tion after tetanus. Although the follower cell was significantly hyperpolarized (sometimes as much as 60 mV below the reversal potential of the inhibitory postsynaptic potential), it is possible that the postsynaptic potential approached its reversal potential sufficiently closely that a ceiling effect might have prevented a clear demonstration of facilitation. We therefore reduced the transmitter output of the presynaptic neuron by hyperpolarizing the presynaptic cell. The amount of transmitter released by L_{10} is directly related to presynaptic membrane potential (*9*). Thus, in a juvenile animal weighing 6 mg, hyperpolarizing L_{10} by 5 mV reduced the postsynaptic potential from 10.3 to 7.3 mV. Despite this, the amount of PTP was essentially unchanged (95 percent with presynaptic hyperpolarization compared to 104 percent without). To rule out a ceiling effect further, we compared two groups of animals at different stages of development where the control postsynaptic potential was almost the same. In stage 11 animals, PTP was nonexistent (102 ± 12 percent; $N = 7$) with a postsynaptic potential of 13.5 ± 7.7 mV, whereas in stage 12 animals, PTP was clearly present (193 ± 42 percent, $N = 7$) with a postsynaptic potential of 13.0 ± 1.6 mV. These results suggest that PTP appears at a late stage in development, in this instance taking at least 1 month to fully develop, after a functional connection has been established (*10*).

To determine the generality of this result in *Aplysia*, we next investigated two identified excitatory synaptic connections that show robust PTP in the adult (*8*). We first examined the excitatory connections of the same presynaptic neuron L_{10} onto another class of follower cells, the RB cells, and found a trend almost identical to that for the inhibitory synapses. In a few instances, we examined both inhibitory and excitatory connections in the same ganglion and found equivalent PTP at both synapses. (In a 1.7-g animal, the PTP was 192 percent for the inhibitory and 206 percent for the excitatory postsynaptic potential; these values were 260 and 262 percent in a 12-g animal and 247 and 247 percent in a 60-g animal.) This experiment independently supports the now well-established idea that PTP is a purely presynaptic process resulting from enhanced mobilization of transmitter (*11*). We observed a similar time course for the emergence of PTP at the identified excitatory synapse made by an axon within the right connective onto identified neuron R_{15} (RC_1 to R_{15}) (*12, 13*) in a similarly detailed study. In each case, the emergence of PTP occurred long after the initial chemical synaptic connections had been established. The finding that synapses involving different presynaptic neurons and different postsynaptic cells show a similar time of onset of PTP suggests that PTP may be induced synchronously throughout a particular neural region at a specific time during development.

The late appearance of PTP during development suggests that the capability for this form of synaptic plasticity is an independent regulatory process that is superimposed upon the basic mechanisms of synaptic transmission. The absence of PTP early in development and its gradual emergence after metamorphosis provide a potentially useful experimental system for elucidating the molecular mechanisms underlying PTP. The appearance of PTP should correlate in time with the appearance of the missing component.

HARUNORI OHMORI*
STEPHEN G. RAYPORT
ERIC R. KANDEL

Center for Neurobiology and Behavior,
Departments of Physiology and
Psychiatry, College of Physicians
and Surgeons, Columbia University,
New York 10032, and
Marine Biological Laboratory,
Woods Hole, Massachusetts 02543

References and Notes

1. G. D. Fischbach, D. K. Berg, S. A. Cohen, E. Frank, *Cold Spring Harbor Symp. Quant. Biol.* **40**, 347 (1975).
2. P. Patterson and D. Purves, *J. Cell Biol.* **59**, 241 (1976).
3. G. D. Fischbach and P. G. Nelson, *Handbook of Physiology, The Nervous System*, E. R. Kandel, Ed. (American Physiological Society, Bethesda, Md., 1977), vol. 1, section 1, pp. 719–774.
4. M. Jacobson, *Developmental Neurobiology* (Plenum, New York, 1978).
5. D. H. Hubel, T. N. Wiesel, S. LeVay, *Philos. Trans. R. Soc. London Ser. B* **278**, 377 (1977); E. R. Kandel, *N. Engl. J. Med.* **30**, 1028 (1979).
6. A. R. Kriegstein, V. F. Castellucci, E. R. Kandel, *Proc. Natl. Acad. Sci. U.S.A.* **71**, 3654 (1974); A. R. Kriegstein, *J. Exp. Zool.* **199**, 275 (1977).
7. E. R. Kandel, W. T. Frazier, R. Waziri, R. I. Coggeshall, *J. Neurophysiol.* **30**, 1352 (1967).
8. H. Ohmori, *J. Physiol.*, in press.
9. E. Shapiro, V. F. Castellucci, E. R. Kandel, *Proc. Natl. Acad. Sci. U.S.A.* **77**, 629 (1980); R. Kretz, E. Shapiro, E. R. Kandel, *Soc. Neurosci. Abstr.* **6**, 677 (1980).
10. In a 25-mg animal, hyperpolarization of the postsynaptic cell to 40 mV below the inhibitory postsynaptic reversal potential resulted in a control postsynaptic potential of 14.5 ± 2.6 mV; in a 10-mg animal, hyperpolarization of the postsynaptic membrane by 60 mV produced a control postsynaptic potential of 23.6 ± 2.1 mV (Fig. 1B). Under these conditions, the correction factors for the ceiling effect (*6*) calculated for the 10- and 25-mg animals were similar; 1.62 and 1.57, respectively. Nonetheless, the slightly older (25-mg) animal showed clear PTP of 148 percent.
11. A. R. Martin, *Physiol. Rev.* **46**, 51 (1966).
12. W. T. Schlapfer, J. P. Tremblay, P. B. J. Woodson, S. H. Barondes, *Brain Res.* **109**, 120 (1976).
13. J. H. Schwartz, V. F. Castellucci, E. R. Kandel, *J. Neurophysiol.* **34**, 939 (1971).
14. Supported by NIH grant GM 23540 and by a grant from the Klingenstein Foundation.

* Present address: c/o Prof. S. Hagiwara, Jerry Lewis Neuromuscular Research Center, School of Medicine, University of California, Los Angeles 90024.

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Demineralization of Porous Solids

Abstract. *When a porous ionic solid is placed in acid, the acid will dissolve surface material. When this dissolved material and the acid diffuse into the solid's pores, they can precipitate more solid. If the acid is buffered, the diffusing species can bring about precipitation in some regions and dissolution in others. When the porous solid contains several chemical species, the diffusion can precipitate one species and dissolve another. The results have implications for the demineralization of teeth.*

This work explores how diffusion and chemical reaction affect the dissolution by acid of porous ionic solids. How this dissolution proceeds depends on the relative speed of diffusion and reaction. When the bulk of the solution next to the solid is rapidly stirred, the acid can diffuse to the solid's surface very quickly and react with it. If the solid is essentially impermeable, containing a very few pores, then any ions produced by the dissolution are quickly swept back into the bulk solution. Because diffusion and chemical reaction occur sequentially, the overall dissolution rate depends on the sum of the resistances of diffusion and reaction. Such a process represents an important limit of corrosion, and it is this limit that is usually studied (*1*).

Alternatively, the solution next to the solid may not be well stirred and the solid may be highly porous (Fig. 1). In this case, the acid concentration will drop as it approaches the solid's surface and continue to drop within the solid's pores. The ions produced as a result of the acid-solid reaction will be present in the highest concentration near the surface. From this maximum, they can diffuse out into the bulk solution or further into the porous solid. Within the solid diffusion and reaction occur simultaneously, so that the overall dissolution rate is no longer a simple sum of the resistances of diffusion and reaction.

To calculate this dissolution rate, we assume that all chemical reactions in the solid are much faster than the diffusion

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so that the reactions reach equilibrium. We also assume that the diffusion coefficients of all species are equal and that the porous solid is present in excess. These assumptions represent reasonable first approximations for systems of this type. We then combine the continuity equations for each solute with the constraints of chemical equilibria to calculate dissolution rates (*2*).

Because this combination is complex, we give only the results for the simple case of a solid hydroxide attacked by acid:

$$\mathrm{M[OH]}_\nu + \nu\mathrm{H}^+ \leftrightarrows \mathrm{M}^{+\nu} + \nu\mathrm{H_2O} \qquad (1)$$

Because the dissolution is rapid,

$$[\mathrm{M}^{+\nu}] = K[\mathrm{H}^+]^\nu \qquad (2)$$

where $[\mathrm{M}^{+\nu}]$ is the metal ion concentration, $[\mathrm{H}^+]$ is the proton concentration, and K is an equilibrium constant. The solid hydroxide $\mathrm{M[OH]}_\nu$ has unit activity and the water is present in excess, and thus concentration terms for neither of these species appear in the equilibrium (*3*). The dissolution rate r_1 can now be calculated in ways similar to those predicting facilitated diffusion or the formation of fog (*4*):

$$r_1 = \left[\frac{D[\mathrm{M}^{+\nu}]\left(\dfrac{\partial \ln [\mathrm{H}^+]}{\partial z}\right)^2}{1 + \nu^2[\mathrm{M}^{+\nu}]/[\mathrm{H}^+]} \right] \{\nu(1 - \nu)\} \qquad (3)$$

where D is the diffusion coefficient and z is the direction of diffusion (Fig. 1). If r_1 is positive, solid is dissolving, but if r_1 is negative, solid is precipitating. The quantity in brackets is positive, so that the sign of r_1 is controlled by the sign of the quantity in braces.

Equation 3 predicts that within the porous solid ionic material will dissolve only if ν lies between zero and unity. It predicts that material will precipitate if ν is greater than one. This surprising prediction is verified experimentally. For example, for $\mathrm{Ca(OH)_2}$ the solubility of $[\mathrm{Ca}^{2+}]$ varies with the square of the acid concentration $[\mathrm{H}^+]$, and so $\nu = 2$. As a result, extra $\mathrm{Ca(OH)_2}$ should precipitate in the pores of a solid being dissolved by acid. To check this, we made a suspension of $\mathrm{Ca(OH)_2}$ stabilized in gelatin. The gelatin both removes any convection and allows us to use such a dilute suspension that we can easily see through it. We then poured 1.0*N* HCl on top of the gelatin. As predicted, we saw that extra $\mathrm{Ca(OH)_2}$ precipitates ahead of the acid front, as shown by the white band in Fig. 2a.

When the chemistry is more complex, other surprising results occur. For example, if a mixture of $\mathrm{Ca(OH)_2}$ and $\mathrm{Ag_2O}$ is attacked with $\mathrm{HNO_3}$, the $\mathrm{Ca(OH)_2}$ precipitates near the interface but both species dissolve below the interface as shown in Fig. 2b. This experiment shows many features of systems containing Liesegang rings (*5*). If $\mathrm{CaCO_3}$ is attacked with a buffered acid, it can dissolve at the acid front, precipitate just ahead of the acid front, and dissolve well ahead of this front. These effects are predicted by the theoretical generalizations of Eq. 3 (*2*).

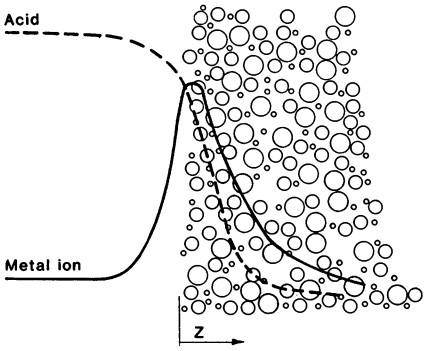

Fig. 1. Dissolution of a porous solid. In this schematic representation, acid diffuses from left to right and is consumed by chemical reaction with the solid. The metal ions produced by this reaction can, under some conditions, diffuse into the pores and precipitate as more solid.

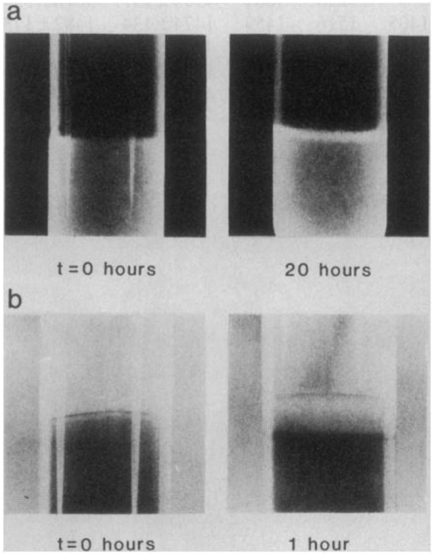

Fig. 2. Dissolution of gel-stabilized suspensions. Dilute gel-stabilized suspensions of insoluble hydroxides were dissolved when acid was poured on top of the suspensions. The gel remained intact. In the $\mathrm{Ca(OH)_2}$ suspension (a), HCl causes dissolution at the suspension's interface and a white band precipitate forms below the interface. For a mixture of $\mathrm{Ca(OH)_2}$ and $\mathrm{Ag_2O}$ (b), $\mathrm{HNO_3}$ causes precipitation of $\mathrm{Ca(OH)_2}$ near the interface but dissolution of both species below the interface.

These more complex cases have practical implications. One such case is the apparent subsurface dissolution of tooth enamel during dental decay. Tooth enamel consists of crystals held in a porous matrix of water, protein, and lipid, which occupies about 15 percent (by volume) of the enamel. The mineral crystals are related to hydroxyapatite, $\mathrm{Ca_{10}(PO_4)_6(OH)_2}$. However, many of the Ca^{2+} ions are missing or replaced by Na^+, Mg^{2+}, or Zn^{2+}; some of the $\mathrm{PO_4}^{3-}$ groups are replaced by $\mathrm{CO_3}^{2-}$; and some of the OH^- groups are replaced by F^-. Tooth decay occurs when bacteria in the plaque on the tooth surface metabolize sugars to produce lactic, acetic, and other organic acids which attack the enamel.

The analysis outlined here shows how this dissolution can take place. For example, imagine that teeth are a solid mixture attacked by a buffered acid. This analysis predicts that dimineralization occurs at the tooth's surface, remineralization occurs near this surface, and demineralization occurs well within the tooth. This behavior is observed both in vitro and in vivo (*6*). The analysis predicts that these effects do not occur without buffer, consistent with experiment (*7*). It predicts that the $[\mathrm{PO_4}^{3-}]$ in remineralized regions should be higher than in the rest of the tooth, which is also observed (*8*). We expect that other equally interesting implications of this analysis exist, such as the corrosion of masonry.

E. L. CUSSLER
Department of Chemical Engineering
and Materials Science,
University of Minnesota,
Minneapolis 55455
JOHN D. B. FEATHERSTONE
Eastman Dental Center,
University of Rochester,
Rochester, New York 14627

References and Notes

1. L. L. Shreir, *Corrosion* (Newnes-Butterworths, London, 1976).
2. E. L. Cussler, *AIChE J.*, in press.
3. M. B. King, *Phase Equilibria in Mixtures* (Pergamon, Oxford, 1969).
4. W. J. Ward, *AIChE J.* **16**, 405 (1970); H. L. Toor, *Ind. Eng. Chem. Fundam.* **10**, 121 (1971).
5. K. H. Stern, *Bibliography of Liesegang Rings* (Miscellaneous Publication 292, National Bureau of Standards, Gaithersburg, Md., 1967).
6. J. A. Gray, *Arch. Oral Biol.* **11**, 397 (1966); L. M. Silverstone, *Oral Sci. Rev.* **3**, 100 (1973); J. D. B, Featherstone, J. F. Duncan, T. W, Cutress, *Arch. Oral Biol.* **24**, 101 (1979).
7. M. J. Larsen and O. Fejerskov, *Scand. J. Dent. Res.* **85**, 420 (1977); J. D. B. Featherstone and B. E. Rodgers, *Caries Res.*, in press.
8. J. D. B. Featherstone, J. F. Duncan, T. W. Cutress, *Arch. Oral Biol.* **23**, 405 (1978).
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