

Neural adaptation and the recovery function: Some insights from a simple mathematical model

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Keywords

NRT, ECAP, neural adaptation, recovery function, deterministic model

Introduction

A greater knowledge of the temporal aspects of the response of the auditory nerve to electrical stimulation is important for understanding how signal processing strategies could be improved in transmitting sound information to the cochlear implant. Neural adaptation measured using Neural Response Telemetry (NRT) demonstrates how the evoked compound action potential (ECAP) changes over time in response to a train of pulses. The response amplitude initially decreases with each additional pulse in the pulse train and eventually settles down to a constant value (Dillier et al, 2005). This final constant response amplitude also varies inversely with the stimulation rate of the pulse train. Furthermore, the response amplitudes initially exhibit an oscillatory character with large variations which eventually settles into a stochastic one with small variations (see Figure 1).

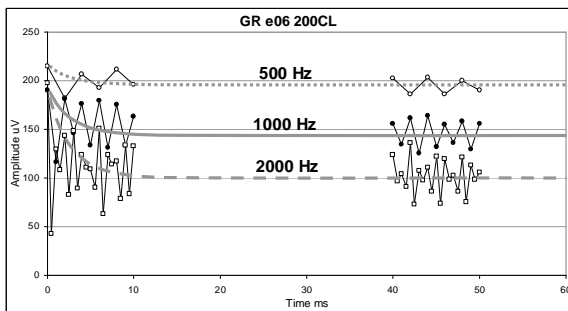


Figure 1: Neural adaptation over time at 3 different stimulation rates

The primary candidate for explaining the adaptation is the refractory behaviour of the stimulated neural population, which can in turn be characterised by a recovery function showing how the response to a given (Probe) pulse is affected by a preceding Masker pulse. When the Probe pulse follows closely (up to about 300µs) after the Masker pulse, the stimulated neural population is still in absolute refractory from the Masker and is unable to produce any response to the Probe. As the Masker Probe Interval (MPI) is increased, the neurons in refractory begin to recover and are increasingly able to respond to the Probe. At sufficiently large MPIs, the forward masking become negligible and a full response to the Probe is elicited every-time. The recovery function can be typically character-

ised by an exponentially rising asymptotic function given by

$$f(MPI) = A \left[1 - \exp\left(-\frac{MPI - T_0}{\tau}\right) \right] \quad \text{Equation (1)}$$

where T_0 is the absolute refractory period, τ the relative refractory period (or time constant) and A the final (recovered) amplitude (Morsnowski et al. 2006).

A simple deterministic model was then constructed to examine the extent of the role the recovery function plays in explaining the adaptation behaviour.

Methods

The proportion n of a given neural population available for stimulation at any given time can be computed as the sum of unfired neurons and neurons that have just recovered. Upon stimulation, a proportion p of these n available neurons respond to the stimulus. These pn neurons then recover over time according to equation 1 above, the final amplitude being determined by pn . The remaining $qn = (1 - p)n$ neurons then make up the amount of unfired neurons available to a subsequent stimulus. The amount of recovered neurons at the time of the next stimulus is computed from equation 1.

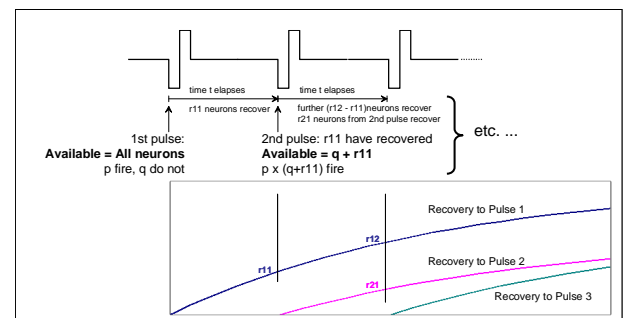


Figure 2. Model description

The model therefore consists of a sequential computation of response amplitudes based on the amount of neurons available for firing at the time of each pulse. For simplicity, the proportion of available neurons at the very start is set to 1.

The following assumptions are also made:

- i) The probability p of firing is constant (0.6) and applies equally to both the recovered as well as the unfired neurons.

ii) The recovery function time constant is assumed to be always the same, with $T_0 = 300\mu s$, and $\tau = 1000\mu s$, which are in the same order as those typical for actual recovery functions.

Results

The above model successfully reproduced the reduction in the response amplitude, as well as the dependence of the final adapted amplitude on the rate of stimulation (see Figure 3). However, the oscillatory character of the response amplitudes could not be reproduced.

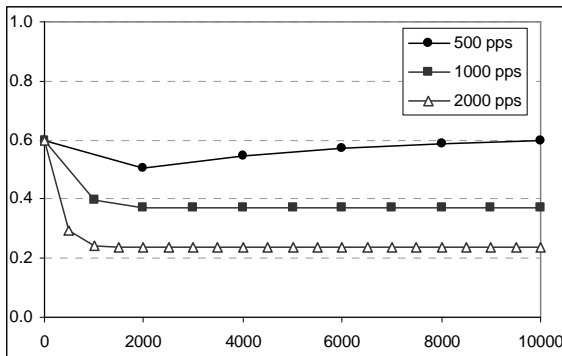


Figure 3: Model results with 3 stimulation rates

Setting a higher firing probability for the unfired neurons (assuming some kind of facilitatory effects from prior stimuli) compared to the recovered neurons did not give rise to any oscillatory behaviour.

Discussion

The success in modelling the amplitude reduction over time as well as with respect to the stimulation rate affirms that in general, the refractory behaviour is the main mechanism responsible for the observed neural adaptation. The failure to reproduce the oscillatory behaviour, however, indicates that some of the basic assumptions are not correct.

A previous model by Hamacher (2004) based on the refractory properties had successfully reproduced the adaptation behaviour, including the oscillatory behaviour. However, Hamacher (2004) used a computational model involving up to 10'000 nerve fibers, taking into account field distributions as well. Constant firing probabilities had also been assumed. One major difference, however, was that the recovery function had stochastic properties in that model. Thus, it is very likely that the present model is too deterministic, and the oscillatory behaviour is unlikely to be reproduced without similarly introducing stochastic properties into the recovery function.

This observation serves as a reminder that NRT data is always averaged, and the recovery function as measured really only shows a mean value. With stochasticity, the time constant and probably also the absolute refractory period would not be defined as single values but instead, a range of values.

Conclusion

It appears that amplitude reduction over time as well as with respect to the stimulation rate is the primary effect of the refractory properties on neural adaptation, and this is easily modelled using deterministic descriptions of the recovery function. However, the oscillatory behaviour is more likely related to stochastic properties, and this cannot be modelled deterministically. The above results serve as a reminder that the recovery function provides only an averaged picture and consequently, a deterministic description of the refractory behaviour.

Reference

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