ward the Golgi apparatus (*21*). Second, conversion of insulin begins midway into the marking period at both glucose concentrations and continues as a pseudo-first-order process for more than 2 hours (*9*). Thus, approximately 50 percent of the proinsulin is converted to insulin by the end of the marking period (*9*). Third, the later part of the marking period coincides with initial secretion of labeled proinsulin and insulin, which begins at about the same time as the conversion process (*9*) and is associated with formation of Golgi-derived secretory vesicles (*21*). Therefore, cellular events occurring during the marking period correspond to the time the newly labeled material is approaching and crossing the Golgi apparatus. Glucose during this period may mark for immediate release vesicles forming in either the rough endoplasmic reticulum or the Golgi apparatus, perhaps shunting new vesicles into a novel, glucose-activated secretory route.

How the cell both marks and recognizes marking, and how marking plays a role in the time-dependent modulation of the secretory rate of insulin in response to a given stimulus remain to be determined. Because nonrandom secretion occurs in other secretory cells, marking may prove to be a common mechanism in a variety of cell types responding to their physiologic regulators.

GERALD GOLD
MIKHAIL L. GISHIZKY
GEROLD M. GRODSKY
Metabolic Research Unit, University of California, San Francisco 94143

References and Notes

1. S. L. Howell, D. G. Parry, K. W. Taylor, *Nature (London)* **208**, 487 (1965).
2. H. Sando, J. Borg, D. F. Steiner, *J. Clin. Invest.* **51**, 1476 (1972).
3. C. Creutzfeldt, N. S. Track, W. Creutzfeldt, *Eur. J. Clin. Invest.* **3**, 371 (1973).
4. R. A. Gutman, G. Fink, J. R. Shapiro, H. Selawry, L. Recant, *J. Clin. Endocrinol. Metab.* **36**, 978 (1973).
5. H. Sando and G. M. Grodsky, *Diabetes* **22**, 354 (1973).
6. H. Schatz, C. Nierle, E. F. Pfeiffer, *Eur. J. Clin. Invest.* **5**, 477 (1975).
7. N. S. Track, in *Insulin and Metabolism*, J. S. Bajaj, Ed. (Excerpta Medica, Amsterdam, 1977), p. 13.
8. G. Gold, G. M. Reaven, E. P. Reaven, *Diabetes* **30**, 77 (1981); P.A. Halban, *Endocrinology* **110**, 1183 (1982).
9. G. Gold, H. D. Landahl, M. L. Gishizky, G. M. Grodsky, *J. Clin. Invest.* **69**, 554 (1982).
10. E. R. Trimble and A. E. Renold, *Am. J. Physiol.* **240**, E422 (1981).
11. S. Suwa and H. Friesen, *Endocrinology* **85**, 1037 (1969).
12. K. C. Swearingen, *ibid.* **89**, 1390 (1971).
13. R. R. MacGregor, J. W. Hamilton, D. V. Cohn, *ibid.* **97**, 178 (1975).
14. Y. Sharoni, S. Eimerl, M. Schramm, *J. Cell Biol.* **71**, 107 (1976).
15. F. Slaby and J. Bryan, *J. Biol. Chem.* **251**, 5078 (1976).
16. J. D. Hoff, B. L. Lasley, C. F. Wang, S. S. C. Yen, *J. Clin. Endocrinol. Metab.* **44**, 302 (1977).
17. H. Sachs, P. Fawcett, Y. Takabatake, R. Portanova, *Recent Prog. Hormone Res.* **25**, 447 (1969).
18. R. M. MacLeod and A. Abad, *Endocrinology* **83**, 799 (1968).
19. B. Collier, *J. Physiol. (London)* **205**, 341 (1969).
20. G. M. Grodsky, H. D. Landahl, D. Curry, L. Bennett, in *The Structure and Metabolism of the Pancreatic Islets*, S. Falkmer *et al.*, Eds. (Pergamon, Oxford, 1970), p. 409; V. Grill, U. Adamson, E. Cerasi, *J. Clin. Invest.* **61**, 1034 (1978).
21. D. F. Steiner, W. Kemmler, J. L. Clark, P. E. Oyer, A. H. Rubenstein, in *Handbook of Physiology, Endocrinology*, section 7, vol. 1, D. F. Steiner and N. Freinkel, Eds. (Williams & Wilkins, Baltimore, 1972), p. 175; L. Orci, A. E. Lambert, Y. Kanazawa, M. Amherdt, C. Rouiller, A. E. Renold, *J. Cell Biol.* **50**, 565 (1971).
22. This work was supported in part by NIH grant AM 01410 and by a grant from the Juvenile Diabetes Foundation. M.L.G. is a recipient of an Achievement Rewards for College Scientists (ARCS) Fellowship, Northern California Chapter.

9 July 1982

Modulation of Striatal Dopaminergic Function by Local Injection of 5′-*N*-Ethylcarboxamide Adenosine

Abstract. *Rats rotated to the left when 5′-*N*-ethylcarboxamide adenosine (NECA) was injected into the left caudate nucleus and apomorphine was administered subcutaneously. The combination of NECA and apomorphine was more potent than L-(phenylisopropyl)adenosine and apomorphine in eliciting rotation, suggesting the involvement of adenosine receptors of the R_a type. The response was reduced when 2′,5′-dideoxyadenosine was injected along with NECA into the caudate nucleus or when theophylline was given intraperitoneally. Higher doses of apomorphine elicited a self-mutilatory response after the injection of NECA into the caudate nucleus. These results suggest that adenosine may be involved in the modulation of dopaminergic function in the striatum.*

The involvement of the basal ganglia in several neurological conditions such as Parkinson's disease, Huntington's chorea, and drug-induced dyskinesias has stimulated research on the molecular and physiological basis of striatal function (*1*). The recent report suggesting that striatal dopaminergic function is altered in patients with the Lesch-Nyhan syndrome implicates the basal ganglia in yet another neurological disease which is characterized by movement disorders (*2*). We report studies herein which suggest that adenosine plays a role as a neuromodulator in the striatum and that imbalances in the striatal "adenosine system" may be involved in the etiology of movement disorders.

There has been much recent interest in adenosine as a potential neuromodulator (*3*). The ability of adenosine to increase adenosine 3′,5′-monophosphate (cyclic AMP) in intact cells was first demonstrated in slices of cerebral cortex (*4*) and has since been demonstrated in several tissues and in numerous cells in tissue culture (*5*). There are multiple types of adenosine receptors (*6*). R_a (A_2) and R_i (A_1) receptors stimulate and inhibit adenylate cyclase, respectively, and are located on the cell surface. Both types of R receptors are blocked by methylxanthines such as theophylline or caffeine. Sites of the P type are believed to be intracellular and may be associated with the catalytic unit of all adenylate cyclase enzymes. P sites mediate inhibition of adenylate cyclase activity by adenosine and are not blocked by methylxanthines.

Adenosine may be a neuromodulator in the basal ganglia since adenosine and adenosine analogs stimulate adenylate cyclase activity in broken cell preparations of rat striatum (*7*). Furthermore, ligand binding studies with tritiated *N*-ethylcarboxamide adenosine and 2-chloroadenosine, and autoradiographic studies with tritiated cyclohexyladenosine, show the striatum contains both R_a and R_i sites (*8*). Since the functional significance of these sites has not been investigated, we have studied rotational behavior in rats to determine the effects of adenosine analogs injected directly into the caudate nucleus. This rotation model has been used extensively to study dopaminergic function in the striatum (*9*). After the dopaminergic innervation to the striatum is destroyed by the administration of 6-hydroxydopamine into the substantia nigra, the systemic administration of directly acting dopamine agonists such as apomorphine causes vigorous turning away from the lesioned side (*10*). This is believed to be due to postsynaptic denervation supersensitivity on the denervated side (*10*). Conversely, when one caudate nucleus is destroyed by kainic acid the systemic administration of apomorphine causes rotation toward the lesioned side (*11*). Theophylline and caffeine have been reported to potentiate the rotational response to apomorphine in rats with lesions of the substantia nigra (*12*). This potentiation may have been due to blockade of R site adenosine receptors rather than inhibition of cyclic nucleotide phosphodiesterase as suggested by the authors.

We examined the rotational behavior of rats after injecting adenosine analogs

0036-8075/82/1001-0058$01.00/0

into one caudate nucleus and administering apomorphine subcutaneously. Male Sprague-Dawley rats (275 to 325 g) were prepared with a microinjection guide sheath implanted stereotaxically directed at the left caudate nucleus. After recovery from surgery (6 to 7 days) adenosine analogs were dissolved in normal saline and injected into the caudate nucleus (*13*). Apomorphine was dissolved in saline containing ascorbic acid (0.2 mg/ml), and theophylline (20 mg/ml) was dissolved (with heating) in saline containing citric acid (10 mg/ml). The animals were placed in metal bowls (40 cm in diameter) and the rotations were counted manually.

The intracaudate injection of 5′-*N*-ethylcarboxamide adenosine (NECA), a potent R site agonist, in amounts up to 6.5 nmole (in 2.0 μl) did not produce rotation or any other obvious behavioral alteration during the 2 hours of observation after the injection. However, when the intracaudate injection of NECA (6.5 nmole) was immediately followed by the subcutaneous injection of apomorphine (1 mg/kg) the animals rotated toward the injected side (Fig. 1A). Rotation was observed within 5 to 10 minutes, reached a maximum rate between 15 and 20 minutes, and had a duration of approximately 1 hour. This duration of rotation was similar to that seen when this dose of apomorphine was given to animals with kainic acid lesions of the caudate nucleus (*11*). The onset of rotation after apomorphine injection was much faster if NECA was injected 30 to 60 minutes before apomorphine. In the experiment shown in Fig. 1A, the dose of apomorphine was the same as in the experiment in which the drugs were injected simultaneously, whereas the amount of NECA injected was half of that used in the first experiment. We interpret the faster onset of the rotational response when the NECA injection preceded the apomorphine injection as reflecting the time needed for NECA to diffuse throughout the caudate nucleus; in subsequent experiments drug injections into the caudate nucleus were made 40 minutes before the apomorphine injection. No rotation occurred when the apomorphine injection was preceded by an injection of saline into the caudate nucleus. These results suggest that NECA inhibited the effect of apomorphine on the caudate nucleus into which it was injected; the effect of the apomorphine on the contralateral caudate nucleus was therefore unopposed and caused ipsilateral rotation.

It is known that NECA is more potent at R sites than its corresponding ester derivative 5′-ethylcarboxylate adenosine (ECA) (*14*). In addition, NECA is more potent than L-(phenylisopropyl)adenosine (L-PIA) at R_a sites, whereas L-PIA is more potent than NECA at R_i sites (*6*). We first determined that 0.5 μl of 1.0 m*M* NECA (0.5 nmole) was the minimal amount necessary for apomorphine (0.3 mg/kg) to produce a significant rotational response. We then determined the rotational response to this dose of apomorphine after the injection of 0.5 and 1.0 μl volumes of 1.0 m*M* solutions of NECA, ECA, and L-PIA (*15*). As shown in Fig. 1B, the rotational response to NECA was considerably greater than that to either L-PIA or ECA, which suggests that the rotational response to NECA and apomorphine was due to an effect of NECA at R_a sites. Thus inhibition of the effect of apomorphine on the side injected with NECA appears to be due to the stimulation of adenosine sensitive adenylate cyclase in the injected caudate nucleus.

If the rotational response to NECA and apomorphine is due to an action of NECA at R_a sites, the response should be antagonized by an adenosine antagonist such as theophylline. Although the data in Fig. 2A show that theophylline decreased the rotational response, the interpretation of this experiment was

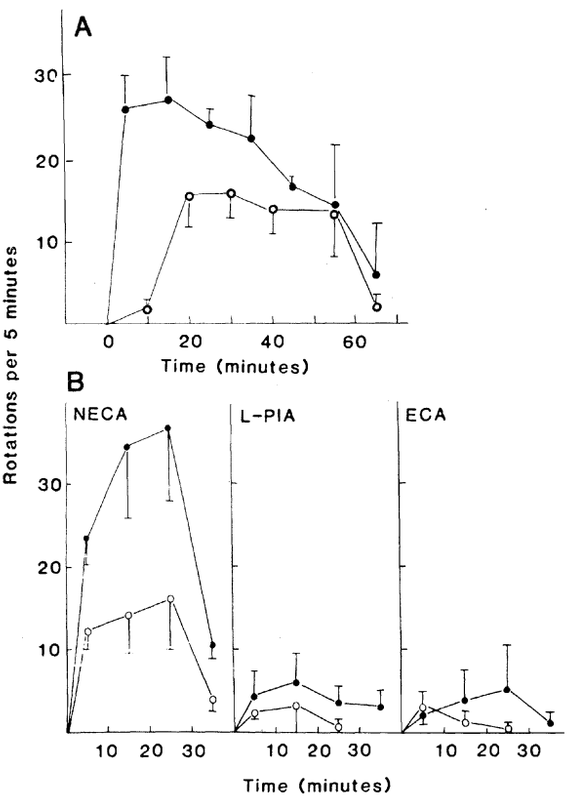

Fig. 1. Rotational responses of rats that received intracaudate injections of adenosine analogs and subcutaneous injections of apomorphine. Points represent mean rotations (± standard error) per 5-minute counting period. Apomorphine was injected at zero time. (A) ○, NECA (6.5 nmole in 2 μl of saline) was injected immediately before apomorphine (1 mg/kg) ($N = 3$); ●, NECA (3.25 nmole in 1 μl of saline) was injected 40 minutes before apomorphine (1 mg/kg) ($N = 3$). (B) Apomorphine (0.3 mg/kg) was injected 40 minutes after 0.5 μl (○) or 1.0 μl (●) of a 1 m*M* solution of NECA, L-PIA, or ECA ($N = 3$ in all groups).

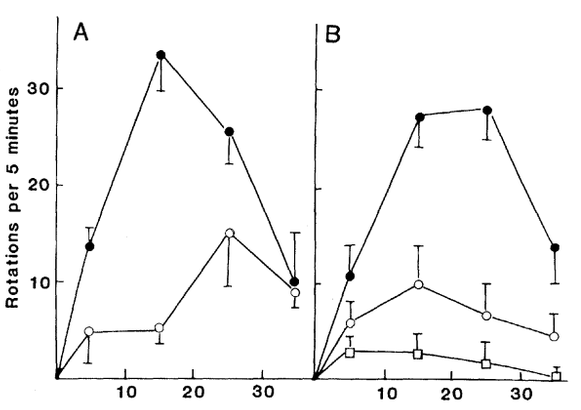

Fig. 2. Effects of (A) theophylline and (B) DDA on rotational responses to NECA and apomorphine. (A) ●, NECA (1 nmole) plus apomorphine (0.3 mg/kg) ($N = 4$); ○, theophylline (100 mg/kg, intraperitoneal) was injected 10 minutes before apomorphine ($N = 3$). The total number of rotations counted at four counting periods was significantly reduced in the theophylline-treated animals ($P < .05$). (B) ●, NECA (1 nmole) plus apomorphine (0.3 mg/kg) ($N = 6$); ○, NECA (1 nmole) plus DDA (1 nmole) plus apomorphine (0.3 mg/kg) ($N = 6$); □, DDA (1 nmole) plus apomorphine (0.3 mg/kg) ($N = 3$). All intracerebrally injected drugs were given in 1 μl of saline. The rotational response in the group that received NECA plus DDA was significantly reduced at 15, 25, and 35 minutes ($P < .05$) compared to the group that received NECA alone.

Table 1. Behavioral effects after the injection of NECA into the caudate nucleus and the systemic administration of high doses of apomorphine. The apomorphine was injected subcutaneously 40 minutes after the injection of NECA or saline. All drugs were given in 1 μl of saline, except the 6.5 nmole of NECA which was in 2 μl of saline. Group 5 received 1 μl of saline injected into the caudate nucleus. Self-mutilation is classified as follows: −, no biting; +, mild biting of tail; ++, continuous tail biting and biting of hind paw on the side ipsilateral to NECA injection; +++, biting sufficient to break skin and initiate mild bleeding; and ++++, severe biting with bleeding.

Group	Treatment		Number of animals showing self-mutilation					Rotational response*
	NECA (nmole)	Apomorphine (mg/kg)	−	+	++	+++	++++	
1	1	5		3				34.3 ± 3.7 (3)
2	3.25	5		2	1			30.0 ± 7.2 (3)
3	6.5	5		1		1	1	28.7 ± 2.4 (3)
4	3.25	10		2			1	40.3 ± 12.7 (3)
5	0	10	5	1				9.0 ± 2.2 (6)

*Mean number of rotations (± standard error) 10 to 15 minutes after apomorphine injection. The number of animals is shown in parentheses.

complicated by motor effects in some of the animals receiving all three drugs. One animal that showed a mild motor effect was included in the data in Fig. 2A; another theophylline-treated rat (not included) exhibited no rotation after apomorphine injection but died during convulsions within 1 hour after the injection. This toxicity appeared to be due to the combination of theophylline and apomorphine because animals receiving, per kilogram of body weight, either 100 mg of theophylline or 1 mg of apomorphine showed no signs of toxicity, whereas the combination of the two agents was fatal in all instances. This toxicity may reflect a tonic inhibition of dopaminergic systems by endogenous adenosine which is blocked by theophylline, thus potentiating the response to apomorphine.

If the rotational response to NECA and apomorphine involves stimulation of adenylate cyclase via the R_a site, a potent P-site agonist such as 2′,5′-dideoxyadenosine [DDA; (*6*)], which would inhibit adenylate cyclase activity when injected into the striatum, should antagonize the rotational response to NECA and apomorphine. Simultaneous injection of DDA and NECA into the caudate nucleus followed by the systemic administration of apomorphine did, indeed, produce less rotation than that seen in animals receiving NECA and apomorphine (*16*) (Fig. 2B).

In several animals, the combination of NECA and apomorphine also resulted in gnawing of the tail and ipsilateral hind paw. Severe self-mutilation followed the administration of higher doses of apomorphine in animals with unilateral lesions of the substantia nigra (*10*). We therefore studied the effects of various doses of NECA and apomorphine (Table 1). All of the animals exhibited some self-mutilation; two of the six animals that received the highest doses of NECA and apomorphine showed severe self-mutilation. One of the animals that exhibited severe self-mutilation was given theophylline (100 mg/kg, intraperitoneally), which blocked the behavior, but the animal subsequently convulsed and died. These data suggest that R receptors are involved in eliciting self-mutilation. All of the animals receiving NECA and apomorphine also exhibited similar rotational behavior. However, the dose response relationships in these experiments may have been obscured since self-mutilation decreased the rotational rate. The high dose of apomorphine (10 mg/kg) induced mild rotation when given to animals injected with saline, thus indicating that the saline, or the previous injection into the caudate nucleus, caused some damage.

That dopaminergic mechanisms in the striatum may be influenced by R-site adenosine agonists suggests that alterations in the "adenosine system" may occur in disease states characterized by abnormal striatal function and associated movement disorders. It has been suggested that methylxanthines might increase the therapeutic effectiveness of L-dopa in the treatment of parkinsonism (*12*). This suggestion was based on the methylxanthine-induced potentiation of the rotational response to apomorphine in rats with unilateral lesions of the substantia nigra (*12*). Although the present results are consistent with this postulate, they suggest that the beneficial effect of the methylxanthine would be due to the blockade of endogenous adenosine at R_a sites rather than an to effect on phosphodiesterase. One might speculate that an interaction or imbalance between the adenosine system and the dopaminergic system is responsible for the self-mutilation in the Lesch-Nyhan patient. This concept is supported by the well-documented alterations in purine metabolism in these patients (*17*) and by the recent finding that dopaminergic mechanisms in the striata of Lesch-Nyhan patients are also altered (*2*). It is not known if there is any relation between the self-mutilation produced by NECA and apomorphine treatment and the self-mutilation that occurs in rats or rabbits treated with high doses of methylxanthines over long periods (*17*). The latter phenomenon, which has been used as a model for the Lesch-Nyhan syndrome, may be due to the development of supersensitivity to adenosine resulting from long-term blockade by theophylline. In this case the self-mutilation would occur when the blood levels of theophylline are minimal and a supersensitive adenosine receptor system responds to endogenous adenosine. Whatever the case, the present experiments strongly suggest a modulatory role of adenosine in the striatum, and suggest new lines of research to further our understanding of the etiology of movement disorders.

RICHARD D. GREEN
HERBERT K. PROUDFIT
SIU-MEI H. YEUNG

Department of Pharmacology, University of Illinois College of Medicine, Chicago 60680

References and Notes

1. O. Hornykiewicz, in *The Neurobiology of Dopamine*, A. S. Horn, J. Korf, B. H. C. Westerink, Eds. (Academic Press, New York, 1979), p. 633.
2. K. G. Lloyd, O. Hornykiewicz, L. Davidson, K. Shannak, I. Farley, M. Goldstein, M. Shibuya, W. N. Kelley, I. H. Fox, *N. Engl. J. Med.* **305**, 1106 (1981).
3. J. W. Phillis, J. P. Edstrom, G. K. Kostopoulos, J. R. Kirkpatrick, *Can. J. Physiol. Pharmacol.* **57**, 1289 (1979); T. W. Stone, *Trends Pharmacol. Sci.* **1**, 273 (1980).
4. A. Sattin and T. W. Rall, *Mol. Pharmacol.* **6**, 13 (1970).
5. A. J. Blume, C. Dalton, H. Sheppard, *Proc. Natl. Acad. Sci. U.S.A.* **70**, 3099 (1973); B. Fredholm, G. Sandberg, U. Ernstrom, *Biochem. Pharmacol.* **27**, 2675 (1978); M. Huang and G. Drummond, *ibid.*, p. 187; G. Marone, M. Plaut, L. Lichtenstein, *J. Immunol.* **11**, 2153 (1978); R. F. Bruns, *Can. J. Physiol. Pharmacol.* **58**, 673 (1980).
6. C. Londos and J. Wolff, *Proc. Natl. Acad. Sci. U.S.A.* **74**, 5482 (1977); C. Londos, D. M. F. Cooper, J. Wolff, *ibid.* **77**, 255 (1980); D. van-Calker, M. Muller, B. Hamprecht, *J. Neurochem.* **33**, 999 (1979).
7. J. Premont, M. Perez, G. Blanc, J.-P. Tassin, A-M. Thierry, D. Herve, J. Bockaert, *Mol. Pharmacol.* **16**, 790 (1979); M. B. Anand-Srivastava and R. A. Johnson, *J. Neurochem.* **35**, 905 (1980).
8. M. Williams, and E. A. Risley, *Proc. Natl. Acad. Sci. U.S.A.* **77**, 6892 (1980); R. R. Goodman and S. H. Snyder, *Abstr. Soc. Geriat. Neurosci.* 7, 613 (1981); S.-M. Yeung and R. D. Green, in preparation. We have found that [^{3}H]NECA binds to two high-affinity sites in rat striatum which we believe are the R_a and R_i sites. Within the concentration ranges that have been studied 2-chloroadenosine and N^6-cyclohexyladenosine bind to R_i sites.
9. S. D. Glick, T. P. Jerussi, L. N. Fleisher, *Life Sci.* **18**, 889 (1976).
10. U. Ungerstedt, *Acta Physiol. Scand. Suppl.* **367**, 69 (1971).
11. R. Schwarz, K. Fuxe, L. F. Agnati, T. Hokfelt, J. T. Coyle, *Brain Res.* **170**, 485 (1979).

12. K. Fuxe and U. Ungerstedt, *Med. Biol.* **52**, 48 (1974).
13. Injections into the caudate nucleus were made with a 30-gauge stainless steel cannula whose tip extended 3 mm beyond the tip of the guide tube. The cannula was connected to polyethylene tubing (PE-20) that was fitted to the needle of a gear-driven 10-μl syringe. Fluid delivery was monitored by observing the movement of an air bubble over a calibrated distance in the tubing. All solutions were microinjected at a rate of 0.5 μl/min and the cannula was left in place for an additional 1 to 2 minutes to minimize flow of the solution up the cannula track. The *p*H of the microinjected solutions was approximately 7.0 and all solutions were passed through a Millipore filter prior to injection. Each animal was used two times with a 5- to 7-day interval between injections. Cannula placements were verified histologically in randomly chosen animals at the completion of experiments.
14. H. H. Stein and R. N. Prasad, in *Physiological and Regulatory Functions of Adenosine and Adenine Nucleotides*. H. P. Baer and G. E. Drummond, Eds. (Raven, New York, 1979), p. 183.
15. The 1-μl injections were made into animals that had been tested with the 0.5-μl dose 1 week previously. The animals received different drugs on the first and second trials.
16. It is interesting that the combination of DDA and apomorphine caused little or no rotation. This supports growing evidence that the rotational response to dopamine agonists is mediated by dopamine receptors that are not coupled to adenylate cyclase [P. Seeman, *Pharmacol. Rev.* **32**, 229 (1980)]. The DDA and apomorphine combination should have caused rotation if the dopamine receptor coupled to adenylate cyclase was involved because the adenylate cyclase on the side injected with DDA would have been inhibited, leaving the effect of apomorphine on the contralateral side unopposed. This line of reasoning is not incompatible with our conclusion that the intracaudate injection of NECA stimulated adenosine-sensitive adenylate cyclase and caused apomorphine to produce rotation toward that side. In the case of DDA the effect of the nucleotide would be to inhibit dopamine-sensitive adenylate cyclase by an action at P sites on the same cells, while in the case of NECA and apomorphine NECA need not necessarily act on the same cells as apomorphine.
17. W. L. Nyhan, *Annu. Rev. Med.* **24**, 4 (1973).
18. The studies were supported in part by funds from the Campus Research Board of the University of Illinois.

16 February 1982

Relation of Soil Water Movement and Sulfide Concentration to *Spartina alterniflora* Production in a Georgia Salt Marsh

Abstract. *It is proposed that differences in plant height and productivity of the salt-marsh cordgrass* Spartina alterniflora *are the result of a dynamic interaction among tidal water movement, dissolved iron and sulfide concentrations in marsh soils, and bacterial sulfate reduction. Tidal water movement regulates the input of iron into marsh soils and the drainage of sulfide-containing interstitial water, and thereby controls the concentration of dissolved sulfide formed as a result of bacterial sulfate reduction. Near tidal creeks, where water movement and plant height and production are greatest, sulfide concentrations are lowest; in more elevated regions of marsh, where water movement and plant production are least, sulfide concentrations are highest. Plant height and productivity may be limited by the effects of sulfide on nutrient uptake.*

Local gradients in production of the halophyte *Spartina alterniflora* are a distinctive feature of Atlantic and Gulf coast salt marshes. The height and biomass of *S. alterniflora* are greater on the banks of tidal rivers and creeks than they are in the more elevated, landward regions of marsh (*1*). Annual net production of the tall growth form is three to five times that of the short form (*2–4*) and, although the tall form occupies only about 10 percent of a marsh surface area, it accounts for 30 to 50 percent of total marsh production (*3, 4*). Plant production (per square meter) along tidal creeks is among the highest of any terrestrial habitat (*5*) and has a significant impact on carbon cycling in estuaries.

The differences in growth of the plants have been explained by salinity stresses (*4, 6*), nitrogen limitation (*7–11*), and iron limitation (*12–14*), but these explanations have proved to be unsatisfactory or have been found inapplicable to a wide range of habitats (*15*). The most consistent current hypotheses suggest that production is regulated by oxygen transport within plants and by the sulfide concentration and oxidation-reduction (redox) status of the growth substrate (*16*). Mendelssohn *et al.* (*17*) have shown that the availability of O_2 within *S. alterniflora* roots is related to physiological differences in energy production or catabolism in the tall and short forms of the plants. Although the observed physiological differences are responsible for differences in the production of plants, the mechanisms resulting in gradients of oxygen availability within marshes have not been clearly delineated. Sulfide may directly affect *S. alterniflora* production as a result of increased mortality (*9*) and inhibition of the transport system involved in nitrogen uptake (*10, 11, 16*); sulfide may also lower oxygen availability, thereby changing patterns of catabolism (*17*). However, controls of sulfide concentration have not been determined nor adequately related to the differences in productivity within marshes. Redox profiles have been positively correlated with productivity and soil water movement in a New England marsh (*16*) and with plant height in a Louisiana marsh (*17*), but the controls of redox status or the mechanisms resulting in gradients within marshes of the southeast United States or Gulf Coasts are unclear.

We propose that the gradients in the edaphic factors that regulate *S. alterniflora* production are controlled by a dynamic relation among tidal water movement, interstitial sulfide and iron concentrations, and bacterial sulfate reduction.

Data supporting the hypothesis were obtained by G.M.K. and M.J.K. from soils of Sapelo Island, Georgia, which contained tall (TS), intermediate (IS), or short (SS) growth forms of *S. alterniflora*. Natural soil water movement is much greater in TS than in SS marshes, as documented by several studies that reveal significant vertical and lateral movement in the TS, but virtually no movement in the SS (*6, 18, 19*). Data were also obtained from two other intermediate marsh sites on Sapelo Island in which soil water flow had been experimentally altered by R.G.W. and A.G.C. Soil in one of the regions (ISD) contained drainage pipe (outer diameter, 15 cm), which had been placed below ground in trenches. The other region (ISR), adjacent to the first, was trenched to simulate disturbances created by laying the pipe, but no pipe was left in place (*20*). Studies of infiltration rates in the experimental sites showed increased movement in the ISD site and restricted movement in the ISR site with respect to the control IS site. Infiltration rates were 2.95, 0.55, and 0.29 liter/min-m^2 in ISD, IS, and ISR plots, respectively. The slowness of the movement in ISR was probably due to packing of soil and decreased capillary space (*20*). In soils where water movement was increased, plant growth was stimulated twofold; where movement was restricted, plant growth was inhibited by a factor of 2 (*20*). Other physical and biological characteristics of these marsh sites have been described (*21, 22*). Interstitial water was collected from all sites during October in both 1980 and 1981, and from TS and SS sites in August 1981, for analyses of dissolved sulfide, sulfate, and iron (*23, 24*). Rates of bacterial sulfate reduction were also determined by a direct injection technique (*25*) on soil cores from the same areas during October in both 1980 and 1981.

Sulfide concentrations vary markedly [Fig. 1A and (*26*)] across Sapelo Island marshes and are inversely correlated with soil water flow and plant production (*3, 4, 6, 18*). The lowest concentration of sulfide (< 90 μmole per liter of interstitial water) is observed in the TS and experimental ISD sites where water flow is relatively high; in the SS and experi-

0036-8075/82/1001-0061$01.00/0