and related work regarding mitigation strategies towards Dementia-related hearing ailments. In parallel to this, analysis of their advantages and disadvantages, identification of the research gaps of each solution, and the contemplation on their applicability to the desired field of research are also looked at. This section also aims to focus on the contrast of the proposed methodology to current existing solutions towards similar research goals.
Majority of the innovation and mitigation strategies involving engineering interventions coupling dementia are inclined towards the early detection of cognitive ailments, as well as providing healthcare assistance [29]. However, there are also a few existing solutions following scientific strategies for relieving patients from the symptoms and effects of dementia. Several solutions towards mitigating the effects of dementia include the Virtual Brain, which is an embedded computer model by which memory improvement drugs can potentially be tested on [30], as well as the telehomecare, which ameliorates the access of seniors for geriatric care [30]. Basilar and auditory models, which are utilized for hearing aids, are also related work that can contribute to this particular research [31,32]. Nonetheless, to the best of our knowledge, engineering solutions in the field of audial mitigation for Dementia had not been widely explored up to date, with the currently mentioned projects being more related towards medical assistance and caretaking for Dementia patients [33].
However, one of the closest engineering based solutions is brain emulation, which can be defined as the recreation of the brain's neurons and synapses [34]. This allows the brain to function as normally as possible despite experiencing cognitive ailments. Such process requires the utilization of various techniques and consideration of substrates. Some of the substrates considered for brain emulation include digital simulations, neuromoric chips, and biological substrates. Once the correct substrate is selected, it is then mapped to the brain and a circuit is created. This circuit is normally embedded into the patient's brain, allowing it to record and assist on the patient's daily activities [34].
In terms of substrate selection, digital simulations can be modelled via partial differentiation equations [35]. This methodology is advantageous in terms of its flexibility and observation of connectivity patterns, as recreation of the brain's neurons must perform on the exact same time scale. However, its accuracy may be questionable, as the human brain is difficult to impersonate through digital simulations. The method of neuromorphic chips, which is subject to silicon neurons, can be done through analog signal simulations [36]. Although favorable in terms of mimicking the behavior of the brain's neurons, it is more difficult to achieve an accurate timing pattern with this method. Finally, biological substrates involve the participation of a test subject in order to carry out the experiment [37]. Despite the advantages of this method in terms of versatility and testing, the responses of the test subjects may not be completely the same as that of an actual Dementia patient.

Overall, although brain emulation can make a notable difference with the patient's cognitive health, it cannot be denied that the process is invasive. Considering the fact that Dementia involves aged individuals, invasive processes are deemed risky for their overall health and well-being. Similarly, such processes require high costs and complexity. Thus, this paper aims to review signal processing methodologies that model and mitigate the auditory tract of Dementia patients, and its connections with the brain. In turn, this eliminates the requirement of the brain emulation. One of the key differences of this to the existing brain emulation solution is the exclusion of embedding a circuit into the brain. As mentioned earlier, embedding a foreign object onto the brain of a patient experiencing cognitive ailments poses for high risks in terms of safety. Hence, an external-based wearable circuit inclusive of the designed filter, similar to a hearing aid, is aimed to be developed in replacement to an invasive embedded chip.

5. Existing filter design techniques for audiogram equalization

5.1. Audiograms

Ensuring and establishing the design of an accurate filter for a non-invasive audiometry device can be challenging. However, as an input to the hearing equalization filter, patients have to undergo a hearing test that would provide their audiogram curve for equalization. An audiogram curve is a graph that results from a hearing test, reflecting the softest of the sounds that a patient can hear at differing frequencies [38]. Both the left and the right ears are taken into consideration, whose curves are combined together in one plot. An example of an audiogram representing mild hearing losses can be seen in Figure 1.

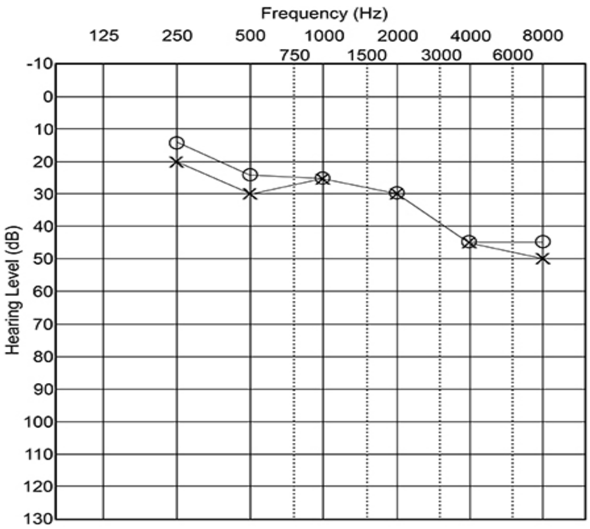

Fig. 1: Sample of an Audiogram [38]. This Sample Is of A Patient Diagnosed with Mild Hearing Loss, Characterized by an Average Audiogram Reading of 25 To 40 Db HL. an "O" from the Audiogram Represents Readings from the Right Ear, While "X" Denotes Readings from the Left Ear [38].

For the aims of this research, the filter must be designed such that it raises the graphs to within the normal hearing level range, which is defined at 0 – 15 dB hearing level [38]. The patient's hearing level is identified according to the average result in dB of their hearing curve, as per Figure 2.

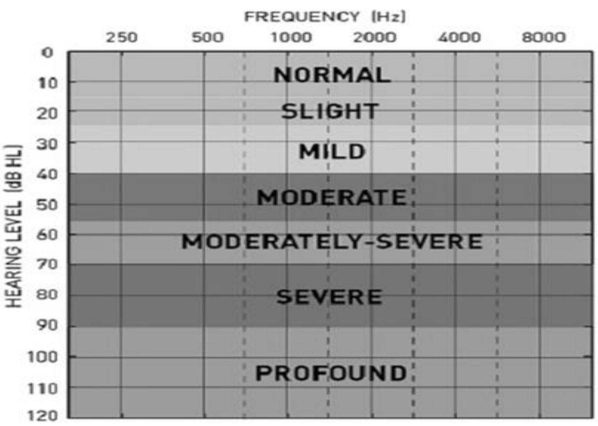

Fig. 2: Degrees of Hearing Losses [38]. Normal Hearing Curves are Defined If the Average of the Hearing Curve Points Rounds Up between 0 To 15 Db HL. Slight Hearing Losses are Defined from 15 to 25 Db HL, While Mild Hearing Losses are Characterized from an Average of 25 To 40 Db HL. Subsequently, Moderate Hearing Losses are Defined by Readings Around 40 to 55 Db. Furthermore, Moderately-Severe Hearing Loss Can Be Found in 55 To 70 Db Results. Finally, Severe Hearing Loss Is Given By A Mean Hearing Level Score of 70 To 90 Db, While Anything Above 90 Db Is Considered Profound [38].

5.2. Equalization filter design techniques

Several notable works had been proposed over the past years with regards to equalizing the audiogram that is affected by hearing losses. An example of a basic design of filter bank for hearing amplification is provided in Figure 3. The main purpose of a filter is to remove the unwanted components of a signal. A filter bank is defined by an array of band-pass filters, which disintegrates the original signal into components according to their frequency sub-bands [39]. The separation of the frequency components of a signal allow for the analysis of more significant components, allowing the elimination of unneeded frequency components.

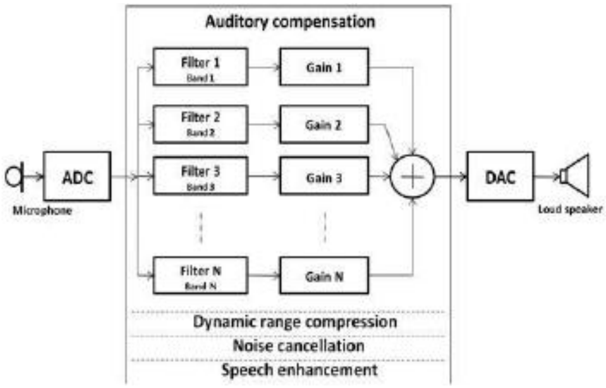

Fig. 3: Filter Bank Block Diagram for Hearing Amplification [40]. the Filter Bank For Hearing Amplification Is Designed Such That the Raw Analog Signal Is First Converted Into A Digital Format. Subsequently, Processes Inclusive of Auditory Compensation, Dynamic Range Compression, Noise Cancellation, and Speech Enhancement are Achieved, Through Separating the Frequency Components Via Filters Prior to Combining Them. after This, the Processed Signal Undergoes Digital to Analog Conversion.

However, as opposed to sole amplification of the signal, an adaptive nature needs to be looked at, as different types of hearing losses require unique hearing aids.

Gaikwad et. al. had proposed the implementation of a Decimation filter through implementing an oversampling concept from the combination of a Cascaded Integrator Comb Filter (CIC), and two Finite Impulse Response (FIR) filters [32]. Similarly, the use of a half-band CIC, along with two FIR filters are also examined. For both methodologies, the first FIR filter is utilized for compensation, while the second is used as a corrector filter. Simulation is achieved via a Simulink model in MATLAB. CIC filters compose of a three stage decimation and interpolation, which provide a systematic way of conducting decimation due to its flexible nature, and its ability to work efficiently without the need of multipliers. FIR filters are then selected due to its linear phase response, which allows it to provide an exceptional control over filter shaping, which is a crucial aspect for audio applications [32]. Comparing the two techniques, the Half-band CIC-FIR-FIR filter appears more advantageous due to its less area and power consumption as opposed to the CIC-FIR-FIR. However, despite the advantages, its FIR filter components still consist of a high filter order. Thus, the overall composition of this type of filter still requires a large storage requirement as well as power consumption when compared to filters that utilize a single FIR filter stage.

Nema and Pathak had also proposed the utilization of FIR filters in the form of a filter bank designed specifically for audiogram matching though the use of MATLAB [39]. It combines the Discrete Wavelet Transform (DWT) for noise cancellation, along with an adaptive Recursive Least Squares (RLS) Filter algorithm in order to produce an FIR filter bank that would be suitable for audiogram matching. Adaptive filtration is utilized such that the transfer function adjusts itself according to the error signals, allowing for an efficient noise cancellation [39]. Although the proposal is promising, it is subject to high sensitivity, such that small errors could influence the performance of the system significantly, especially in terms of speech intelligibility. In addition to this, as more multipliers are added, FIR filters tend to escalate the computational costs.

Following the previous methodology's disadvantage when it comes to speech intelligibility, Deshmukh et. Al. had proposed the use of the Filter Design Analysis (FDA) Tool provided in MATLAB, in order to improvise speech intelligibility in filter design [35]. The idea is to separate speech into two supporting parts based on the frequency in order to work towards the issue of spectral masking. Filter coefficients are first calculated through MATLAB's FDA Tool, and are then exported into code. The filter is then further designed according to the unique audiogram pattern of the patient, and the filtered signal is then provided to the patient in a silent environment [41]. Subjects tested by the researchers had proven a reduced effect of spectral masking and enhanced speech perception.

On the account of the large storage requirement as well as the power consumption disadvantages of MATLAB simulation based filters, Das and Mahapatra had proposed an adaptive hearing aid algorithm based on the Booth-Wallace Tree Multiplier in order to produce a filter that requires less storage area while requiring less output latency at the same time [42].The adaptive filter block diagram is provided in Figure 4.

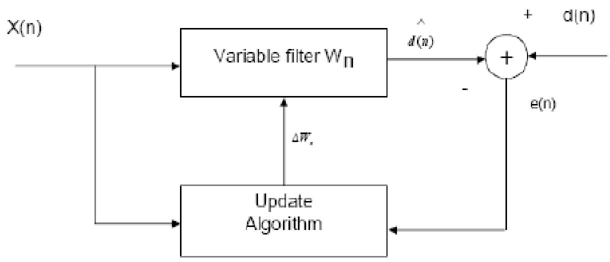

Fig. 4: Adaptive Filter Block Diagram [39].

Wallace trees do not require a specific method for interconnections, but rather, it makes for a systematic implementation when it comes to parallel accumulation of data. This allows for the low power consumption advantage characterized by the system. The design proposed by Das and Mahapatra starts with spectral sharpening aimed at enhancing the speech, which uses a high pass filter as a compensator for the spectral tilt of speech. Similarly, spectral sharpening is also aimed to target noise reduction [42]. Overall, this method is proven efficient in terms of speed, as well as power and storage requirements.

Finally, Arai and Konishi had proposed a novel hearing equalizer for human voices targeted for the elderly [43]. When speaking, vowels tend to be represented by lower frequencies, and consonants are represented by higher frequencies. It has been found that for elderly people, high-frequency components in human voices are difficult to hear. In the system proposed by Arai and Konishi, input is represent-

ed by speech formants, which undergo 32 decomposition filter banks prior to a nonlinear equalizer multiplier. Following this, the output then goes to a 32 reconstruction filter bank for final equalization. High shelving filters and the Haar wavelet transformation are used for correction, which allows the enhancement of high frequency components without affecting the low frequency components [43]. Low pass filters are then used for noise reduction. Overall, this method gathered 2 to 55% voice recognition success ratio [43]. The device is advantageous in terms of its compactness, as it is based on a mobile device. Thus, it minimizes the risk of disruptiveness, allowing the patient a user-friendly, comfortable experience. However, the success ratio rate requires further improvement in order to prove its reliability. Furthermore, its equalization is limited to language and human voices, and has not been tested for any other forms of audio.
In selecting a filter for equalizing an audiogram, success rate, intelligibility, and computational costs remain as priority considerations. This is due to the fact that filter design is unique for every patient depending on their requirements. Thus, in order to find an advisable technique from the methodologies mentioned, their advantages and disadvantages are summarized in Table 1.

Table 1: Summary of Advantages and Disadvantages for Existing Methods

Reference	Method	Advantages	Disadvantages
[39]	Decimation Filter (CIC and FIR Combination)	Flexibility, exceptional control over filter shaping	Large storage requirement, large power consumption
[40]	Audiogram Matching through Adaptive RLS and DWT	Efficient noise cancellation	Small errors return significant effects on the speech intelligibility, high computational costs
[41]	Speech separation through FDA Tool	Reduced effect of spectral masking, enhanced speech perception	Needs further research exploration
[42]	Adaptive Algorithm via Booth-Wallace Tree Multiplier	Smaller storage requirements, Less output latency, Fast speed	Intelligibility can still be improved
[43]	Decomposition and Reconstruction Filter banks	Compactness and mobility	Success ratio requires further improvement in order to be deemed reliable, limited to language and voice equalization.

6. Conclusion

Overall, as per the advantages and disadvantages of notable signal processing techniques for hearing equalization as summarized in the previous section, it can be inferred that an adaptive algorithm through a Booth-Wallace Tree multiplier is deemed efficient due to its reasonable storage and power requirements, as well as its speed. However, the intelligibility component of this algorithm can still be improved. Such improvement can be facilitated through the integration of speech separation methods [40]. Furthermore, flexibility can also be a subject of further improvement through incorporating half-band Cascaded Integrator Comb (CIC) filters, which is found to be advantageous in terms of flexibility and the elimination of the multiplier requirements, which increases its computational efficiency [38]. Nonetheless, such improvements are proposals for the future direction of this research, and will be explored in the implementation stage of our research.

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