WESPAC IX 2006
The 9th Western Pacific Acoustics Conference
Seoul, Korea, June 26-28, 2006

ADAPTIVE DYNAMIC RANGE OPTIMIZATION FOR HEARING AIDS

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ABSTRACT

Clinical trials of the adaptive dynamic range optimization (ADRO) amplifier show that it produces more comfortable sound, higher speech recognition in quiet at low input levels, higher speech recognition in background noise, and improved sound quality relative to conventional wide dynamic range compression (WDRC) hearing aids. Instead of attempting to compress a wide range of input sounds into a narrower range of hearing, ADRO uses statistical rules to select the most informative parts of the intensity range and presents it at a comfortable level for the listener. Typically, ADRO uses a higher number of narrow frequency channels and slower adaptation rates than WDRC. First used in cochlear implants, ADRO is particularly well-suited to bimodal and hybrid stimulation which combine electric and acoustic stimulation in opposite ears, or in the same ear respectively.
KEYWORDS: ADRO, Hearing Aids, Amplification, Cochlear Implants

INTRODUCTION

Modern hearing aids are changing very rapidly. The market has changed from 80% analog in 2000 to 83% digital devices in 2004 [1]. This trend has enabled a new generation of digital signal processing algorithms [2, 3] that are revolutionizing many aspects of the hearing health industry. One of these new algorithms is the digital amplification strategy known as Adaptive Dynamic Range Optimization (ADRO™) [4, 5]. The ADRO amplifier is intrinsically digital and would have been extremely difficult to implement as an analog circuit. It uses statistical analysis of the output signal in many narrow frequency bands (usually 32 or 64 bands) and fuzzy logic rules to control the gain independently in each frequency band. Several clinical trials have confirmed that the ADRO strategy provides benefits over conventional linear and nonlinear amplifiers for hearing aids [6, 8, 8] and cochlear implants [9, 10]. The scientific evidence supporting these benefits, and the underlying reasons for the benefits are reviewed here.

COMFORT, AUDIBILITY, and SOUND QUALITY

The dynamic range of hearing is usually considered to be the range between the hearing threshold at the softer end, and the discomfort level, or uncomfortable level at the louder end. It is well-known that this dynamic range varies with frequency in listeners with normal hearing [11], and that the dynamic range is reduced in listeners with impaired hearing [12]. One of the goals of a hearing aid is to place sounds within this reduced dynamic range for listeners with impaired hearing in order to achieve audibility and comfort levels similar to those of a person with normal hearing in normal listening environments. In 1937, Fletcher and Munson [12] suggested that compression of the output signal would be an appropriate way to achieve this goal. The first successful compression hearing aids appeared in the 1980's, and wide dynamic range compression (WDRC) is now used in almost all hearing aids to achieve the goals of comfort and audibility. The type and amount of compression is usually determined with a prescription such as NAL-nonlinear [13], Desired Sensation Level i/o [14], or CamFit [15].

Although WDRC is used in most hearing aids, linearity is a desirable quality for amplifiers used by people with normal hearing because it provides the best sound quality. Compression would usually be considered a distortion of the sound in most high fidelity sound systems. WDRC hearing aids must therefore make a compromise between sound quality, which requires long time constants and compression ratios close to one [16], and comfort and audibility which may require short time constants and high compression ratios [17].

In addition to linearity, frequency response is also a factor in subjective judgments of sound quality amongst listeners with normal hearing. People will often adjust the base or treble, or the graphics equalizer, as well as the volume control on their sound system to suit their own preferences with regard to sound quality and loudness. In effect, they are optimizing the frequency response and the volume of the linear sound system, taking into account the sound they are listening to, the environmental noise, and their own preferences.

The fundamental idea behind ADRO is to produce a linear amplifier that automatically optimizes its frequency response and output levels for any sound, in any environment, and is fitted taking into account the preferences and hearing loss of the listener.

THE ADRO ALGORITHM

One of the main differences between ADRO and other nonlinear amplifiers is that ADRO is linear most of the time, and only becomes nonlinear when the output levels are no longer in the optimum range for the listener. ADRO uses fuzzy logic rules to optimize the output signal of the hearing aid in each narrow frequency channel. A "fuzzy" logic rule is one that is not always true or false, but can be true for part of the time (see the description of the comfort and audibility rules below). The rules ensure the comfort and audibility of sounds by keeping the output level between a comfort target and an audibility target. If a sound falls below the audibility target, it is made louder. If it rises above the comfort target, it is made softer. While the sound is within the optimized range, the hearing aid gain does not change. Instead, it operates in a linear fashion. This approach is quite different from the alternative compression strategies that continuously vary gain according to fixed input/output functions in a smaller number of broader overlapping frequency bands.

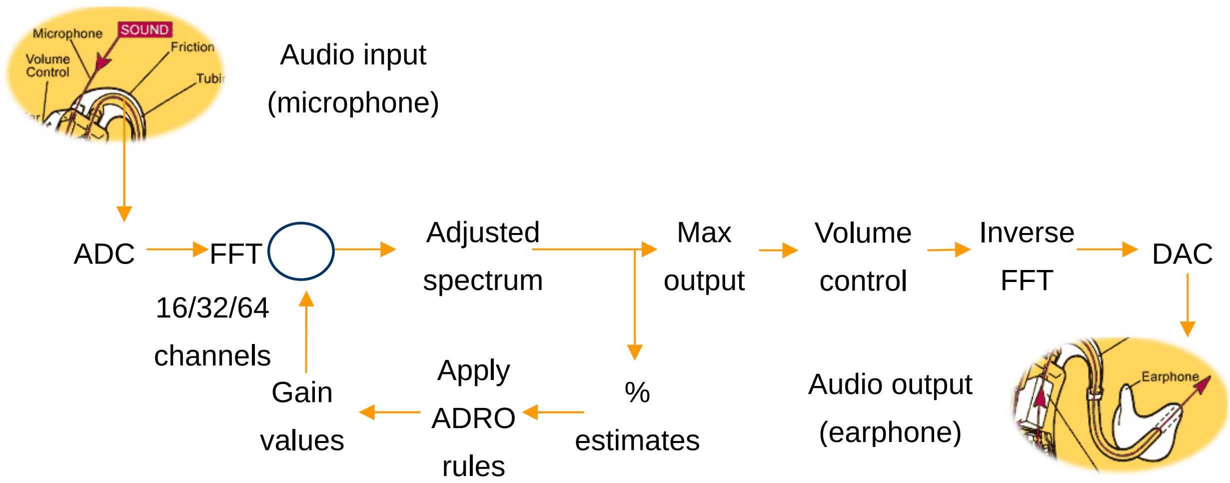

Figure 1. *Sound processing stages for a typical FFT-based implementation of ADRO in a hearing aid. ADC is analog to digital converter; DAC is digital to analog converter; FFT is fast Fourier transform.*

The gain in each frequency channel for ADRO is selected using statistical rules that keep the sound comfortable and audible. There are four ADRO processing rules that are applied independently in each frequency channel. They use statistical analysis of the sound intensity in each channel to control the loudness of the sound.

- The “comfort rule” reduces the gain in the frequency channel if the output level for the channel exceeds the “comfort target” more than 10% of the time. This rule ensures that sustained sounds are not too loud.
- The “audibility rule” increases the gain in the frequency channel if the output level for the channel falls below the “audibility target” more than 30% of the time. The audibility rule ensures that sustained sounds are not too soft.
- The “hearing protection rule” limits the output level in each channel so that it never exceeds a maximum value. This rule ensures that sudden loud sounds are not uncomfortably loud.
- The “background noise rule” limits the maximum gain in each channel. The background noise rule ensures that low-level background noise is not amplified to a level that becomes annoying to the listener.

The overall effect of the four rules is to select the most information-rich part of the sound dynamic range and place it between the audibility and comfort targets at every frequency. Figure 2 shows a hypothetical distribution of sound levels in a single frequency channel of an

ADRO hearing aid. The 90th percentile is the sound level that is exceeded 10% of the time. The 30th percentile is the sound level that is exceeded 70% of the time. Typically for speech in a quiet environment, the 30th percentile lies between the low level background noise and the speech as shown in Figure 2. This occurs because running speech has gaps that account for about 30% of the time. Thus ADRO will automatically place most of the speech signal above the audibility target, but the background noise is not required to be above the audibility target.

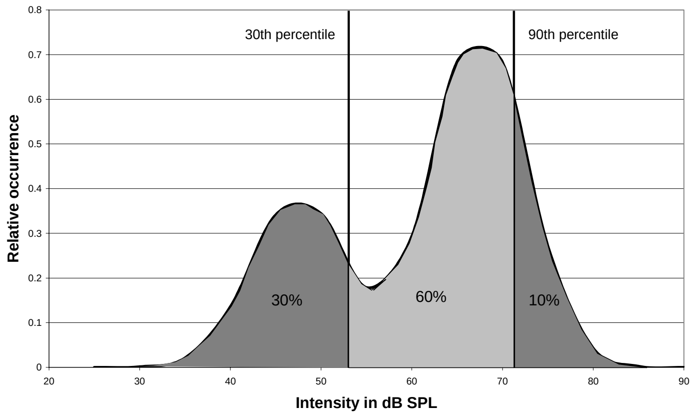

Figure 2. *Hypothetical distribution of intensity measurements in one frequency channel, showing 30th and 90th percentiles. The lower peak in the distribution corresponds to low level background noise, and the higher one to speech.*

SPEECH INTELLIGIBILITY

In quiet. The ADRO amplifier has been implemented in several digital signal processing hearing aids and evaluated in several hearing aid trials [6, 7, 8]. Each trial has compared the ADRO processing with an alternative amplifier in the same hearing aid hardware.

Figure 3 shows perception scores for the City University of New York (CUNY) sentences [18] from a comparison study of ADRO with WDRC. Both amplifiers were implemented in a BTE hearing aid especially for the trial. The WDRC amplifier had three channels and was fitted with the NAL-NL1 prescribed gains. The WDRC attack and release time constants were 10 ms and 80 ms respectively. Nineteen people with pure-tone-average hearing thresholds from 33 to 97 dB HL were tested with both amplifiers in the same hearing aid hardware without knowing which program was ADRO and which was WDRC after 8 weeks of take-home experience in which they could switch between the two programs at will. At the end of the trial, 16 people had an overall preference for ADRO, and 3 had an overall preference for WDRC. Figure 3 indicates that there was a significant ($p<0.01$) speech intelligibility benefit in quiet across the range from low to normal levels (53, 60, and 66 dB). This benefit for speech perception in quiet has been replicated in every evaluation of ADRO with hearing aids and cochlear implants.

The speech intelligibility results indicate that the ADRO rules provided good speech intelligibility as well as audibility and comfort for all sounds.

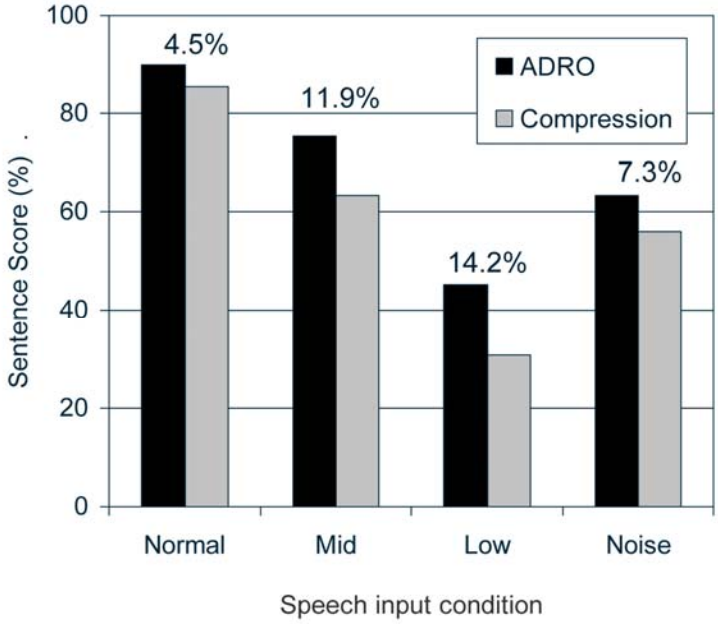

Figure 3. Average *CUNY sentence scores in quiet at 3 input levels, and in noise for 19 listeners in a blind trial comparison of ADRO and WDRC.*

In Noise. ADRO was also evaluated with speech in background noise. The results in Figure 3 show that the average percentage of words correct for sentences in noise was 7.3% higher for ADRO than for WDRC. A paired t-test ($t = 3.81$, $df = 18$, $p < 0.01$) showed that this difference was statistically significant. This advantage of ADRO over WDRC in noise was achieved without additional noise reduction algorithms, showing that noise reduction is “built in” to ADRO.

HOW IS ADRO FITTED?

The values of the comfort targets, maximum output levels, and maximum gain values are usually expressed in dB values that will be very familiar to people who have fitted hearing aids before. They have a clear and intuitive interpretation: larger values indicate louder output, and smaller values indicate softer output sounds. There is no need to predict complex cross-over frequencies, kneepoints, and compression ratios.

There are four easy steps to fitting an ADRO hearing aid:

Enter the audiogram. The fitting program will then calculate initial Comfortable Levels for the next step.

Balance loudness across frequencies at a comfortable level. This is like setting the graphics equalizer on your stereo. The fitting software will probably have an in-situ measurement facility to generate narrow-band noises with controlled level and frequency inside the hearing aid. The audiologist (or the listener) should adjust these until they are in the comfortable range and equally loud across frequencies. This should take no more than a few minutes per ear.

There is no need to establish the Maximum Comfortable Level or to do Loudness Scaling. The fitting software will automatically calculate the initial ADRO fitting from the audiogram and the Comfortable Levels.

Adjust the overall volume to the preferred level for conversational speech. This is like adjusting the volume on your stereo – one adjustment makes everything louder or softer. Different clients will have different preferences, even if they have the same audiogram. Just turn on the hearing aid and have a natural two-way conversation with the client while you are adjusting the volume. It is much easier for clients to choose the best volume setting this way than to rely on loudness scaling with beeps and pure tones.

Fine tune Maximum Gains and Maximum Output Levels (if necessary). The Maximum Gains control the loudness of soft sounds. If soft background noises are too loud, the maximum gain should be reduced at the appropriate frequencies. If soft speech is too soft, the maximum gain should be increased. The low-frequency maximum gain settings can also be used to change the sound of the client's own voice. The high-frequency maximum gain settings can be reduced to avoid feedback if necessary. The Maximum Output Levels (MOLs) control the loudness of sudden loud sounds. If loud sounds sound distorted, then the MOLs should be raised. If sudden loud sounds are uncomfortable, then the MOLs should be reduced at the appropriate frequencies.

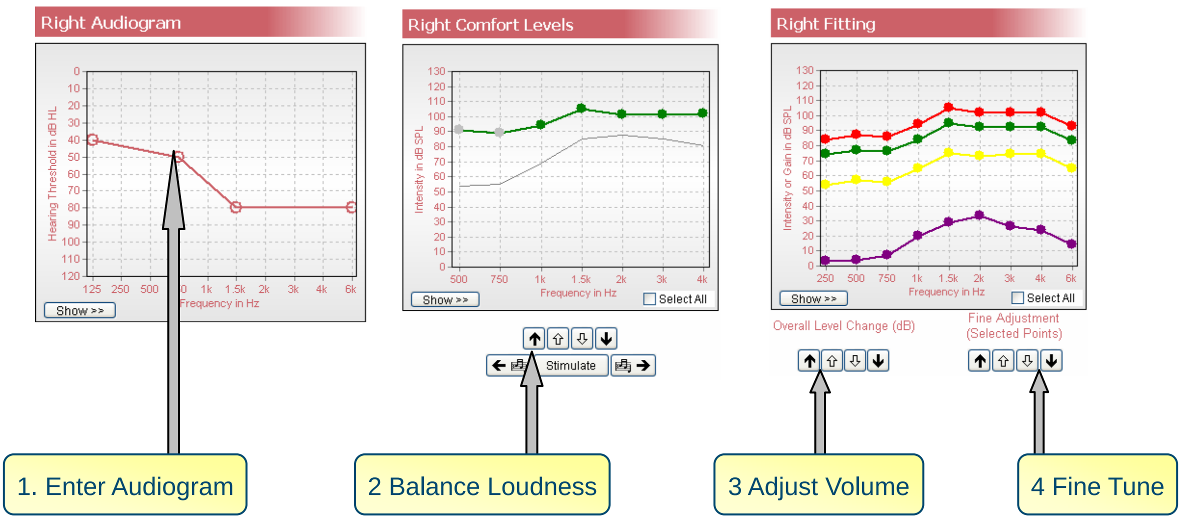

Figure 4. *Steps required to fit an ADRO hearing aid illustrated with screen shots from the Configure™ software used in the clinical trials of ADRO.*

SUMMARY

The introduction of digital signal processing into hearing aids has enabled the development of new algorithms such as the ADRO amplifier. ADRO is easy to fit to any hearing loss, from mild to severe, in an interactive and intuitive manner with the client. Once the hearing aid has been fitted, the ADRO rules will keep sounds in the comfortable range for every frequency. There is now a large body of evidence to show that ADRO provides speech perception benefits over linear and WDRC hearing aids at the same time as providing excellent sound quality and user acceptance.

ADRO is an adaptive linear hearing aid with frequency response and output levels that are always optimized to the listener's preferences in every environment.

ACKNOWLEDGEMENTS

The clinical trials reviewed here were approved by the Human Research and Ethics Committee of the Royal Victorian Eye and Ear Hospital (Projects 99/379H, 02/458H, and 03/529). The research was supported by the National Health and Medical Research Council of Australia, the Cooperative Research Centre for Cochlear Implant and Hearing Aid Innovation, the University of Melbourne, the Bionic Ear Institute, and AusIndustry. ADRO™ is the trademark of Dynamic Hearing Pty Ltd.

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