References and Notes

1. J. D. Anderson, W. A. Gillespie, M. H. Richmond, *J. Med. Microbiol.* **6**, 461 (1973); J. D. Anderson, L. C. Ingram, M. H. Richmond, B. Wiedeman, *ibid*, p. 475.
2. R. P. Novick and S. I. Morse, *J. Exp. Med.* **125**, 45 (1967).
3. E. Ottolenghi and C. M. MacLeod, *Proc. Natl. Acad. Sci. U.S.A.* **50**, 417 (1963).
4. J. E. Conant and W. D. Sawyer, *J. Bacteriol.* **93**, 1869 (1967).
5. J. B. Graham and C. A. Istock, *Mol. Gen. Genet.*, **16**, 287 (1978).
6. F. E. Young and G. A. Wilson, in *Spores VI*, P. Gerhardt, R. N. Costilow, H. L. Sadoff, Eds. (American Society for Microbiology, Washington, D.C., 1975), pp. 596–614.
7. S. Borenstein and E. Ephrati-Elizur, *J. Mol. Biol.* **45**, 137 (1969).
8. R. J. Erickson, *Curr. Top. Microbiol. Immunol.* **53**, 149 (1970).
9. H. Saito and K. Miura, *Biochim. Biophys. Acta* **72**, 1619 (1963).
10. S. Siegal, *Nonparametric Statistics for the Behavioral Sciences* (McGraw-Hill, New York, 1956), pp. 166–173.
11. S. Wright, *Proceeding of the Sixth International Congress of Genetics* **1**, 356 (1932); in *Evolution and the Genetics of Populations* (Univ. of Chicago Press, Chicago, 1977), vol. 3, pp. 443–473.

12. We thank Professors F. Young, E. Caspari, U. Nur, S. Graham, G. Wilson, S. Hattman, K. Bott, and G. O'Donovan for discussion. Supported by NIH predoctoral traineeship to J.B.G. and NSF grants DEB-02578 and DEB-7724615 to C.A.I.

5 October 1978; revised 15 December 1978

Tectorial Membrane: A Possible Effect on Frequency Analysis in the Cochlea

Abstract. *Mathematical analysis and computer and network simulations of the cochlea show that, given appropriate values of specific physical constants, radial shear motion between the tectorial membrane and the reticular lamina may provide the sharpening of frequency analysis observed in cochlear nerve fibers in comparison with the mechanical amplitude distribution on the basilar membrane. According to the analysis, the sharpening occurs through an interaction of the longitudinal mechanical propagation constant of the tectorial membrane with the wavelength on the basilar membrane.*

On the basis of model investigations, Békésy (*1*) suggested that a coarse mechanical frequency analysis in the cochlea of the inner ear is sharpened by neural processes. More recent experiments confirm that neural tuning curves derived from the responses of cochlear nerve fibers are considerably sharper than corresponding mechanical filter curves measured on the basilar membrane (BM) of the cochlea (*2, 3*). Békésy's hypothesis in connection with these and related findings induced one of us (*4*) to suggest a specific neural sharpening mechanism. However, the suggestion has been invalidated by recent recordings from cochlear inner hair cells, which revealed that their receptor potentials as well as their impedance changes are as sharply tuned as the nerve fiber responses (*5*). This seems to restrict the possible sharpening mechanisms to mechanical ones acting either directly on the inner hair cells or distally to them. Although some such mechanisms have been suggested in the past (*6, 7, 8*), they are either difficult to reconcile with the currently available empirical information, are based on misconceptions, or lack plausible physical implementations. As a consequence, we attempted to look again at cochlear micromechanics. Somewhat unexpectedly, we saw a potential mechanism so obvious after the fact that it is difficult to understand how it could have remained undiscovered until now.

It is generally accepted that cochlear hair cells, like similar mechanoreceptors of the vestibular and lateral line systems, are excited by the deflection of their stereocilia toward their kinocilia or basal bodies (*9*). In the cochlea, this means a deflection in an approximately radial direction, away from the spiral bony lamina. In view of the observed mode of BM motion (*10*) and the structural relationships within the scala media, such a deflection is expected to occur during BM displacement toward the scala vestibuli (*11*). For the outer hair cells, the deflection must result from radial shear motion between the reticular lamina (RL), in which the cells are embedded, and the tectorial membrane (TM) to which their stereocilia are attached (*12*). Evidence for a similar attachment of the stereocilia of the inner hair cells is controversial but does not appear to be essential since the endolymph in the narrow gap between TM and RL must participate in the shear motion and entrain the stereocilia. In this respect it should be noted that the stereocilia are interconnected (*13*) so that the endolymph should not be able to move freely among them. Whether maximum excitation of the inner hair cells occurs during maximum BM velocity or displacement (*14, 15, 16*) is not crucial for the following analysis, however.

If the excitation of the hair cells is proportional to radial shear motion between the RL and TM, it must follow essentially the same distribution along the cochlea as the shear motion does. The latter must depend on the radial components of the mechanical coupling of the part of the TM overlying the hair cells to the organ of Corti and to the spiral limbus. If this part were tightly coupled to the organ of Corti and loosely to the spiral limbus, for instance, it would move together with the RL and no shear motion would occur. We show that, in addition, the shear motion must depend on the longitudinal coupling within the TM and on the wavelength on the BM. The situation is illustrated in Fig. 1. In agreement with anatomical evidence, the TM is assumed to be attached to the organ of Corti, most strongly at its outer margin and at the three or four rows of the outer hair cells and more weakly at the Hensen's stripe and the inner hair cells (*17, 18*). Near the basal end of the cochlea, the wavelength is the longest, and the phase of BM motion changes slowly with distance. Accordingly, the TM is driven in the same radial direction over a substantial length and should be maximally entrained. Thereby the radial shear motion between the TM and the RL should be minimized. As the wavelength becomes shorter toward the vibration maximum of the BM, the radial force on the TM rapidly changes direction with distance, and its effect should be partially nullified by the averaging effect of the longitudinal coupling within the TM. This averaging effect should minimize the radial TM motion and maximize the radial shear motion. The mechanism of enhancing the shear motion in regions of short wavelengths can be approximated analytically in terms of the mechanical analog shown in Fig. 1B. The longitudinal coupling in the TM per unit length is represented by the mechanical admittance $\mathbf{Y}_1$; $\mathbf{Z}_2$ is the mechanical impedance per unit length of the attachment to the organ of Corti, and $\mathbf{Z}_3$ the impedance of the corresponding coupling to the spiral limbus. $\mathbf{Y}_1$, $\mathbf{Z}_2$, and $\mathbf{Z}_3$ are assumed to apply to the radial components of motion of the TM and RL. Morphological appearance as well as static measurements (*10*) suggest that, outside the compliance of the BM, the mechanical elements are either constant throughout the cochlear length or vary slowly by comparison with the longitudinal space constant of the TM, so that their longitudinal space derivatives can be neglected. Since the purpose of this report is to demonstrate a principle rather than to describe the exact conditions in the cochlea, we assume for simplicity that the mass of the TM is negligible and that all the impedances, $1/\mathbf{Y}_1$, $\mathbf{Z}_2$, and $\mathbf{Z}_3$, reflect similar viscoelastic

0036-8075/79/0511-0639$00.50/0

properties so that, although their magnitudes may differ, their angles are approximately the same. The structure (*17, 18*) and mechanical properties (*10*) of the TM as well as of the stereocilia (*13*) suggest that such assumptions may not be far from the truth. We note, however, that their partial relaxation does not abolish the mechanism under consideration and can introduce additional effects that further enhance the cochlear frequency analysis. We assume further that the impedances $\mathbf{Z}_2$ and $\mathbf{Z}_3$ and the admittance $\mathbf{Y}_1$ are independent of amplitude, and we neglect the bending moments within the TM. Some nonlinear effects are mentioned at the end of the report. Judging from Békésy's (*10*) description of the mechanical properties of the TM, the bending moments are unlikely to be important. In any event, they would not affect the fundamental process under consideration.

The mechanical network of Fig. 1B implies that the TM with its attachments is equivalent to a transmission line having a propagation constant $\gamma = (\mathbf{Y}_1\mathbf{Z}_{23})^{1/2}$, with $\mathbf{Z}_{23} = \mathbf{Z}_2 + \mathbf{Z}_3$. Since the impedance angles are assumed to be the same, the propagation constant is real and equal to the space constant, $\gamma = \alpha$. A purely real propagation constant means that the motion of the TM produced at one location decays exponentially along the membrane without phase lag. Thus, a radial RL motion $\dot{\eta}_R(\xi, t_0)$ at location ξ and time t_0 contributes at location x a TM motion $d\dot{\eta}_T(x, t_0) = K\dot{\eta}_R(\xi, t_0) \exp(-\alpha|x - \xi|)d\xi$, where K is to be determined from the impedances. The total motion at location x can be found by integrating over ξ, which gives

$$\dot{\eta}_T(x, t_0) = K\int_0^x \dot{\eta}_R(\xi, t_0) \exp[-\alpha(x - \xi)] \cdot d\xi + K\int_x^\ell \dot{\eta}_R(\xi, t_0) \exp[-\alpha(\xi - x)] \cdot d\xi$$

where ℓ is the length of the TM. The integrals may be evaluated numerically for any reasonable function $\dot{\eta}_R(\xi, t_0)$. For our first-order simulation, we assumed that the radial motion of the RL, $\dot{\eta}_R(\xi, t_0)$, is directly proportional to BM motion perpendicular to its resting position. This is reasonable for vibration amplitudes within normal physiological range.

When the wavelength along the basilar membrane, λ_B, is much greater than the space constant α of the TM, the function $\dot{\eta}_R(\xi, t_0)$ may be approximated by a constant $\dot{\eta}_{RC}(t_0)$. Under such conditions the integration yields $\dot{\eta}_{TC}(t_0) = 2K\dot{\eta}_{RC}(t_0)/\alpha$, except near $x = 0$ and $x = \ell$, and the longitudinal symmetry of the structure dictates that $\dot{\eta}_{TC}(t_0) = \dot{\eta}_{RC}(t_0)\mathbf{Z}_2/(\mathbf{Z}_2 + \mathbf{Z}_3)$, so that $K = \alpha\mathbf{Z}_2/2(\mathbf{Z}_2 + \mathbf{Z}_3)$. When $\mathbf{Z}_2 \gg \mathbf{Z}_3$, $K \simeq \alpha/2$ and $\dot{\eta}_{TC}(t_0) \simeq \dot{\eta}_{RC}(t_0)$. This means that, for a negligible mass and a substantially stronger coupling of the part of the TM overlying the hair cells to the organ of Corti than to the spiral limbus, the radial motion of the TM becomes nearly equal to that of the RL. As a result, the shear motion between the RL and the TM approaches 0, and stimulation of the hair cells is minimized. When $\lambda_B \ll 1/\alpha$, the radial motion of the TM tends toward 0. This result can be demonstrated by taking the convolution integrals over one wavelength, since $\exp(-\alpha|x - \xi|) \simeq \exp[-\alpha(|x - \xi| + \lambda_B)]$. If, over one wavelength, the wave pattern can be approximated by a sinusoid, the integrals nearly vanish. When the radial motion of the TM is minimum, the shear motion between it and the RL is maximized. In the cochlea, the wavelength decreases from the base to somewhat beyond the vibration maximum of the BM, then almost suddenly becomes infinite as the BM resonance is passed (*19, 20*). Accordingly, the derived effect of the wavelength on the shear motion is capable of sharpening the spatial distribution of hair-cell stimulation.

The observed mode of BM motion (*10*) suggests that the radial motion of the RL is not constant but decreases from the outer hair cells toward the spiral lamina, being intermediate at the inner hair cells. Because of its coupling to the organ of Corti in the vicinity of the outer hair cells on one side and to the stationary limbus on the other, the TM should exhibit a similar but not necessarily identical gradient of radial motion. If we denote the motions of the RL and TM in the vicinity of the outer hair cells by $\dot{\eta}_R$ and $\dot{\eta}_T$ and, in the vicinity of the inner hair cells, by $C_R\dot{\eta}_R$ and $C_T\dot{\eta}_T$ (C_R, $C_T < 1$), the resultant shear motion at the level of the inner hair cells R will be $\dot{\eta}_{SI} = C_R\dot{\eta}_R - C_T\dot{\eta}_T$. If

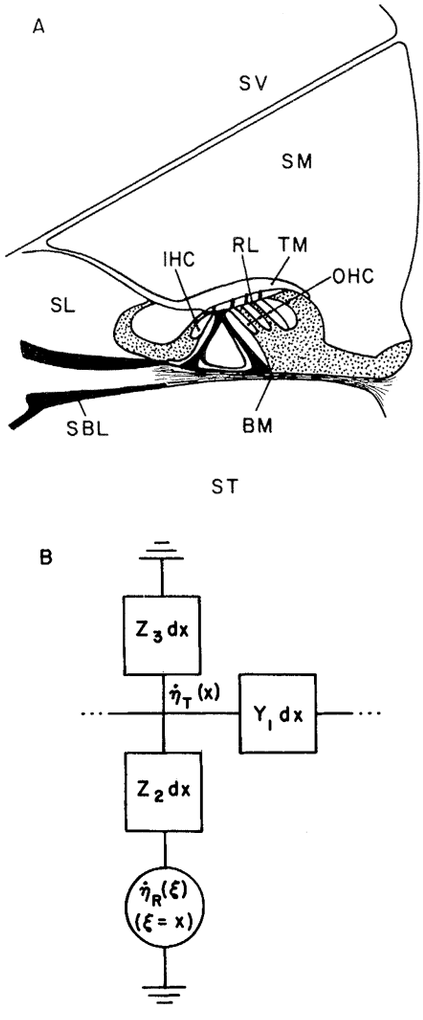

Fig. 1. (A) Schematized cross section through the organ of Corti and associated structures. (B) A network model of the tectorial membrane with its attachments. Abbreviations: *BM*, basilar membrane; *IHC*, inner hair cells; *OHC*, outer hair cells; *RL*, reticular lamina; SBL, spiral bony lamina; SL, spiral limbus; *SM*, scala media; *ST*, scala tympani; *SV*, scala vestibuli; *TM*, tectorial membrane; $\dot{\eta}_R$ and $\dot{\eta}_T(x)$, radial velocities of the reticular lamina and tectorial membrane, respectively; $\mathbf{Y}_1dx$, mechanical admittance of the longitudinal coupling within the tectorial membrane per length element; and $\mathbf{Z}_2\,dx$ and $\mathbf{Z}_3dx$, mechanical impedances of tectorial membrane attachments to the organ of Corti and to the limbus.

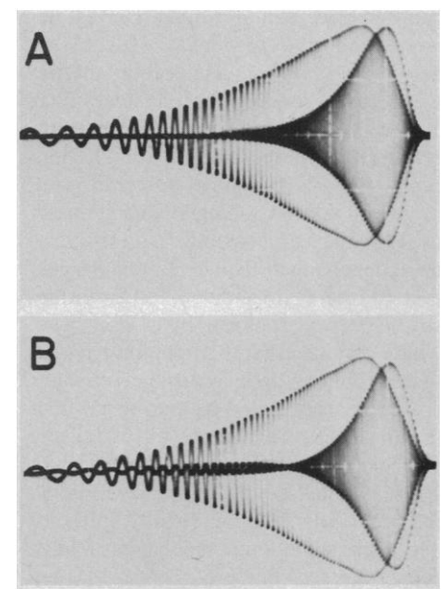

Fig. 2. Analog voltage amplitudes of BM displacement (broad maximum) and of shear motion between the RL and the TM at one point of a cochlear network analog as a function of frequency. The periods of the oscillations are proportional to the frequency and to the constant sweep speed. The amplitudes have been normalized to have approximately equal maxima. (A) The ratio C_T/C_R was chosen to minimize the analog shear motion at low frequencies. (B) The ratio was increased somewhat to show the phase reversal of the shear motion at low frequencies.

$\dot{\eta}_T \simeq \dot{\eta}_R$ for long waves, the shear motion becomes $\dot{\eta}_{SI} \simeq \dot{\eta}_R(C_R - C_T)$. Depending on whether $C_T = C_R$, $C_T < C_R$ or $C_T > C_R$, the shear motion may vanish, be in phase, or in phase opposition with the motion of the RL. In the last case, maximum excitation of the inner hair cells and of the primary neurons ending on them should occur during the displacement of the BM toward scala tympani. Such phase reversals occurred systematically in Mongolian gerbils (*15, 16*).

We modeled the shear motion at the inner hair cells, through the use of both digital and analog simulation. In the latter, an electrical network was constructed for the TM on the basis of electromechanical analogies of the second kind ($V_R \rightarrow \dot{\eta}_R$, $Z_{electrical} \rightarrow Y_{mechanical}$) and connected to a network analog of the cochlea (*21*). The results obtained for one point along the cochlea as a function of log frequency are shown in Fig. 2 by means of oscilloscopic traces. The trace with the broad envelope corresponds to the amplitude of the BM, and that with the narrow envelope, to the amplitude of the shear motion. The maximum is sharpened toward both low and high frequencies, in qualitative agreement with the tuning curves obtained on mammalian cochlear nerve fibers. A direct quantitative comparison of a model tuning curve and an average neural tuning curve is shown elsewhere (*22*). In Fig. 2A the ratio of constants C_T/C_R was so chosen as to make the model shear motion practically disappear at low frequencies; in Fig. 2B the ratio was slightly increased to show the phase reversal at these frequencies. The reversal can be seen by comparing the oscillation phases of the two traces. The phase reversal is accompanied by a minimum in the model shear motion below the main maximum. The minimum may correspond to a notch sometimes observed in neural tuning curves below the characteristic frequency (*23*).

Only experiments can determine whether sharpening of cochlear frequency analysis involves the mechanism we have described. What our model results demonstrate is the availability of such a mechanism, given appropriate physical constants. The results are in agreement with the recordings of receptor potentials and transmembrane impedance changes in the inner hair cells (*5*). Furthermore, they are consistent with response phases observed in the cochlear nerve at low sound frequencies (*15, 16*) and with an earlier conclusion that these phases arise from an interaction of two components that nearly cancel each other (*4*). The linear mechanism described does not replicate the well-known nonlinear phenomena in the cochlea, however, especially the phenomenon of two-tone suppression (*24*). In preliminary experiments we have demonstrated that two-tone suppression is produced in our model when the model coupling between the organ of Corti and the TM is made to increase with the magnitude of the shear motion. Such an increase appears plausible in a mechanical system.

J. J. ZWISLOCKI
E. J. KLETSKY

Institute for Sensory Research,
Syracuse University,
Syracuse, New York 13210

References and Notes

1. G. v. Békésy, *Phys. Z.* **29**, 973 (1928).
2. E. F. Evans and J. P. Wilson, in *Basic Mechanisms in Hearing*, A. R. Møller, Ed. (Academic Press, New York, 1973), p. 519.
3. C. D. Geisler, W. S. Rhode, D. T. Kennedy, *J. Neurophysiol.* **37**, 1156 (1974).
4. J. J. Zwislocki, *Acustica* **31**, 354 (1974).
5. I. J. Russell and P. M. Sellick, in *Psychophysics and Physiology of Hearing*, E. F. Evans and J. P. Wilson, Eds. (Academic Press, New York, 1977), p. 71.
6. W. H. Huggins and J. C. R. Lickleider, *J. Acoust. Soc. Am.* **23**, 290 (1951).
7. J. Tonndorf, *ibid.* **32**, 238 (1960).
8. J. B. Allen, *ibid.* **62**, 930 (1977).
9. Å. Flock, in *Handbook of Sensory Physiology*, vol. 1, *Principles of Receptor Physiology*, W. R. Loewenstein, Ed. (Springer-Verlag, New York, 1971), p. 396.
10. G. v. Békésy, *Experiments in Hearing* (McGraw-Hill, New York, 1960).
11. H. Davis, in *Physiological Triggers and Discontinuous Rate Processes*, T. H. Bullock, Ed. (American Physiological Society, Washington, D.C., 1956), p. 60.
12. R. S. Kimura, *Acta Oto-Laryngol.* **61**, 55 (1966).
13. Å. Flock, in *Psychophysics and Physiology of Hearing*, E. F. Evans and J. P. Wilson, Eds. (Academic Press, New York, 1977), p. 15.
14. P. Dallos, M. C. Billone, J. D. Durrant, C.-y. Wang, S. Raynor, *Science* **177**, 356 (1972).
15. J. J. Zwislocki and W. G. Sokolich, in *Facts and Models in Hearing*, E. Zwicker and E. Terhardt, Eds. (Springer-Verlag, New York, 1974), pp. 107-117.
16. W. G. Sokolich, R. P. Hamernik, J. J. Zwislocki, R. A. Schmiedt, *J. Acoust. Soc. Am.* **59**, 963 (1976).
17. A. C. Hilding, *Ann. Otol. Rhinol. Laryngol.* **61**, 354 (1952).
18. D. J. Lim, *Arch. Otolaryngol.* **96**, 199 (1972).
19. J. Zwislocki-Moscicki, *Acta Oto-Laryngol. Suppl.* 72 (1948).
20. W. S. Rhode, *J. Acoust. Soc. Am.* **49**, 1218 (1971).
21. J. J. Zwislocki, in *Physiology of the Auditory System*, M. B. Sachs, Ed. (National Educational Consultants, Baltimore, 1971), p. 45; *ibid.*, p. 80.
22. J. J. Zwislocki, *Acta Oto-Laryngol.*, in press.
23. N. Y. S. Kiang, M. C. Liberman, R. T. Levine, *Trans. Am. Otol. Soc.* **64**, 79 (1976).
24. M. B. Sachs, *J. Acoust. Soc. Am.* **45**, 1025 (1969).
25. Supported by grant NS-03950 from the National Institute of Health.

6 July 1978; revised 18 January 1979

Hippocampal Afterdischarges: Differential Spread of Activity Shown by the [^{14}C]Deoxyglucose Technique

Abstract. *Differential spread of afterdischarge activity initiated electrically in ventral and dorsal parts of the hippocampal formation was studied by the* [^{14}C]*deoxyglucose technique in rats. Afterdischarges initiated in either the ventral or dorsal hippocampal formation, without activation of the ventral subicular cortex, increased glucose utilization in the lateral septum. In contrast, afterdischarges initiated by direct activation of the ventral subicular cortex increased glucose utilization in extensive areas of the ipsilateral amygdala, claustrum, hypothalamus, preoptic region, and basal forebrain.*

The hippocampal formation (*1*) has been implicated in various functions including memory, spatial orientation, and the neuroendocrine control of specific hormones (*2*). It is also the structure most frequently showing pathology in patients with temporal lobe epilepsy (*3*). Related to this finding is its extremely low threshold to electrical stimulation for eliciting afterdischarges (AD's), paroxysmal bursts of intense activity involving the synchronous firing of many neurons.

MacLean's suggestion in 1949 (*4*) of functional differences between ventral and dorsal hippocampal formation has been supported by a growing body of anatomical (*5, 6*) and physiological (*7, 8*) evidence showing significant differences in the projections of ventral and dorsal parts of the hippocampal formation. Recently, a unit study in the awake primate demonstrated that while the dorsal hippocampus projects almost exclusively via the fornix system, the ventral hippocampus influences hypothalamic and basal forebrain nuclei primarily via nonfornix pathways (*8*).

It seemed appropriate to study these differential projections by using the [^{14}C]deoxyglucose (DG) technique, developed by Sokoloff and colleagues (*9, 10*), to metabolically map the spread of AD's electrically initiated in the ventral and dorsal hippocampal formation. Our results show markedly increased metabolic activity throughout the amygdala, hypothalamus, preoptic region, and basal forebrain associated with hippocampal AD's only when there is direct activation of the ventral subicular cortex (*1*). In contrast, hippocampal AD's initiated in either the ventral hippocampus or dorsal hippocampal formation resulted in a

0036-8075/79/0511-0641$00.50/0