Auditory coding mechanisms

by

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One of the first things one should do when trying to understand the origin of tinnitus (TI) is to take a look at signal transmission in the auditory system in general and at the coding mechanisms in particular.

The reader is presumed to be familiar with the general anatomy of the auditory system, both its afferent and efferent portions. As has been pointed out repeatedly before (Davis, 1961; Tonndorf, 1975), the energy traveling in the mechanical domain up to the level of the hair cells is mechano-acoustic in nature and that traveling in the neural domain beyond that point is chemo-electric energy in nature and supplied by internal sources. The transition between the two forms of energy takes place at the level of the hair cell/nerve fiber junction. It should be further pointed out that our understanding of the events evoked is good in the mechanical domain, including cochlear mechanics, less good at the level of the mechano-neural transformation and least in the neural domain. This is mainly due to the fact that, while there are good man-made 'models' for the mechanical events, there are only very few for those taking place within the neural domain that could aid our understanding of the underlying processes.

In the mechanical domain, transmission is governed by the laws and rules of Acoustics, i.e., Physics. On reaching the cochlea, signal frequencies, or their components in the case of complex signals, are spatially distributed along the cochlear partition, high frequencies at the cochlear base and, with the lowering of frequency, systematically more and more toward the cochlear apex.

This space/frequency distribution is caused by the traveling-wave mechanism discovered by Békésy (1928). It represents the first (mechanical) part of cochlear coding, and may be referred to as Place Coding.

We must now discuss the mechano-neural coding that is given by the events associated with signal transformation at the hair cell/nerve fiber junction. As first described by Davis (1961) and amply confirmed in all details since, an acoustic signal generates an electric, pre-synaptic (receptor) potential within those hair cells that happen to be located at and around the place of maximal mechanical stimulation by the signal frequency in question. Next, the hair cell, through the induced activity of its pre-synaptic rod and vesicles located at the bottom of the cell, releases a chemical neurotransmitter that travels across the synaptic gap to elicit a post-synaptic potential in the attached afferent dendrite. This latter potential is also known as the generator potential for it triggers the characteristic neural discharges, the action potentials (AP), the only ones capable of traveling along the nerve fiber. At each higher synapse, a similar triad of reception, chemical transmission and generation of new APs repeats itself.

Hair cells when stimulated produce two electric potentials, one of them an ac potential that is synchronized with the signal received and the other a dc potential. Since both potentials spill over into the cochlear fluids, they were first

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recorded extra-cellularly, the cochlear microphonic (CM) (Wever and Bray, 1930) and the summating potential (SP) (Davis *et al.*, 1950). Recording of the potentials from inside single hair cells, a much more difficult task, was only achieved in recent years (Russel and Sellick, 1977). Hair cells contain mitochondria, the energy storage sites of cells, in rather large quantities, mainly at their top, where the signal comes in, and at the bottom, where the neurotransmitter is released.

One, still hypothetical, way of presenting the events going on inside a given hair cell on acoustic stimulation is as follows: By excitation of their hair-bearing ends, the content of the hair cell is being vibrated and this in turn leads to conformational molecular changes that are synchronized with the signal. The input into the cell may conceivably be aided by the contractile action of actin that is present in the hairs and in the cuticular plate, in which the hairs are implanted (Flock, 1980). According to this view, the CM and SP would simply be the electric counterparts of the biochemical events. Such a mechanism could well account for the extremely high sensitivity of hair cells to mechanical stimulation (Neumann, 1982). If and when this hypothesis is proven the dividing line between the mechanical domain and the neural one will become somewhat uncertain.

There are currently four different hypotheses about the specific chemical nature of the cochlear neurotransmitter (Békésy, 1928). The only thing that is certain is that there is indeed a neurotransmitter and that it is chemical in nature. The transmitter, once released, is probably received at specific receptor sites of the dendrites, where it just 'fits'. The agent may either be de-activated within the dendrite or returned to the hair cell, where it would be re-incorporated in a pre-synaptic vesicle for repeated future use. If the latter notion is correct this would represent an excellent economic measure.

Each cochlear nerve fiber responds only to a narrow band of frequencies—it is sharply tuned—but this specific tuning is actually due to the mechanical tuning of the place along the cochlear partition it is connected to (Kiang *et al.*, 1965).

In the entire process, but only at frequencies below 3–4 kHz, the incoming acoustic 'analog' signals are converted into 'digital' signals. If the signal is complex, there will be a number of parallel series that are spatially distributed in many fibers, depending on their frequency content. These signals are somewhat 'noisy', mainly due to the spontaneous activity of the nerve fibers.

This 'digital' coding represents the second part of signal coding. It is called 'periodicity' coding, as the periodicity of the original acoustic signal is preserved, although only for frequencies below 3–4 kHz.

Regularly-repeated brief signals reveal a characteristic property of nerve-fiber responses: their frequency of occurrence with time after the signal adapts fast in an exponential way, approaching a lower level in an asymptotic manner (Kiang *et al.*, 1965).

Whereas the acoustic properties of the original signal are quite well preserved for frequencies below 3–4 kHz, as was just stated, beyond that limit nerve fibers do not fire periodically anymore, but completely at random. This is so because the controlling receptor potential is no longer the ac (CM) component, but rather the dc (SP) component. There is simply no periodic input signal the nerve response could synchronize with.

Starting at the cochlear nucleus, coding becomes more complicated. There are no longer any easily-recognizable 'digital' responses. Four kinds may be distinguished, each of them associated with distinct cell types (Pfeiffer, 1966): 1. 'primary-like', but it is only the random kind seen in the cochlear nerve in response to high-frequency stimulation; 2. 'pausers', in which the random activity starts only after a pause, following a sharp onset event; 3. 'choppers', i.e., groups of responses with breaks in between; however, their repetition rate is not at all related to the frequency of

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the acoustic signal; and 4. 'on-responders', i.e., there is no further induced activity after a sharply limited onset response. (These four terms were originally coined by Pfeiffer (1966), who first described and classed the responses.) All but the 'primary-like' responders show relatively broad tuning, indicating that they respond to wider groups of cochlear-nerve fibers, tuned to different, but still rather closely related, frequencies. Except that all four kinds are associated with distinct cell types, as was already stated, there is as yet no convincing explanation of their coding significance for further transmission, except timing in the case of the 'on-responders'.

One property, however, stands out: the frequency/space distribution that was so distinct in the mechanical cochlear domain and in the cochlear-nerve responses is preserved at all higher levels, including the cortex. Obviously, place is an important clue for frequency recognition, especially for that of high frequencies.

The phase of the responses at the various levels is determined by three components: 1. that of the mechanical travel delay along the cochlear partition; at all levels, therefore, the phase delay of low frequencies is consistently larger than that of high frequencies; 2. the synaptic delay from one neuron to the next following one; 3. some additional delay representing the travel time along a given fiber; however, since the latter is rather fast, the travel-time delay usually cannot be separated from the synaptic delay, which is much larger. It can only be recognized under exceptional circumstances.

The efferent system, anatomically, is an exact duplicate of the afferent system. Although in anesthetized preparations it exercises a control over the cochlear output into the nerve fibers, not unlike that of a governor on a piece of machinery, in awake and unrestrained animals its action is more subtle, having to do with masking and the signal/noise ratio, and also with frequency discrimination (Trahotis and Elliott, 1970).

When the cochlea is missing and an electrical input is employed with the aid of a cochlear prosthesis, no place coding is achieved at the present state of the art. Periodicity coding is apparently maintained up to about 600 Hz, since there is some recognition of lower pitches on the part of the subject. Nevertheless, place coding is needed, especially at higher frequencies, 600 Hz being in the lower part of the speech frequency spectrum. Its absence is currently one of the major shortcomings of cochlear prostheses.

Finally, a few remarks about TI: It is known to originate at all levels of the auditory system. 1. Those kinds generated in the mechanical domain (muscular and vascular noises) are often called 'objective', since a bystander is able to hear them with the aid of an auscultation tube, and sometimes even without it. Their mode of origin is clear. 2. With respect to the kinds that are generated at the cochlear level, the present author (Tonndorf, 1981) recently suggested a potential mechanism: noises—broad or narrow bands, depending on the extent of the lesion—ought to be generated when the hair cells are partially decoupled from the tectorial membrane due to ciliary pathology or dysfunction, both of which have been observed. Conceivably, however, there may be other, additional mechanisms as the paper by Tyler in the present volume will suggest. 3. Least is known, understandably, about the modes of origin of TI in the neural domain, at least not enough to present a coherent hypothesis. It has been suggested (cf. Eggermont in the current volume) that the rates of spontaneous discharges, in the cochlear nerve for example, may increase to the point that they might then represent a 'signal' for the higher auditory centers. (This notion was first presented by H. Davis several decades ago.) Another possibility, likewise discussed by Eggermont, would be that the random firings in nerve fibers are being arranged in a regular, periodic manner so that, again, they may be recognized as 'signals' by the higher auditory centers. Shulman, also in the present volume, will present his observations about the desynchronization

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of evoked brainstem potentials by an interfering TI. However, all of these latter three hypotheses present only signs of, but not the ultimate causes of, TI. Whether or not the efferent system may also be involved in the generation of TI, although it is conceivable, is not clear at the time of this writing. No tangible suggestions in this regard have been put forward.

At the end, let me express the hope that this brief overview might be helpful for the thinking about the phenomena that are observed clinically.

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Note: This bibliography is highly selective. Further references may be found in the articles cited and in the Handbook of Sensory Physiology, Auditory System (Keidel, W. D. & Neff, W. D. eds), Springer, Berlin, 1975.

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