Toward fractal coding in auditory prostheses

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Abstract

Fractal-rate behavior is a ubiquitous and important aspect of normal mammalian cochlear-nerve activity, which may well be absent in nerve fibers excited by present cochlear prostheses. We propose simple methods for introducing fractal fluctuations into a cochlear prosthesis, thus providing the natural statistical character of eighth-nerve fiber spike trains.

Fractal behavior is ubiquitous in mammalian cochlear-nerve activity.[1] All single-unit recordings of sufficient length examined to date, in both the chinchilla[2] and the cat,[3] exhibit fractal fluctuations, as evidenced by a number of statistical measures. The periodogram and the relative variance of the number of counts, for example,[4] show that nonfractal models such as the refractoriness-modified Poisson process fail to give results that accord with the data. Rather, fractal models are required.[1–6]

One of the simplest statistics that shows the fractal nature of this activity is the rate. The rate of a particular cochlear-nerve fiber (CNF) may be estimated by dividing a neuronal recording into M equal, contiguous windows of duration T seconds each, and counting the number of action potentials N_k that fall within the k-th window for all k between 1 and M. The rate estimate $\widehat{\lambda_k}$ for the k-th window is then simply given by $\widehat{\lambda_k} = N_k/T$. Figure 1a displays the rate estimates obtained from a normal cat CNF (upper trace), from a fractal model which fits the data (middle trace), and from a nonfractal model (lower trace), using a counting time $T = 0.2$ sec for all plots. Figure 1b also displays these rates, but with $T = 2$ sec. One hallmark of fractals is that the rate contains statistical copies of itself. For the CNF data (and for the fractal model which fits it), increasing the counting time by a factor of ten (compare top traces of Figs 1a and 1b), which reveals activity on a larger time scale, only results in a small amplitude change. Such scaling behavior is a characteristic of fractals; the nonfractal model (compare lower traces of Figs 1a and 1b) appears smoother and qualitatively different for the longer time scale. Since a fractal model is required to fit the data for a number of statistical measures, we conclude that the rate is indeed fractal. This fractal behavior occurs in *all* afferent mammalian CNF neurons examined to date.

Such behavior almost certainly occurs in humans, where it likely plays a number of roles. First, fractal activity represents a type of memory at the periphery, with slow fluctuations in the firing rate existing over time periods ranging from seconds to hours. Second, fractal rates lie between those of white-noise processes (which have no memory) and Markov processes with long time constants (which do not readily respond to new input). They therefore represent a balance between response to novelty and memory of the past. Third, many natural sounds themselves are fractal, and thus fractal activity in the auditory system may represent a form of matching between the receiver and natural signals of interest. Finally, since this fractal behavior exists in all CNFs examined to date, it is no doubt something which higher auditory processing stages in the brain expect and upon which they presumably depend. Thus fractal behavior in CNFs is expected to serve a functional role in normal hearing.

Exocytosis of neurotransmitter at various types of synapses has fractal properties,[7] so that fractal behavior in an afferent CNF likely arises at the inner hair cell. It is therefore likely to be absent when a CNF is stimulated by an electrical signal originating in a cochlear implant.

It may therefore well be useful to impart fractal fluctuations to the signals generated by a cochlear implant. Gstöttner *et al.*[8] performed preliminary work in this area by injecting a fractal electrical waveform (rather than an auditory signal) into the electrodes of a cochlear prosthesis. Conventional prostheses, of course, use auditory signals without an added fractal component. We propose to add fractal current fluctuations to the current produced by the prosthesis in response to an auditory stimulus. Figure 2a displays an example of a synthetic current waveform both without (upper trace) and with (lower trace) a fractal rate. (The results are similar for currents generated in response to natural auditory waveforms.) The same traces are shown in Fig 2b at a longer time scale. Over the short time scale, the two waveforms look much the same, showing that the fractal fluctuations will not interfere with the regular operation of a prosthesis. Over the longer time scale, the effect of the fractal rate becomes apparent, although it still has a much smaller magnitude than that due to the auditory signal. Further improvements will include providing a different fractal signal to each channel, since each hair cell has a different activity pattern. Finally, there is some evidence that the auditory signal and fractal rate may be multiplied rather than added in the normal cochlea, so amplitude and frequency modulation of the auditory signal by the fractal rate should also be evaluated.

References

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Legends for Illustrations

FIGURE 1a) Rate functions computed for afferent CNF data (upper trace), for a fractal model (middle trace), and for a nonfractal model (lower trace). Window size is $T = 0.2$ sec for all three plots. The mean rate for all three traces is 109 sec^{-1}, and the vertical extent of the graph corresponds to a difference of 310 sec^{-1}. All three models yield similar results, although results of the nonfractal model appear to lack fluctuations over several adjacent windows.
b) Rate functions computed for afferent CNF data (upper trace), for a fractal model (middle trace), and for a nonfractal model (lower trace). Window size is $T = 2$ sec for all three plots. The mean rate for all three traces is 109 sec^{-1}, and the vertical extent of the graph corresponds to a difference of 170 sec^{-1}. The fractal model agrees well with the data, showing substantial fluctuations over several windows. The nonfractal model, in contrast, is more smooth, with an absence of such fluctuations.
FIGURE 2a) Synthetic current waveforms without added fractal noise (upper trace), and with added fractal noise (lower trace). Over this time scale, the two traces do not differ appreciably, illustrating that adding fractal noise should not interfere with the normal operation of a cochlear implant.
b) Synthetic current waveforms without added fractal noise (upper trace), and with added fractal noise (lower trace). Over this longer time scale, the difference between the two waveforms becomes apparent. Although still smaller than the auditory waveform, the fractal component is sufficient to model normal CNF behavior.

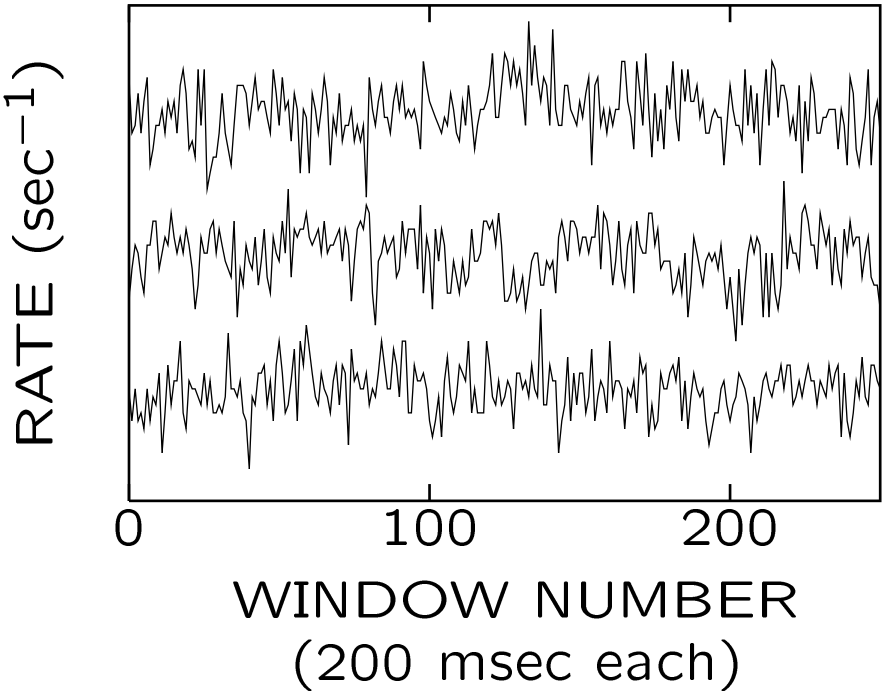

Fig. 1a

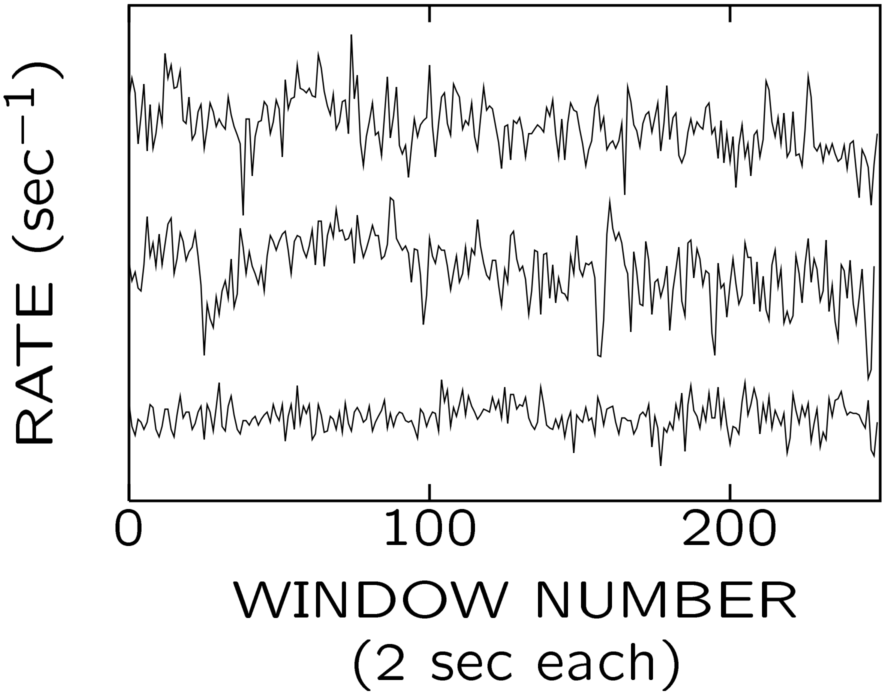

Fig. 1b

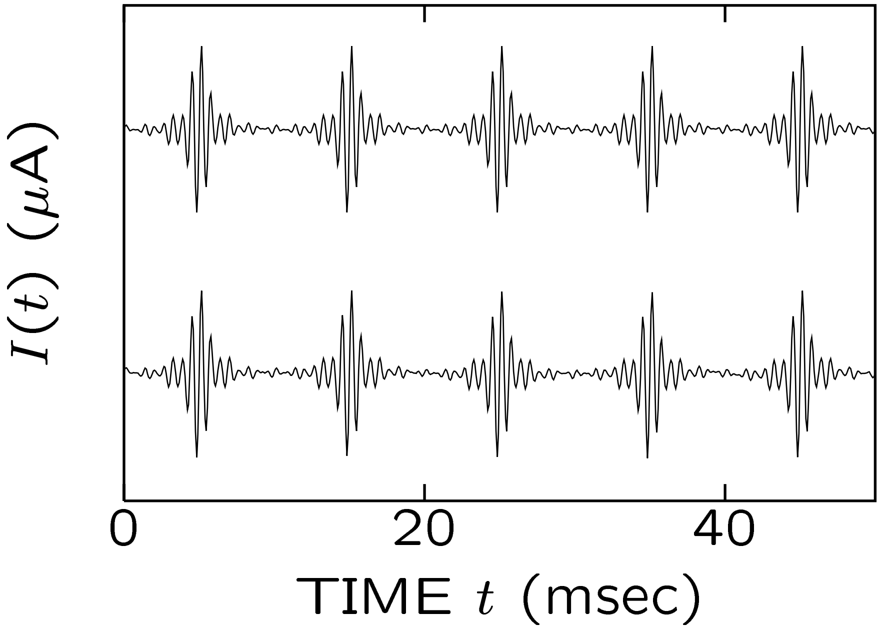

Fig. 2a

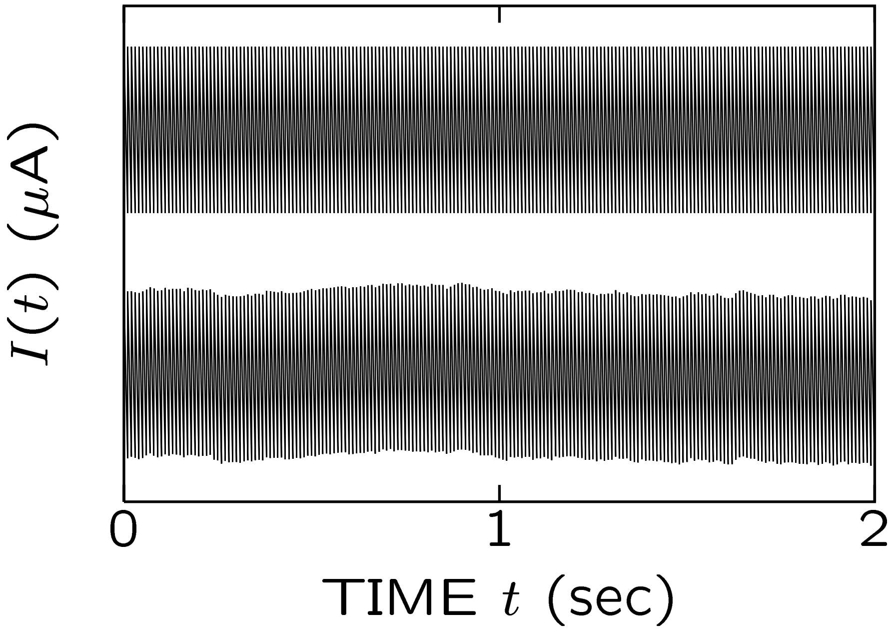

Fig. 2b