Individual Fitting of an Auditory Nerve Model for CI Users: Spatial and Temporal Responses

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Introduction

Individually fitted models of the electrically stimulated auditory nerve might play an important role in improving cochlear implant (CI) speech perception. A fitted model must be able to represent the response of the neural population based on individual patients' electrophysiological data. Most CIs can be used for measuring the nerve's compound activity in the vicinity of every channel-related neural cluster, resulting in a recorded response known as the electrically evoked compound action potential (ECAP). In the present work, the auditory nerve was modelled as a population of nerve fibers and all parameters were fitted based on individual ECAP measurements of spatial and temporal responses.

Model Structure

The structure of the model is based on a population of uncoupled nerve fibers equally spaced along the cochlear length. The neural activity of each fiber is modelled using a novel phenomenological model for pulse train stimulation, taking into account the temporal behavior of the response [8, 12, 13]. An identical set of properties is applied to all fibers. The set is composed of fixed parameters (taken from animal data) and adaptable parameters (to be fitted for patient data). The fixed parameters are membrane integration time (with respect to the leaky integrator approach), relative spread, latency and jitter functions [8]. The fitting parameters are the membrane mean threshold, the refractoriness recovery function (mean threshold shift during absolute and relative refractory periods) and the facilitation functions (threshold shift during pulse interactions of low amplitude and short time intervals).

With the aim to model the electrode-nerve interface, a stimulation weight function is defined for each electrode position along the longitudinal array. In order to provide an input for the phenomenological model, the stimulation function must represent how the cochlea alters the current applied at a specific electrode and reaching each fiber along the array. Based on the observed behavior of the electrical field in the cochlea with CI stimulation [2, 10], the current weight function used is a linear decay in Decibels along the longitudinal length in apical and basal directions (symmetric) [3, 7]. The parameters that shape this type of stimulation function (differing for each electrode) are: center point, peak amplitude and decay rate.

Fitting procedure

In this work, the fitting procedure is presented for a single patient, using electrophysiological responses recorded when subjected to stimulation of 3 electrodes at different positions in the cochlea (E6 - basal; E12 - middle; E18 - apical). The patient data (S3) was taken from the work presented by Cohen [5], where similar fitting assumptions and procedures were applied. The recorded ECAP amplitude (as well as loudness sensation) are assumed to be proportional to the total number of spikes, therefore, considering the model structure, also to the excitation width. Equal loudness sensation between different electrodes represents equal excitation width. The excitation width, for a maximum comfort loudness level (MCL), was arbitrarily assumed to be 4mm [9].

Amplitude growth

The first fitting step concerns finding a membrane mean threshold (V) and a symmetric decay rate (dB/mm) to fit the ECAP amplitude growth (for the model, excitation width growth), of all electrodes. A mean threshold, peak and decay rate were obtained, all centered at the middle of the array. Figure 1 show the results of the first part of the fitting procedure.

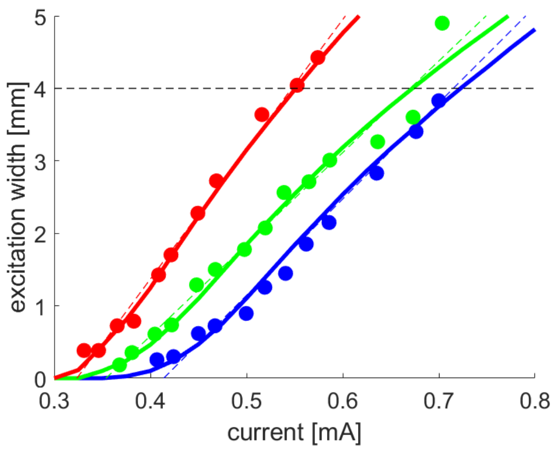

Figure 1: ECAP amplitude growth and excitation width fit. Legend: electrodes (E6, E12, E18); normalized ECAP data (•); Modelled excitation width (−).

Temporal response

During the first part, the ECAP amplitude growth was fitted using the modelled response distribution for growing current amplitude in single pulse stimulation. In order to fit the parameters related to temporal behavior of a neural population response, the ECAP refractory recovery is taken from the patient's recorded data. This measurement procedure collects ECAP responses to masker-probe stimulation at a fixed probe level for varying masker-probe intervals and masker electrode offsets. A mean ECAP recovery between cochlear regions (apical, middle and basal) is considered for the fitting procedure at different masker offsets (−1.3dB, 0dB and 1.3dB). It is important to state that all recovery recordings were obtained for a condition where masker and probe are at the same electrode (position).

With the aim to model the response of masker-probe stimulation, the proposed approach used for each nerve fiber is based on finding threshold shift functions related to observed temporal behavior of auditory neurons. This work is focuses on representing refractoriness and facilitation [4], with respect to masker-probe intervals and masker-offsets.

For the patient in question, a single threshold shift to model refractory recovery (full response recovery after firing due to masker stimulation) was used to represent the recovery behavior across different regions. The parameters that shape this function are: t_{ARP} (absolute refractory period), t_{RRP} (relative refractory period) and p (decay steepness)[11].

Regarding the facilitation behavior (lower masker amplitudes/offsets and short masker-probe intervals), a best fit was achieved for threshold shifts varying with masker offset. A facilitation threshold weight function, proposed by [12], was used with the addition of a variable weight coefficient c_f according to the masker offset. Figure 2 shows the results of the normalized recovery using the fitted refractoriness (constant among masker offset conditions) and facilitation (variable among masker offset conditions) functions.

Spatial response

The last part is related to moving the center of each stimulation weight function in order to find a set of positions that would best fit the response of masker-probe interaction between different electrodes. It is assumed, using a coarse approach, that the ECAP spread of excitation (SOE) can be represented by a joint probability between masker and probe responses obtained with the model. Thus, the SOE amplitude represents how well a probe electrode is masked by a masker electrode, at the same or different positions in the longitudinal length. A gradient descendent optimization method was used to find the best combination of center points for each weight function, where the constraints were defined by stimulation weight functions, ECAP/excitation width growth and current ranges. This approach was based on previous works presented in the literature [1, 6].

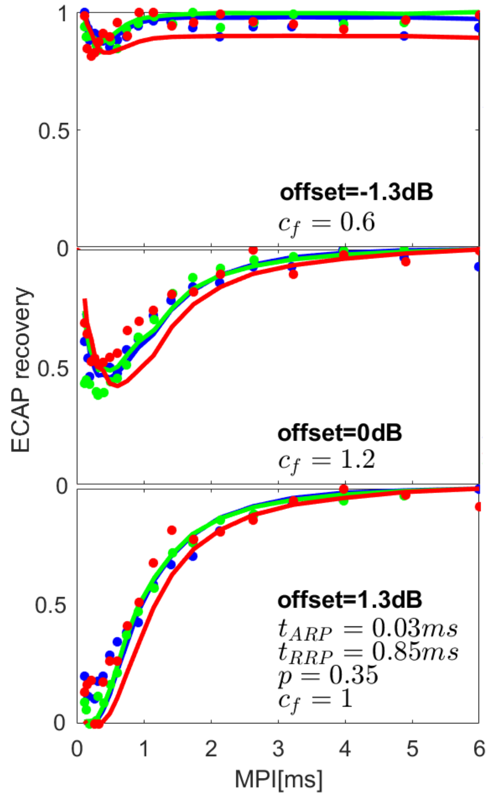

Figure 2: Normalized refractory behaviour results using the model for different masker offset conditions. Legend: electrodes (E6, E12, E18); ECAP data (•) ; model (—)

Figure 3 shows the results for the optimized center points of the coarse method and the comparison with SOE data. This approach for spatial response fitting was also evaluated using the parameters fitted for the ECAP refractory recovery. The inclusion of the temporal behavior (refractoriness and facilitation) has led to a spatial response similar to the one obtained with the joint probability approach.

Summary

This study shows the feasibility of the novel phenomenological nerve fiber model for an individual CI patient fitting procedure, mainly based on electrophysiological data. For this specific patient, the spatial fitting of stimulation weight functions was similar between the analyzed methods, confirming the usability of a coarse method with low computational cost. The facilitation behavior was nonlinearly modelled with respect to the masker offset, which led to an increase in the amount of parameters. In future work, considering asymmetric stimulation functions might play a role in decreasing the error obtained in spatial modeling. As a long term goal, extending the fitting to psychophysical tests will enable the evaluation of individual stimulation parameters with the aim to improve CI strategies.

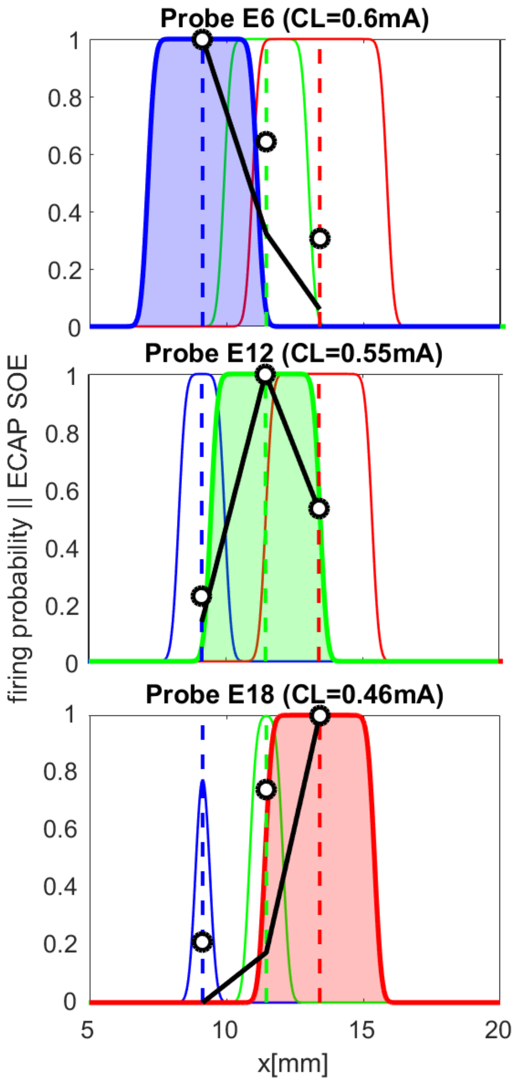

Figure 3: SOE results for the coarse approach with different probe electrode conditions. Legend: Masker electrode probability distribution (E6, E12, E18); SOE data (○) ; SOE model (—).

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