Inverse Function Theory for Hearing Correction via the ABR in Memory of Swamy Laxminarayan

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Abstract The use of inverse function theory is discussed for hearing correction within the context of clinically measured ABR signals. Given an ABR for a modestly damaged auditory system it is shown how it can be corrected by a concatenation of two nonlinear systems to yield a type of hearing aid. Future extensions are mentioned.

1 Introduction

As Swamy was very interested in future visions for biomedical engineering, we present some visions via recent ideas towards the future of non-invasive correction of hearing and possibly other impairments. For concreteness we concentrate on the use of ABR signals which are now customarily used as a diagnostic tool [1].

Acoustic Brainstem Responses, ABR, and Otoacoustic Emissions, OAE, are two classes of signals presently used to evaluate hearing in situations where patients are unable to communicate with clinicians, such as for babies and animals [2]. These are signals which result from clicks or other known sounds applied to the ear. For the ABR they are measured as potentials on the scalp and for OAEs they are measured at the ear itself as reflected pressure waves. Since the signals are very weak they also require measurement in a sound controlled environment and quite sophisticated signal processing to eliminate background signals as may come

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from the heart beat or eye/body motion. But in any event through sufficient averaging the desired signals can be extracted and then used for clinical purposes [3]. Thus, actual responses can be compared to normal ones in order to determine damage to the audio signal paths involved in hearing.

Due to their clinical use there is an extensive literature on the ABR itself as well as means to measure and extract it [4]. The use of OAEs is somewhat older, and previously known as Kemp Echoes, with also an extensive literature. In both cases we have developed theoretical means, and transistor VLSI circuits to model the biological system that is processing the signals [5, 6].

Here we primarily discuss a means of correcting the ABR so that a damaged ABR can be restored to a more normal one. Many more details and hardware realizations can be found in the dissertation of the first of us [7] from which the figures created for that work are taken.

2 The ABR Signal

Figure 1 shows a typical normal ABR signal due to a click in one ear.

As shown there are five important peaks (and corresponding valleys) with their amplitude and time delays of interest. These are quite small being in the micro-volt range and usually embedded in milli-volt signals. They occur over a few millisecond time scale and show with a short delay from the exciting click. In Fig. 2 is shown the set-up for measuring the ABR for which three electrodes are typically used, one for the signal ground and two for differencing to remove background noise.

Figure 3 shows an ABR for a damaged ear.

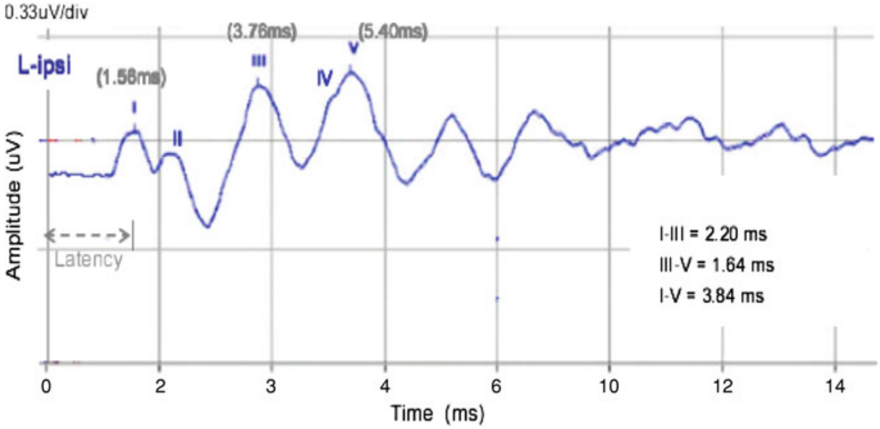


Fig. 1 Normal ABR showing the five clinically useful peaks [6, Fig. 1.2]

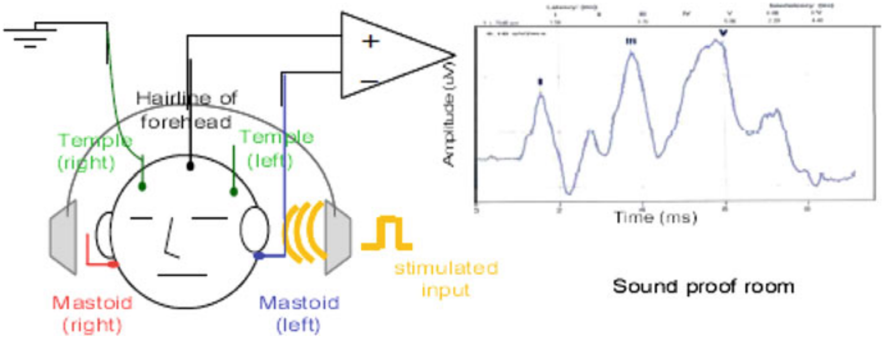


Fig. 2 Measurement scheme for ABR recording [6, Fig. 3.1]

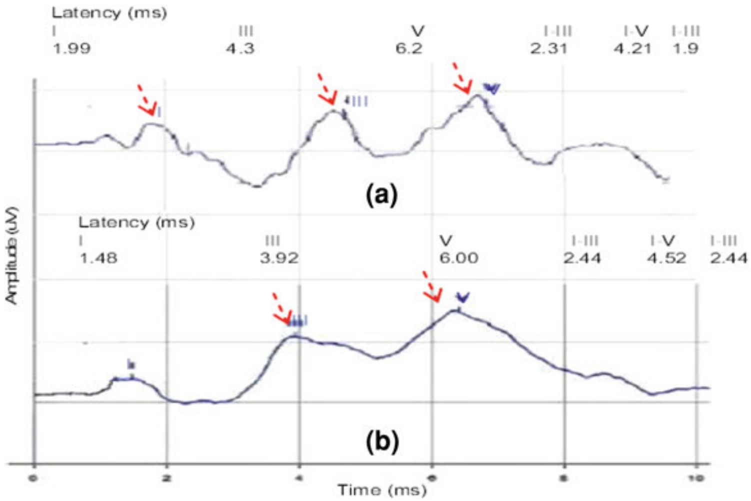


Fig. 3 Two abnormal ABRs **a** due to conductive hearing loss and **b** due to mild sensorineural hearing loss [6, Fig. 2.5]

As can be seen from Fig. 3 there is often enough differentiation in the peaks and valleys for a clinician to be able to tell that hearing loss has occurred without any vocal or other type input from the individual being evaluated. It is, though, natural to question what is it which determines the peaks and valleys and in a clinical sense what can go wrong to reshape them? For that purpose it is instructive to look at Fig. 4 where different audio pathways to the brain are indicated with an inference on how signals at each position may influence the signals detected on the scalp. To say the least, the there are myriad paths and almost definitely the measured signals contain numerous contributions from different paths. Even if one could be certain of where damage has occurred it would be a difficult task to carry out a corrective operation (though this is actually done in the case of cochlea implants!).

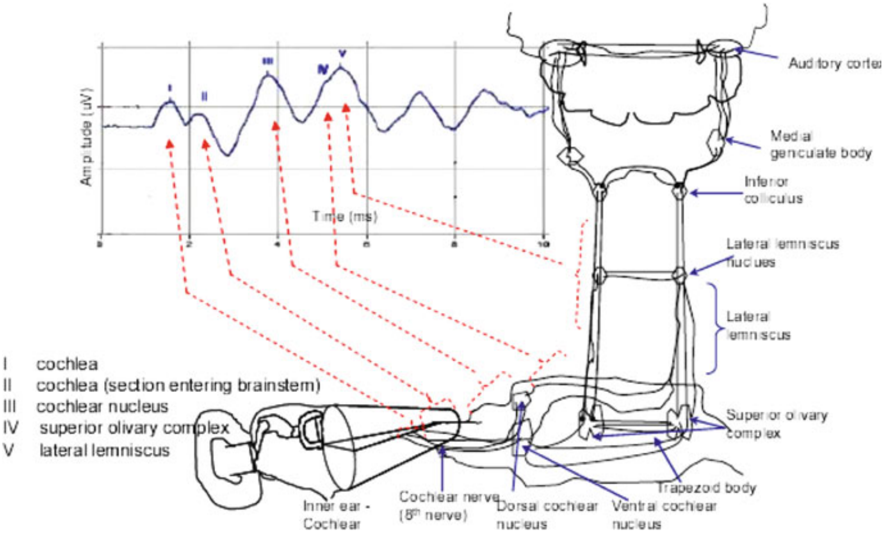


Fig. 4 Possible paths for ABR signals [6, Fig. 2.2]

By whatever means, the desire is to take a response as shown in Fig. 3 and turn it into one as shown in Fig. 1. Although this may not always be possible, in many cases it can be done. In fact the ABR is used in such a manner when implanting cochlear implants to be sure the implant is most effectively positioned. Our proposal is to do this via hardware worn in the same manner as present hearing aids such that no implantation is necessary. The key idea was expressed earlier [7] and is in the use of inverse function theory.

3 Inverse Systems for ABR Correction

Given a function $y = f(u)$, such as the ABR, the inverse function is given by solving for u to get a new function $g(y) = u$, in which case we write $f^{(-1)} = g$ and have $f(g(y)) = y$. That is $f(g(.)) = Id(.)$ where $Id(.)$ is the identity. In our case we have $y =$ ABR signal and $u =$ click in the ear. We have a measured ABR, y_{meas}, and assume that we know the desired ABR, y_{des}, both for the same click, u. Thus,

$$y_{mes} = f_{meas}(u) \tag{1}$$

$$y_{des} = f_{des}(u) \tag{2}$$

and we wish to insert a device in the ear to change y_{meas} into y_{des}. Since the body is the fixed part of the system, the aid signal will need to go through the aid before going through the fixed system; this means the function to be corrected, $f_{meas}(.)$ should be inverted prior to its input. In other words, we wish to work with

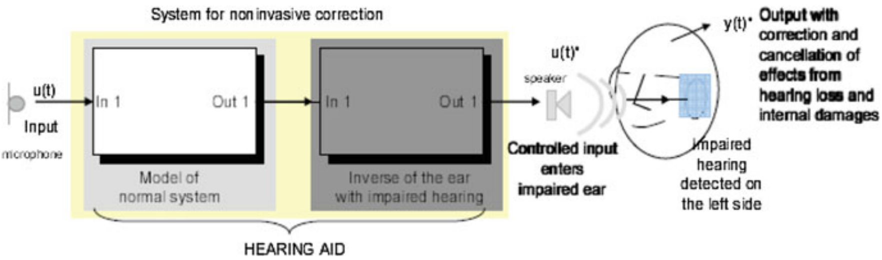


Fig. 5 Diagram illustrating use of the inverse system to correct the ABR [6, Fig. 4.2]

$$y_{des} = f_{meas}\left(f^{(-1)}_{meas}(y_{des})\right) \tag{3}$$

On substituting (2) into (3) we obtain

$$y_{des} = f_{meas}\left(f^{(-1)}_{meas}(f_{de}s(u))\right) \tag{4}$$

From this we see that we wish to make a system to insert into the ear which is described by

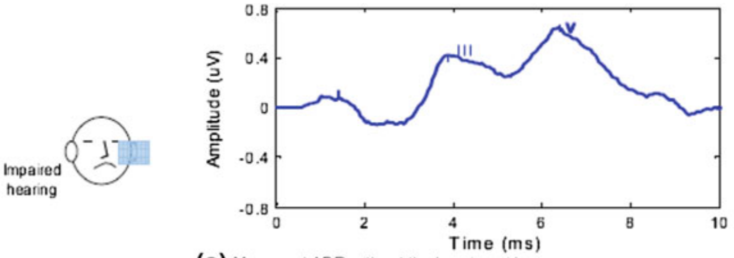
$$g(\cdot) = f^{(-1)}_{meas}(f_{des}(\cdot)) \tag{5}$$

That is, we wish to concatenate in front of the ear two systems, one for $f^{(-1)}_{meas}(.)$ and one for $f_{des}(.)$, combining them into one system described by the g(.) of Eq. 5. The ABR click signal u first enters the sub-system described by $y1 = f_{des}(u)$ and this sub-systems output, y1, is the input of the second sub-system described by $y2 = f^{(-1)}_{meas}(y1)$. The output of this second subsystem is fed into the ear whose ABR output is then $y = f_{meas}(y2) = f_{meas}(f^{(-1)}_{meas}(f_{des}(u)) = f_{meas}(g(u)) = f_{des}(u)$. In the end this gives the possibility of correcting the ABR from an abnormal one to a desired more normal one. Pictorially this mathematics is illustrated in Fig. 5.

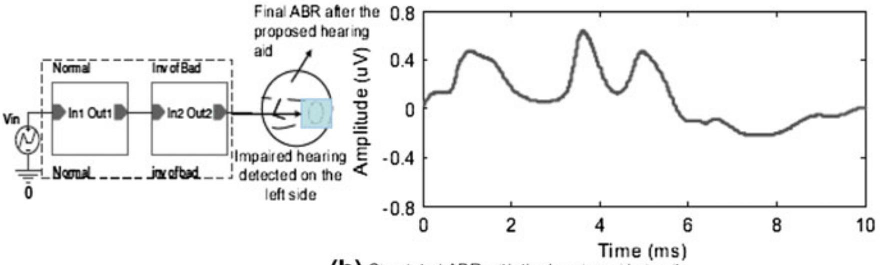
This technique has been simulated on an abnormal ABR, obtained from Dr. Permsarp Isipradit of the Department of Otolaryngology, Chulalongkorn University, with the results shown in Fig. 6. As can be seen the results give an ABR much closer to the normal one. More details can be found in [6, 8].

4 Discussion

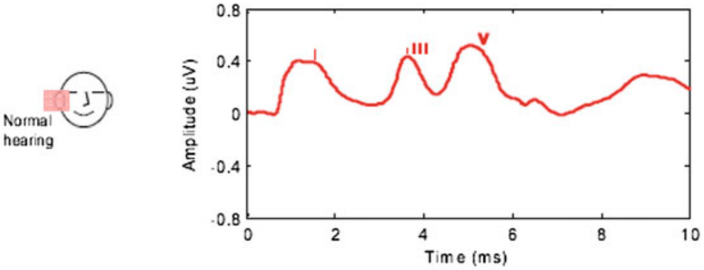
The use of an inverse system allows the cancellation of undesired responses and, as a consequence, can be used to correct some abnormal ABR and OEA recordings. If the system is linear taking the inverse amounts to division by a transfer function in the single input single output case. But if there is no ABR present this division is by zero pointing out that the method is not a cure all. However, in the case where damage is recoverable the use of this inverse system method could give



(a) Measured ABR without the hearing aid



(b) Simulated ABR with the hearing aid circuit



(c) Normative ABR from good working right sided ear/hearing

Fig. 6 An example of abnormal ABR correction [6, Fig. 5.13]

very favorable results, though as yet it has not been put to practice on actual human patients. Nevertheless, in [6] transistor Very Large Integrated Circuits are designed which could be fabricated to make hearing aids based upon the material developed here.

As seen by Fig. 4, where the auditory pathway is rather complicated and consists of a number of neural interfaces, the function determining the ABR is quite nonlinear. In fact large signals exciting the ear are necessary for the clinician to be able to have strong enough signals on the scalp for extracting an ABR. That being the case the mathematical determination of the inverse is not straightforward. Consequently, we have turned to the use of neural networks in describing the auditory system since neural networks are quite capable of capturing system nonlinearities. Again details are given in [6]. In some cases one may be able to linearize. Such has been successfully done in the case of OEAs [5] for which digital filters can serve as the description of the system for which the inverse replaces poles by zeros, and vice versa, in the z-transform domain.

Different clinics use different signals for measuring the ABR [9]. For instance we concentrated upon the use of a click for the input to the ear. But some clinics use speech sounds such as “da”. What is important for the method discussed here is that the actual input giving the output is known since the output detected as the ABR does depend upon the input. Also in the choice of an input one would like signals which can serve as mathematical basis functions in order to adequately describe mathematically the class of systems under discussion. For the ear these are often sine signals with frequencies over the hearing band. But clicks can be seen to be similarly useful since their Fourier transform is frequency rich.

Normally the ABR is measured with one ear excited but since there are two ears the input could excite both in which case the input u becomes a 2-vector. One can also place many sensors on the scalp (in fact the 10–20 electrode system is an important standardized system) in which case the output y also becomes a vector. Consequently, the theory is appropriately developed for multi-input multi-output, MIMO, systems. This necessitates the inversion of nonlinear MIMO systems, for which again neural networks appear as among the most important available tools. Of course the mathematical theory is not limited to auditory systems and could be applied to sight, smell, taste, or even control of limbs.

Going beyond what is discussed above, we can turn the systems around and use the inverse system as the actual one. In the case of reciprocity this would mean that when we put ABR signals into the scalp we would obtain coming out of the ears the clicks which went into the ear to give them. Although reciprocity from the ear to the scalp probably does not hold, reciprocity from the scalp into neurons of the brain may. If so, we could externally make a system to take sound waves into ABR signals and then apply those ABR signals to the scalp so that a person with totally destroyed audio pathways may still be made able to hear. Since the scalp acts as a good insulator to electric fields, a system to do this would preferably work with magnetic fields. Once this is realized, one can conceive of using ABR type magnetic signals for control of many biological functions, including such things as epileptic fits and Parkinson’s tremors.

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