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SECTION 16. SPEECH PROCESSING

CROSS-FIBER INTERSPIKE INTERVAL PROBABILITY DISTRIBUTION IN ACOUSTIC STIMULATION: A COMPUTER MODELING STUDY

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INTRODUCTION

Electrical stimulation strategies for cochlear implants may be improved by studying temporal frequency coding in single auditory fibers and across fibers in acoustic stimulation (Clark et al, this suppl, section 5). In single nerve fibers, phase locking between action potentials and the acoustic stimulus can only be maintained at frequencies below about 600 Hz. At these frequencies, the time interval between successive action potentials, called the interspike interval (ISI), is distributed around the period of the stimulus, and it can therefore be used to code frequency within single fibers. At higher frequencies, the phase locking of individual nerve fibers diminishes, but it may still be possible to retain phase-locking properties by combining the action potentials in an ensemble of nerve fibers. In an ensemble of fibers, the ISI in each nerve is affected by factors such as the spectral shape of the stimulus, the characteristic frequency, and the firing characteristics of the nerve. The ISI between the fibers, however, is further affected by the propagation or phase delay of the traveling wave. It is therefore uncertain how these factors would affect frequency coding across fibers. It is possible that the propagation delay between the fibers may lower the phase locking in an ensemble of nerves — because the probability that the majority of nerves in an ensemble will fire simultaneously may be low. It is also possible that the combined firing statistics of the fibers in an ensemble may result in a higher degree of synchrony such that the predominant intervals in an ensemble are preserved over a wider frequency range than in a single fiber. Are these accurate postulations of the physical system? In a future electrical stimulation strategy that incorporates temporal frequency coding, is it necessary to mimic the spatial-temporal delay in the firing patterns caused by the traveling wave? These are important questions that need to be studied and answered.

To try to shed some light on these questions, this paper investigates the statistical relationship of spike events between pairs of nerve fibers with different spatial separations and propagation delays by using a mathematical model of the cochlea, a hair cell–auditory neuron transduction model, and an integral expression for the cross-fiber interspike interval (CFISI) probability distribution. Given a time-varying acoustic stimulus, the cochlear model simulates the propagating waves in the cochlear fluid, resulting in vibrations of the basilar membrane and shearing movements of the hair cells. The auditory neuron model then takes the hair cell shearing displacements and converts them into the fluctuating firing probabilities of the neurons. The CFISI distribution is then calculated from the firing probabilities by means of the integral expression. The effect of the propagation delay on the CFISI is studied and its implications for cross-fiber temporal frequency coding are discussed.

COCHLEAR MODEL

The cochlear model is a linear, active, time domain model that is based on a frequency domain model published by Neely and Kim.[1] The cochlea is modeled as a fluid-filled rectangular box with rigid boundaries, and it is separated into upper and lower halves by a flexible cochlear partition. The endocochlear fluid is assumed to be inviscid and incompressible, and the propagation of waves in the fluid is restricted to one dimension in order to simplify the solution. The cochlear partition is modeled as a fourth-order spring-mass-and-damper vibration system (Fig 1[1]). It is driven by the fluid pressure difference across the partition Pd and a frequency-dependent active feedback pressure source Pa that is proportional to the hair bundle displacement given by the relative motion of the two masses. A simplified middle ear model is also included to provide the air-to-fluid coupling from the eardrum to the stapes, so that the input stimulus may be specified as the sound pressure at the eardrum or the acceleration of the stapes. The output of the model is the basilar membrane displacement or the hair cell shearing displacement. The frequency domain response of the model at five different frequencies from 500 Hz to 10 kHz is shown in Fig 2.

According to Neely,[2] the boundary condition at the stapes is solved in the time domain by means of spatial integration to conserve the volume of fluid in the cochlea. However, computer simulation shows that this causes stability problems when the waves are reflected from the apex because of the inaccurate model of the helicotrema. To overcome this problem, the present model uses temporal integration to solve the boundary condition at the stapes, and the helicotrema can be modeled either as zero pressure difference across the apical wall or as a vibrating apical wall with a pure damping impedance.

HAIR CELL–AUDITORY NEURON MODEL

The vibration pattern on the basilar membrane is converted to the fluctuating probability of an action potential by means of an auditory synapse model based on a model published by Meddis et al.[3] The input to the model is the instantaneous shearing displacement on the hair cell at any one position on the basilar membrane, and the output is the fluctuating firing probability of the auditory nerve. However, this firing probability does not take into account the refractory period after the nerve has been fired. It simply represents the instantaneous probability of an action potential irrespective of the last
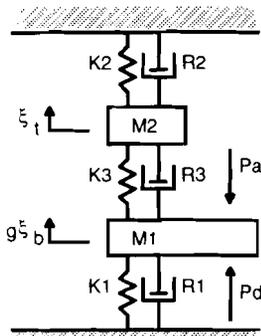
Fig 1. Micromechanical model with 2 *df*. (Modified from Neely and Kim.[1])

Fig 2. Hair bundle displacement versus normalized distance from stapes with eardrum pressure at 0 dB sound pressure level.

action potential. To simulate the effect of an absolute refractory period, the Meddis model generates nerve spikes by comparing the instantaneous firing probability with a random number, and suppresses all action potentials when the nerve is in the refractory period. With such a model, a post-stimulus time histogram can be obtained by feeding the same stimulus through the model repeatedly until a reasonable number of spikes are obtained, which may require a lot of computational time when the probabilities are small. Even more iterations may be required if one wants to estimate the firing probabilities after they have been modified by the refractory period. To overcome this problem, the present model has been altered to calculate directly the modified firing probabilities according to equation 22 in an article by Edwards and Wakefield.[4] For a step refractory function with no relative refractory period, the equation can be simplified to

$$(1) \quad Pk = s(k\delta t)\delta t - s(k\delta t)\delta t \sum_{i=1}^{n} Pk - i$$

where pk is the modified firing probability of the kth time-bin including refractory effect, sk is the unmodified rate, δt is the size of each bin, and n is the number of bins in the absolute refractory period. A 1-millisecond absolute refractory period is used in the present model.

CROSS-FIBER INTERSPIKE INTERVAL PROBABILITY DISTRIBUTION

Neural firing response can be modeled as a self-exciting point process that for many applications is well approximated by an inhomogeneous Poisson process[5] (also Irlicht and Clark, this suppl, section 16). The most obvious technique for evaluating the statistical relationship between action potentials is to use cross-correlation. However, cross-correlation measures the probability of the interval between any two nerve spikes, and not just the interval between successive spikes. The following describes an improvement on the cross-correlation method that measures the temporal probability distribution of only successive nerve spikes. First, we define the Poisson rate of nerve i as λi. Then, the probability that nerve i fires between time $t - d$ and $t - d + \delta t$ but not again in the next d seconds is

$$(2) \quad \lambda i(t - d)\delta t e^{-\int_{t-d}^{t} \lambda_i(s)ds}$$

Similarly, the probability that nerve j fires between time t and $t + \delta t$ but has not fired in the last d seconds is
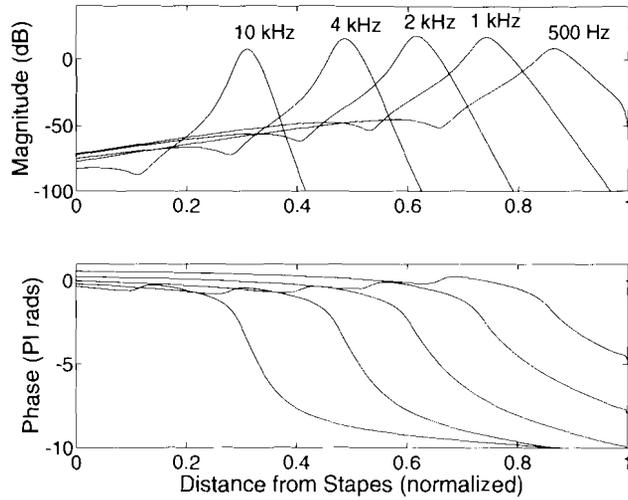
$$(3) \quad \lambda j(t)\delta t e^{-\int_{t-d}^{t} \lambda_j(s)ds}$$

Using equations 2 and 3, and assuming statistical independence between the nerves i and j, we derive an expression that provides the normalized probability of intervals of d seconds between action potentials of nerve i and nerve j:

$$(4) \quad \text{Normalized } Pr(d) = \frac{\int_d^T \lambda_i(t - d)e^{-\int_{t-d}^{t} (\lambda_i(s)+\lambda j(s))ds} \lambda_j(t)dt}{T - d}$$
where $T \to \infty$

The auditory models provide the probability of neural firings in small time bins. When the bins are sufficiently small such that the firing probability of each bin is small, the probability divided by the bin size approximates the Poisson rates of the action potentials. Equation 4 can therefore be used to calculate the CFISI.

RESULTS

The CFISI distribution for several pairs of nerve fibers with various spatial separations and corresponding phase delays are calculated from the model for five frequencies from 500 Hz to 10 kHz. The cross-fiber synchronization indices are then calculated and compared. The results are summarized in Fig 3.

Figure 3A shows the CFISI distribution at 500 Hz and 10 kHz for two scenarios: 1) both fibers at the characteristic place (at CP), and 2) one fiber at the characteristic place and the other at a more apical position (apical). For the solid curve, the first and highest peak is at zero firing delay, meaning there is a high probability for both nerves to fire simultaneously. The fast decay of the curve indicates that the CFISI is likely to be a small multiple of the period. Also, the high peak-to-trough ratio is indicative of good phase locking to the positive phase of the sine wave. For the dashed curve, the fibers are separated and the probabilities are smaller. The position of the first peak is now shifted to the right to a position determined by the propagation delay of the traveling wave, but the difference between the peaks remains the same as the period of the stimulus. At 10 kHz, the distribution is flatter for both scenarios such that the probabilities for more cycles between nerve spikes are now comparable with the probabilities for
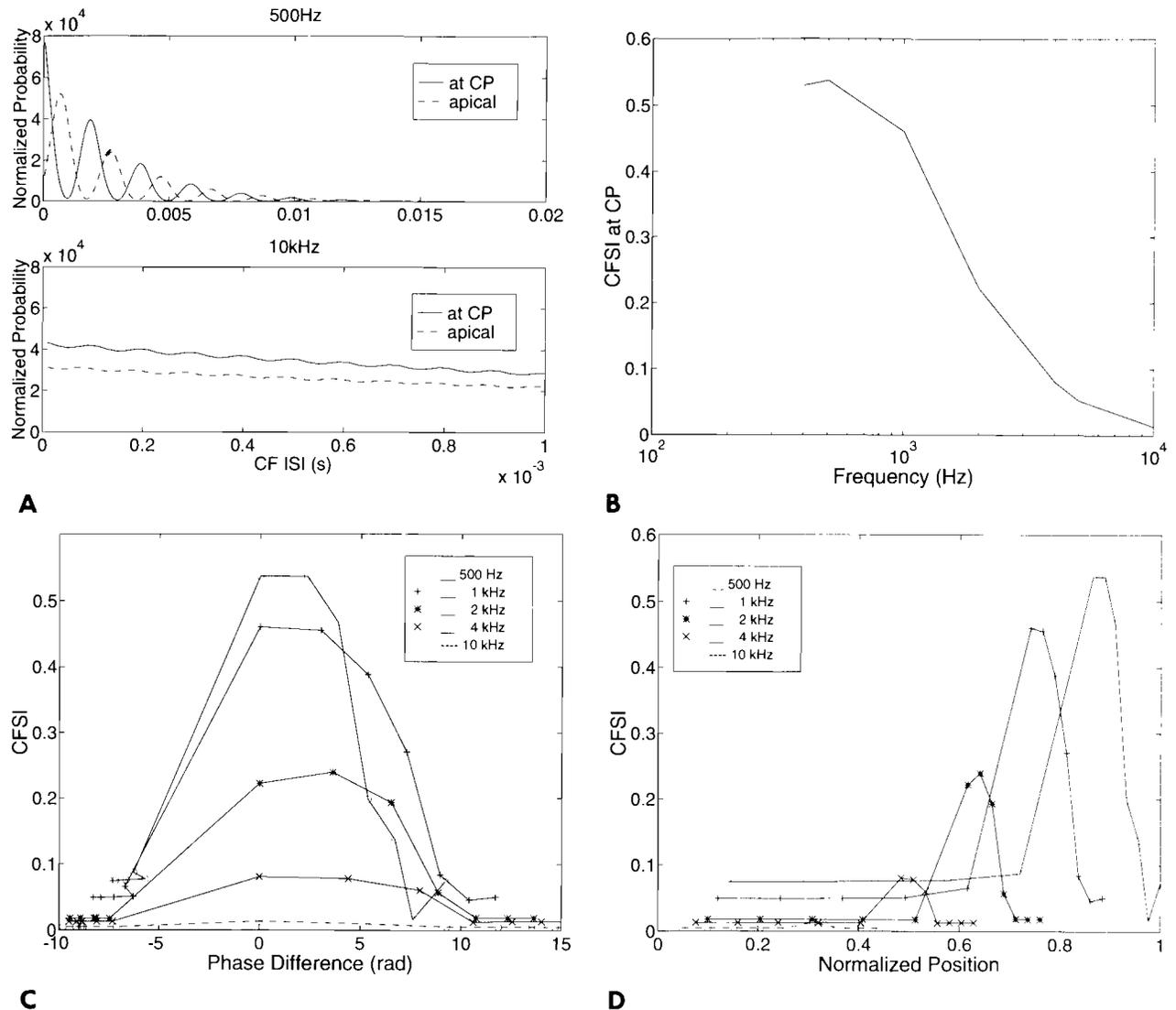
Fig 3. A) Cross-fiber interspike interval (CF ISI) probability distribution for 500 Hz and 10 kHz. B) Cross-fiber synchronization index (CFSI) at CP versus characteristic frequency. C) CFSI versus phase difference between fibers. rad — radians. D) CFSI versus normalized distance from stapes.

fewer cycles. In other words, the rate of decay of the probability with respect to the number of cycles between nerve spikes at 10 kHz is significantly lower than at 500 Hz. The phase locking between the fibers is also poor, as indicated by the low peak-to-trough ratio.

To obtain a measure for the synchronization between the fibers, we define the cross-fiber synchronization index (CFSI) as the quotient of the fundamental component of the Fourier transform of the CFISI distribution and the DC component. Figure 3B shows a plot of the CFSI against the input frequency with both fibers at the characteristic place. At low frequencies, the CFSI is high. But for frequencies above 1 kHz, the CFSI drops rapidly, reaching almost zero at 10 kHz. This suggests that temporal frequency coding across fibers may be limited to frequencies below 1 to 2 kHz.

The effect of the propagation delay of the traveling wave on the cross-fiber synchronization is also investigated. A plot of the CFSI against the phase difference between the fibers for

five frequencies from 500 Hz to 10 kHz is shown in Fig 3C. In this Figure, one fiber is fixed at the characteristic place and the other is moved from basal positions to apical positions. The results show that for all five frequencies, the CFSI is good only for phase differences smaller than 6 to 8 radians on the basal side and 8 to 10 radians on the apical side, suggesting that only fibers with a phase difference within this range can participate in cross-fiber temporal frequency coding.

To investigate the cross-fiber synchronization in the spatial domain, the CFSI is replotted against the normalized distance from the stapes, as shown in Fig 3D. It shows that the spread of fibers that are in synchrony is narrower in the basal region but wider in the apical region. This can be explained by the different slopes in the phase response of the basilar membrane in the basal and apical regions of the cochlea.

CONCLUSION

This computer modeling study shows that temporal fre-

quency coding can take place across fibers, but it can be affected by factors such as the frequency of the stimulus and the phase delay due to the traveling wave. The results for the CFSI show that temporal frequency may occur across fibers only for frequencies below 1 to 2 kHz and for phase differences smaller than 6 to 8 radians. Finally, the spread of fibers that may be involved in temporal frequency coding is smaller in the basal region than in the apical region. Further work will be required to extend the results of this study to a population of nerve fibers.

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