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## Kinetics and Concentration Dependency of cAMP-Induced Desensitization of a Subpopulation of Surface cAMP Receptors in *Dictyostelium discoideum*<sup>†</sup>

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**ABSTRACT:** Extracellular cAMP induces the rapid activation of guanylate cyclase, which adapts within 10 s to constant cAMP concentrations. A new response can be induced either by a higher cAMP concentration or by the same cAMP concentration at some time ( $t_{1/2} = 90$  s) after removal of the previous stimulus. Stimulation of guanylate cyclase is supposed to be mediated by a subpopulation of cell surface cAMP receptors (B-sites). These sites can exist in three states, B<sup>F</sup>, B<sup>S</sup>, and B<sup>SS</sup>, which interconvert in a cAMP and guanine nucleotide dependent manner. It has been proposed that the transition of B<sup>S</sup> to B<sup>SS</sup> represents the activation of a guanine nucleotide regulatory protein [Van Haastert, P. J. M., De Wit, R. J. W., Janssens, P. M. W., Kesbeke, F., & DeGoede, J. (1986) *J. Biol. Chem.* 261, 9604-9611]. Binding of [<sup>3</sup>H]cAMP to these sites was measured after a short preincubation with an identical concentration of nonradioactive cAMP. [<sup>3</sup>H]cAMP could still bind to B<sup>F</sup> and B<sup>S</sup>, but not to B<sup>SS</sup>, indicating that the transition of B<sup>S</sup> to B<sup>SS</sup> is blocked by the preincubation with cAMP. This blockade was rapid and showed first-order kinetics with  $t_{1/2} = 4$  s. A half-maximal blockade was induced by 0.7 nM cAMP; at this concentration only 5% of the B-sites are occupied with cAMP. The blockade of the transition of B<sup>S</sup> to B<sup>SS</sup> was released by two conditions: (i) When the concentration of cAMP was increased, the blockade was released within a few seconds. (ii) When cAMP was removed, the blockade was released slowly with  $t_{1/2} = 90$  s. Finally, cAMP did not induce the blockade under conditions where guanylate cyclase did not adapt, i.e., at 0 °C and in cells starved for 2 h or less. These results suggest that the interaction of cAMP with the B-sites induces a rapid and reversible blockade of the terminal step in the generation of an active G-protein and that this blockade could be the molecular basis of adaptation of guanylate cyclase.

The eukaryotic microorganism *Dictyostelium discoideum* is a suitable organism to study desensitization of signal transduction pathways. In this organism the hormone-like substance is cAMP, which is detected by cell surface receptors. Extracellular cAMP induces the rapid activation of guanylate cyclase (Mato & Malchow, 1978) and the slower activation of adenylate cyclase (Roos & Gerisch, 1976). Intracellular cGMP reaches a peak at 10 s and declines to prestimulated levels within about 30 s (Mato et al., 1977). Intracellular cAMP reaches maximal levels after 60-120 s and is secreted, thus acting as an autocatalytic feedback loop (Gerisch & Wick, 1975).

Prolonged stimulation of *D. discoideum* cells with constant cAMP concentrations induces desensitization by at least two mechanisms: (i) One is down-regulation of cAMP-binding activity after a long incubation (5 min) with high cAMP

concentrations (above 0.1 μM). After removal of cAMP, cells resensitize with a half-life of about 60 min (Klein & Juliani, 1977; Klein, 1979). (ii) Another is a rapid desensitization of the cAMP-mediated activation of adenylate and guanylate cyclases by nanomolar cAMP concentrations with the characteristics of adaptation; i.e., the activity of the cyclases fades in the presence of a constant cAMP concentration but can be reactivated by increasing the cAMP concentration (Devreotes & Steck, 1979; Van Haastert & Van der Heijden, 1983). After removal of cAMP, cells deadapt with a half-life of 1-2 min for the guanylate cyclase and 3-4 min for the adenylate cyclase. Adaptation of the cAMP-mediated cGMP accumulation is completed within 10 s, while adaptation of the cAMP accumulation is completed after about 5 min (Dinauer et al., 1980a,b; Van Haastert & Van der Heijden, 1983).

Adaptation of adenylate cyclase stimulation has been correlated with a covalent modification, presumably phosphorylation, of the receptor (Devreotes & Sherring, 1985; Klein, C., et al., 1985; Klein, P., et al., 1985, 1987). This receptor modification is probably not the molecular mechanism for adaptation of guanylate cyclase stimulation, since adaptation

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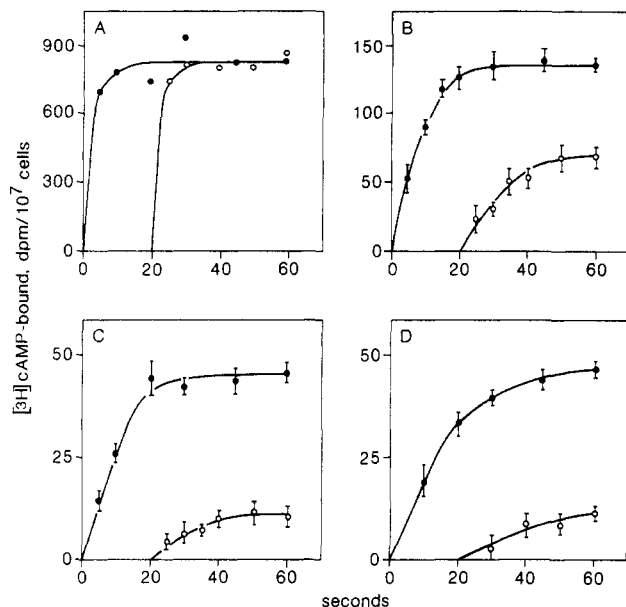


FIGURE 2: cAMP-induced blockade of the binding of  $[^3\text{H}]\text{cAMP}$  to  $\text{B}^{\text{SS}}$ . (A–C) *D. discoideum* cells ( $90\ \mu\text{L}$ ) were incubated at  $t = 0\ \text{s}$  with  $10\ \mu\text{L}$  of cAMP, yielding  $5\ \text{mM}$  dithiothreitol and  $10\ \text{nM}$  cAMP. At  $t = 0$  (●) or at  $t = 20\ \text{s}$  (○),  $50\ \mu\text{L}$  of  $10\ \text{nM}$   $[^3\text{H}]\text{cAMP}$  and  $5\ \text{mM}$  dithiothreitol was added. Thus, the concentrations of cAMP and dithiothreitol did not change. In (A)  $145\ \mu\text{L}$  of the incubation mixture was placed above silicon oil, and cells were centrifuged through the oil at the times indicated. In (B) and (C)  $145\ \mu\text{L}$  of the incubation mixture was added to  $1\ \text{mL}$  of  $0.1\ \text{mM}$  cAMP and  $5\ \text{mM}$  dithiothreitol at the times indicated, and cells were centrifuged through the oil  $10\ \text{s}$  later (B) or  $2\ \text{min}$  later (C). (D) The same conditions as for (C) except that the final concentration of cAMP and  $[^3\text{H}]\text{cAMP}$  was  $2\ \text{nM}$ , the volume of  $[^3\text{H}]\text{cAMP}$  was increased to  $100\ \mu\text{L}$ , and  $190\ \mu\text{L}$  of the incubation mixture was added to the  $1\ \text{mL}$  of  $0.1\ \text{mM}$  cAMP. The results shown are the means of duplicate (A) or quadruplicate (B–D) incubations from a typical experiment repeated at least 2 times. Bars indicate the standard deviation.

**Preincubation with cAMP Blocks the Binding of  $[^3\text{H}]\text{cAMP}$  to the  $\text{B}^{\text{SS}}$ -State but Not to the Other Binding States.** *D. discoideum* cells were incubated with  $10\ \text{nM}$  cAMP plus  $[^3\text{H}]\text{cAMP}$  at  $t_0$ ; binding to the sum of all sites rapidly increases to an equilibrium value obtained after about  $10\ \text{s}$  (Figure 2A). In the second condition, cells are preincubated with  $10\ \text{nM}$  cAMP for  $20\ \text{s}$ , during which equilibrium of binding will be reached toward the same number of sites occupied with cAMP. Then the  $[^3\text{H}]\text{cAMP}$  is added in such a way that the cyclic nucleotide concentration remains  $10\ \text{nM}$ . The  $[^3\text{H}]\text{cAMP}$  rapidly binds to the cells to the same equilibrium value as without the preincubation with cAMP. This implies that the cAMP which was bound during the preincubation did exchange with  $[^3\text{H}]\text{cAMP}$  during the subsequent incubation. In this experiment binding was detected as the sum of all sites.

Binding of  $[^3\text{H}]\text{cAMP}$  to  $\text{B}^{\text{S}} + \text{B}^{\text{SS}}$  is detected after a  $10\text{-s}$  chase with excess cAMP, after which all  $[^3\text{H}]\text{cAMP}$  bound to the fast dissociating sites has been released. Binding to  $\text{B}^{\text{SS}}$  is detected after a chase of  $2\ \text{min}$ . An experiment with the same protocol as described above reveals that a  $20\text{-s}$  preincubation with  $10\ \text{nM}$  cAMP results in a  $50\%$  inhibition of binding of  $[^3\text{H}]\text{cAMP}$  to  $\text{B}^{\text{S}} + \text{B}^{\text{SS}}$  (Figure 2B) and in an  $80\%$  inhibition of the binding to  $\text{B}^{\text{SS}}$  (Figure 2C). Apparently, the preincubation with cAMP prevents the binding of  $[^3\text{H}]\text{cAMP}$  mainly to  $\text{B}^{\text{SS}}$ . What could be the mechanism for the reduced binding of  $[^3\text{H}]\text{cAMP}$  to  $\text{B}^{\text{SS}}$ -sites? It has been shown that occupied  $\text{B}^{\text{SS}}$  dissociate very slowly with  $t_{1/2} = 150\ \text{s}$  (Van Haastert et al., 1986). Therefore,  $\text{B}^{\text{SS}}$  occupied with cAMP cannot exchange with  $[^3\text{H}]\text{cAMP}$  in the subsequent incubation.

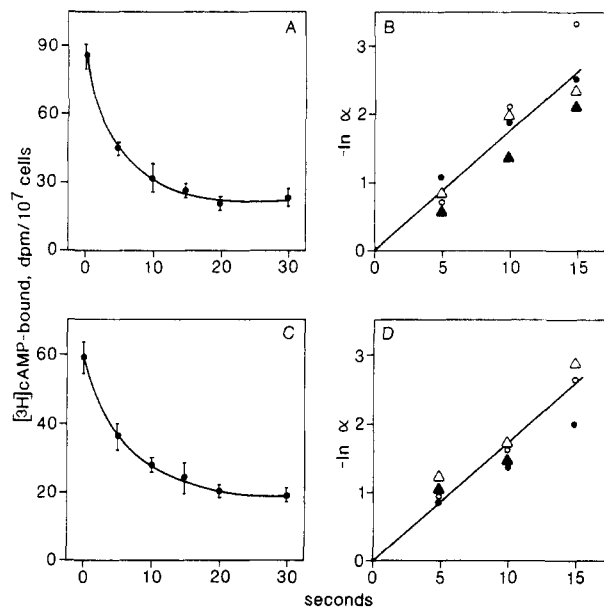


FIGURE 3: Kinetics of the blockade. (A) Cells ( $90\ \mu\text{L}$ ) were mixed with  $10\ \mu\text{L}$  of cAMP at  $t = 0$ , yielding  $5\ \text{mM}$  dithiothreitol and  $10\ \text{nM}$  cAMP. At the times indicated  $50\ \mu\text{L}$  of  $10\ \text{nM}$   $[^3\text{H}]\text{cAMP}$  and  $5\ \text{mM}$  dithiothreitol was added, and binding of  $[^3\text{H}]\text{cAMP}$  to  $\text{B}^{\text{SS}}$  was measured at  $60\ \text{s}$  (i.e., the incubation mixture was added to  $1\ \text{mL}$  of  $0.1\ \text{mM}$  cAMP and  $5\ \text{mM}$  dithiothreitol at  $60\ \text{s}$ , and cells were centrifuged through silicon oil at  $180\ \text{s}$ ). (C) Same conditions as in (A), except that the concentration of both cAMP and  $[^3\text{H}]\text{cAMP}$  was  $2\ \text{nM}$  and the volumes of the cell suspensions of cAMP and  $[^3\text{H}]\text{cAMP}$  were 2 times larger. (B, D) Logarithmic transformations of A and C, respectively  $\alpha = [\text{dpm}(t) - \text{dpm}(30)] / [\text{dpm}(0) - \text{dpm}(30)]$ . The fact that both curves pass the origin and have identical slopes ( $k = 0.17\ \text{s}^{-1}$ ;  $t_{1/2} = 4\ \text{s}$ ) indicates that the reduction of  $[^3\text{H}]\text{cAMP}$  bound between  $0$  and  $30\ \text{s}$  shows first-order kinetics. The results of (A) and (C) are the means and standard deviations of quadruplicate incubations from a typical experiment. The different symbols in (B) and (D) represent the data from four independent experiments.

tion. It could be hypothesized that  $[^3\text{H}]\text{cAMP}$  does not bind to  $\text{B}^{\text{SS}}$  simply because all  $\text{B}^{\text{SS}}$ -sites are occupied with cAMP. However,  $10\ \text{nM}$  cAMP is below the apparent  $K_d$  of  $\text{B}^{\text{SS}}$  (which is  $15\ \text{nM}$ ), and only  $40\%$  of the  $\text{B}^{\text{SS}}$ -sites were occupied during the preincubation with cAMP. Furthermore, essentially the same result is obtained when the experiment is repeated with  $2\ \text{nM}$  cAMP, by which only  $10\%$  of the  $\text{B}^{\text{SS}}$ -sites are occupied with cAMP and  $90\%$  would still be available to bind  $[^3\text{H}]\text{cAMP}$  (Figure 2D). This suggests that the occupied  $\text{B}^{\text{SS}}$ -state can no longer be formed after a  $20\text{-s}$  preincubation with cAMP. Do the other sites still bind  $[^3\text{H}]\text{cAMP}$  after the incubation with cAMP? Detailed calculations which correct for the partial dissociation of  $\text{B}^{\text{S}}$  and  $\text{B}^{\text{SS}}$  during the  $10\text{-}$  and  $120\text{-s}$  chases with excess cAMP have shown that the other binding states (including  $\text{B}^{\text{S}}$ ) still could bind  $[^3\text{H}]\text{cAMP}$  after a preincubation with cAMP (Van Haastert et al., 1986).

These experiments reveal that a preincubation of cells with cAMP for  $20\ \text{s}$  blocks the formation of the occupied  $\text{B}^{\text{SS}}$ -state. Since these sites can only arise from a transition of the occupied  $\text{B}^{\text{S}}$ -state, this implies that cAMP induces a blockade in the transition of  $\text{B}^{\text{S}}$  to  $\text{B}^{\text{SS}}$ , which, according to our model (Figure 1), implies that a G-protein is no longer activated.

**Kinetics of the Blockade.** The kinetics of the blockade were investigated by adding cAMP to the cells at  $t = 0\ \text{s}$  and by adding  $[^3\text{H}]\text{cAMP}$  at different times between  $0$  and  $30\ \text{s}$ . Binding of  $[^3\text{H}]\text{cAMP}$  to the  $\text{B}^{\text{SS}}$ -state was detected at  $60\ \text{s}$  (Figure 3). The blockade is completed after  $20\text{--}30\ \text{s}$  and is equally rapid at  $2$  or  $10\ \text{nM}$  cAMP. Parts B and D of figure 3 reveal that the blockade follows first-order kinetics with a

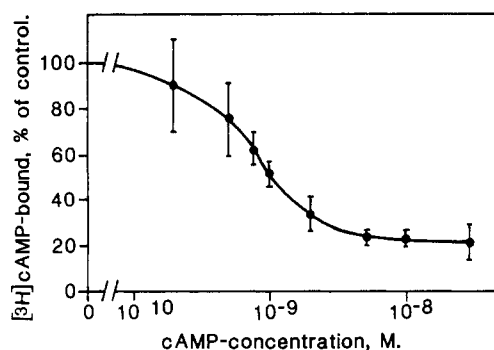


FIGURE 4: Dose-response curve of the blockade. Cells (180  $\mu$ L) were incubated with 20  $\mu$ L of cAMP at  $t = 0$ , yielding 5 mM dithiothreitol and the cAMP concentrations as indicated on the abscissa. At  $t = 20$  s 100  $\mu$ L of [ $^3$ H]cAMP (of the same concentration as the final cAMP concentration) was added, and the binding of [ $^3$ H]cAMP to  $B^{SS}$  was measured at  $t = 60$  s. In the control the cAMP and [ $^3$ H]cAMP were added simultaneously at  $t = 0$ . The results shown are the means and standard deviations of three experiments, each with quadruplicate incubations.

rate constant of  $0.17\text{ s}^{-1}$  for both cAMP concentrations ( $t_{1/2} = 4$  s).

**Dose-Response Curve of the Blockade.** In the previous section it was shown that 2 nM cAMP, which occupied only 10% of the sites, effectively blocked the binding of 2 nM [ $^3$ H]cAMP to the other  $B^{SS}$ -sites. It can be expected that the blockade cannot be induced at very low cAMP concentrations. cAMP (between 0.3 and 30 nM) was added to the cells at  $t = 0$ ; an identical concentration of [ $^3$ H]cAMP was added at 20 s, and binding of [ $^3$ H]cAMP to  $B^{SS}$  was detected at 60 s (Figure 4). This binding is compared with the binding of [ $^3$ H]cAMP at 60 s when cAMP and [ $^3$ H]cAMP were added simultaneously at 0 s (control). This demonstrates that 0.3 nM cAMP only slightly reduces the subsequent occupation of the  $B^{SS}$ -state with [ $^3$ H]cAMP. A half-maximal blockade is induced by about 0.7 nM cAMP, and it saturates at about 5 nM cAMP. It should be noted that the blockade is never more than 80%.

**Release of the Blockade by an Increase of the cAMP Concentration.** The results, showing a blockade in a transition of the B-sites that presumably transduce the cAMP signal to guanylate cyclase, may suggest that the blockade is the basis of adaptation of the cAMP-induced activation of guanylate cyclase. The guanylate cyclase of cells adapted to cAMP can be reactivated by adding a higher cAMP concentration (Van Haastert & Van der Heijden, 1983). The question whether the blockade can be released simply by increasing the cAMP concentration was answered by the experiment shown in Figure 5. The filled circles represent the binding to  $B^{SS}$  of 2 nM [ $^3$ H]cAMP plus 2 nM cAMP, both added at 0 s. The filled triangles represent the binding of [ $^3$ H]cAMP when 2 nM [ $^3$ H]cAMP is added at 20 s after 2 nM cAMP; as shown previously, binding of [ $^3$ H]cAMP is very low due to the blockade. During this incubation (open triangles) the cAMP concentration was increased at 40 s by the addition of 25 nM cAMP (nonradioactive). Binding of [ $^3$ H]cAMP to  $B^{SS}$  increases immediately and reaches almost the level when cells were incubated with 2 nM [ $^3$ H]cAMP plus 25 nM cAMP from the beginning (open circles). Apparently, the blockade in the transition of  $B^S$  to  $B^{SS}$  that induced by 2 nM cAMP is released (temporally) by an increase of the cAMP concentration to 25 nM.

The relationship between the cAMP concentration that induces the blockade and the subsequently added [ $^3$ H]cAMP concentration that releases the blockade is shown in Figure

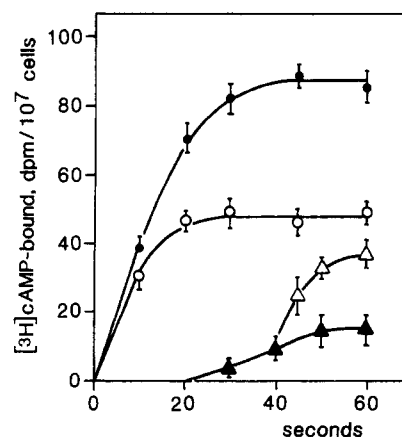


FIGURE 5: Kinetics of the release of the blockade by increasing the cAMP concentration. Cells (180  $\mu$ L) were incubated with 20  $\mu$ L of cAMP at  $t = 0$ , yielding 5 mM dithiothreitol and 2 nM cAMP. [ $^3$ H]cAMP (100  $\mu$ L, 2 nM) was added either at  $t = 0$  (●) or at  $t = 20$  s (▲). cAMP (10  $\mu$ L, yielding 25 nM) was added at  $t = 40$  s to a part of the incubation that received [ $^3$ H]cAMP at 20 s (Δ). The control, in which 2 nM cAMP, 2 nM [ $^3$ H]cAMP, and 25 nM cAMP were added at  $t = 0$  s, is also shown (○). The results are the means and standard deviations of triplicate incubations from an experiment repeated once.

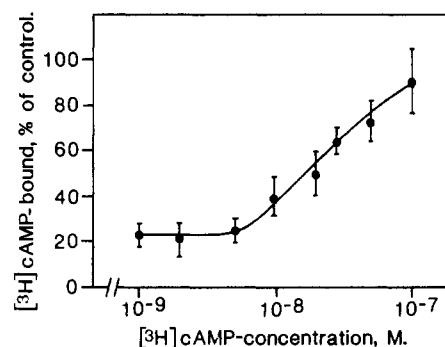


FIGURE 6: Release of the blockade by increasing the cAMP concentration; dose-response curve. Cells (180  $\mu$ L) were incubated with 20  $\mu$ L of cAMP at  $t = 0$ , yielding 5 mM dithiothreitol and 5 nM cAMP. At  $t = 20$  s 100  $\mu$ L of [ $^3$ H]cAMP was added (with the concentrations as indicated on the abscissa). Binding of [ $^3$ H]cAMP to  $B^{SS}$  was detected at 60 s. In the control incubation cAMP and [ $^3$ H]cAMP were added simultaneously at  $t = 0$  s. The results shown are the means and standard deviations of three experiments, each with triplicate incubations.

6. Cells were incubated with 5 nM cAMP at  $t = 0$ . At  $t = 20$  s different concentrations of [ $^3$ H]cAMP (1–100 nM) were added, and the binding of [ $^3$ H]cAMP to  $B^{SS}$  was detected at 60 s. This binding is compared with the binding of [ $^3$ H]cAMP when cAMP and [ $^3$ H]cAMP were added simultaneously at 0 s (control). The preincubation with 5 nM cAMP inhibits the subsequent binding of 5 nM [ $^3$ H]cAMP by about 80%. This inhibition remains identical when the concentration of [ $^3$ H]cAMP is lower than 5 nM (by which the total cAMP concentration is reduced). The inhibition is reduced when the concentration of [ $^3$ H]cAMP is higher than 5 nM. The blockade is removed almost completely by an increase from 5 to 100 nM. A half-maximal release of the blockade is obtained at about 30 nM.

**Release of the Blockade by Removing All cAMP.** It can be expected that the blockade will be released when all cAMP is removed (e.g., by degradation by cell surface phosphodiesterase). If adaptation of the cAMP-mediated activation of guanylate cyclase is caused by the blockade of the transition of  $B^S$  to  $B^{SS}$ , then the rate of deadaptation ( $t_{1/2} = 90$  s) should be identical with the rate at which the blockade is released.

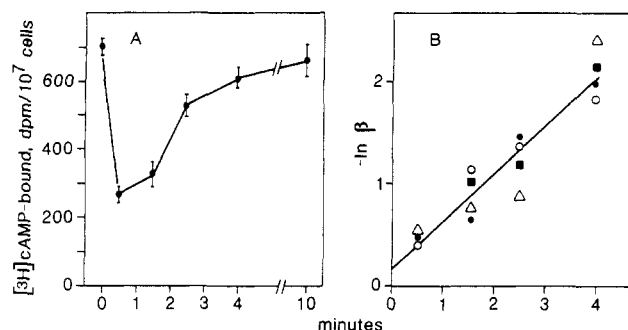


FIGURE 7: Release of blockade by reducing the cAMP concentration. (A) Cells (1 mL) were incubated with 10  $\mu$ L of cAMP without dithiothreitol (the cAMP concentration after addition was 10 nM). Due to the absence of the phosphodiesterase inhibitor, cAMP is degraded with a half-life of about 10 s. At 0.5, 1.5, 2.5, 4, and 10 min portions of the cell suspension (180  $\mu$ L) were incubated with 20  $\mu$ L of [<sup>3</sup>H]cAMP (yielding 5 mM dithiothreitol and 10 mM [<sup>3</sup>H]cAMP), and binding to B<sup>SS</sup> was measured 30 s later. The [<sup>3</sup>H]cAMP bound at 0 min represents the binding of 10 nM [<sup>3</sup>H]cAMP to B<sup>SS</sup> when cells were not prestimulated with cAMP. (B) Logarithmic transformation of the data of (A).  $\beta = 1 - \text{dpm}(t)/\text{dpm}(0)$ . The straight line indicates that the recovery of bound [<sup>3</sup>H]cAMP has first-order kinetics. The slope is  $7.6 \times 10^{-3} \text{ s}^{-1}$ , which yields a half-life of about 90 s. The results in (A) are from a typical experiment with triplicate incubations. The results in (B) are from four independent experiments.

The results of Figure 7 indeed show that this is the case. Cells were incubated at  $t = 0$  with 10 nM cAMP without the phosphodiesterase inhibition dithiothreitol, by which cAMP is degraded with a half-life of about 10 s. At different times thereafter, the cells were incubated with 10 nM [<sup>3</sup>H]cAMP for 30 s, and binding to B<sup>SS</sup> was measured (Figure 7A). At 30 s cells show a strongly reduced ability to bind [<sup>3</sup>H]cAMP. This ability is recovered slowly, and restored only after 4–10 min. Apparently, the blockade induced by cAMP is released only slowly after removal of the cAMP. This release shows first-order kinetics (Figure 7B) with a rate constant of  $7.6 \times 10^{-3} \text{ s}^{-1}$  ( $t_{1/2} = 90 \text{ s}$ ).

**There Is No Blockade When Cells Do Not Adapt.** Experiments on the cAMP-mediated cGMP response have revealed that *D. discoideum* cells show a strongly reduced adaptation at two conditions. First, aggregative cells at 0 °C adapt at least 30-fold slower than at 20 °C (Van Haastert, 1987). Second, undifferentiated cells do not show adaptation, cells starved for 1–2 h adapt partially, and adaptation is complete after a starvation period of about 2 h (Wuster & Butz, 1983, and unpublished results). The results of Figure 8A show that this developmental regulation of adaptation correlates well with the blockade of [<sup>3</sup>H]cAMP binding after a preincubation with cAMP.

At 0 °C the kinetics of association and dissociation of the cAMP-binding sites is only 2–3-fold slower than at 20 °C (Van Haastert et al., 1986). Nevertheless, adaptation of the cAMP-mediated cGMP response is strongly reduced (Van Haastert, 1987). A preincubation of cells with 4 nM cAMP at 0 °C inhibits the subsequent binding of [<sup>3</sup>H]cAMP to B<sup>SS</sup> by only 15% (Figure 8B). At 20 °C this inhibition is about 80%.

## DISCUSSION

The cAMP-mediated activation of adenylate and guanylate cyclase in *D. discoideum* is regulated by an adaptation process (Devreotes & Steck, 1979; Van Haastert & Van der Heijden, 1983). Cells adapt to constant cAMP stimuli but remain responsive to increments of the cAMP concentration. Adaptation of adenylate and guanylate cyclase stimulation are probably independent. (i) Adaptation of guanylate cyclase

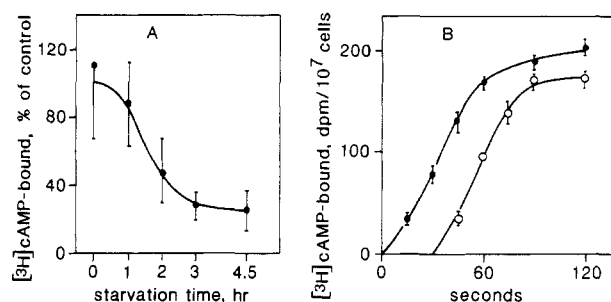


FIGURE 8: Reduced blockade in undifferentiated cells (A) and at 0 °C (B). (A) Cells were starved in suspension for different times. For each starvation period cells (180  $\mu$ L) were incubated at 20 °C with 20  $\mu$ L of cAMP at  $t = 0 \text{ s}$ , yielding 5 mM dithiothreitol and 4 nM cAMP. At  $t = 20 \text{ s}$  200  $\mu$ L of 4 nM [<sup>3</sup>H]cAMP was added, and binding of [<sup>3</sup>H]cAMP to B<sup>SS</sup> was measured at 60 s. The control contained cAMP and [<sup>3</sup>H]cAMP at  $t = 0$ . (B) Aggregative cells (90  $\mu$ L) were incubated at 0 °C with 10  $\mu$ L of cAMP at  $t = 0 \text{ s}$ , yielding 5 mM dithiothreitol and 4 nM cAMP. At  $t = 0 \text{ s}$  (●) or at  $t = 30 \text{ s}$  (○) 100  $\mu$ L of 4 nM [<sup>3</sup>H]cAMP was added, and the binding of [<sup>3</sup>H]cAMP to B<sup>SS</sup> was measured at the indicated times. The results shown are the means and standard deviations of triplicate (A) or quadruplicate (B) incubations from an experiment repeated once with similar results.

at 20 °C is 20 times faster than adaptation of adenylate cyclase (half-times are 3 s and 1 min, respectively). (ii) Adaptation of guanylate cyclase is absent at 0 °C, while adaptation of adenylate cyclase is only 2-fold slower than at 20 °C. (iii) Guanylate cyclase does deadapt at 0 °C, while adenylate cyclase does not (Van Haastert, 1987). (iv) Cells transformed with a mutated *ras* gene show an increased adaptation of guanylate cyclase, while adaptation of adenylate cyclase is not affected (Van Haastert et al., 1987). It has been suggested that covalent modification of the surface cAMP receptor (presumably phosphorylation) is the molecular mechanism of adaptation of adenylate cyclase. This hypothesis is based on the observation that receptor modification and adaptation of adenylate cyclase show similar kinetics, dose dependency, reversibility, and temperature dependency (Devreotes & Sherring, 1985). It should be noted that the phosphorylation state of the receptor does not influence the cAMP-mediated activation of guanylate cyclase. First, the stimulation of guanylate cyclase has adapted after a few seconds when the receptor has not yet been phosphorylated. Second, the receptor becomes phosphorylated at 0 °C, but guanylate cyclase stimulation does not adapt at this lowered temperature.

The differential adaptation of adenylate and guanylate cyclase agrees with, but does not prove, the hypothesis that signal transduction of extracellular cAMP to adenylate and guanylate cyclase proceeds via two subpopulations of surface receptors, which we designated A- and B-sites, respectively (Van Haastert, 1985; Kesbeke & Van Haastert, 1985). The B-sites show a series of transition upon binding of cAMP (Van Haastert et al., 1986). Initially, cAMP binds to a fast-exchanging state (B<sup>F</sup>), which has a half-life of dissociation of about 2.5 s. B<sup>F</sup> is converted rapidly ( $t_{1/2} = 4 \text{ s}$ ) to a more slowly dissociating state (B<sup>S</sup>) ( $t_{1/2} = 15 \text{ s}$ ), which is subsequently converted to a very slowly dissociating state (B<sup>SS</sup>) ( $t_{1/2} = 150 \text{ s}$ ). The B<sup>S</sup>- and B<sup>SS</sup>-states are sensitive to guanyl nucleotides and are transformed to the B<sup>F</sup>-state. A cycle of interactions between receptor, G-protein, and guanyl nucleotides has been proposed to account for these observations (Figure 1). In this cycle, and probably in any cycle of receptor conversion, the response induced by cAMP is proportional to the rate at which the cycle turns around. Therefore, it is probably more important to measure the transitions of occupied binding states than binding to these sites per se. The

transition leading to an activated G-protein is especially important. According to the model this transition equals the conversion of  $B^S$  to  $B^{SS}$ . In *D. discoideum* this transition is easily measured, because the occupied  $B^{SS}$ -state arises only by the transition from the occupied  $B^S$ -state and not by association of cAMP to empty  $B^{SS}$  (Van Haastert et al., 1986).

In this paper we have further investigated the hypothesis that the activation of guanylate cyclase is directly or indirectly mediated by the B-sites. The interconversions of the different states of the B-sites were examined under conditions in which the stimulation of guanylate cyclase was adapted. The major findings are the following: (i) A short incubation of *D. discoideum* cells with cAMP prevents the subsequent binding of [ $^3$ H]cAMP to  $B^{SS}$  if the total cAMP concentration is not increased by the addition of [ $^3$ H]cAMP. (ii) The cAMP-induced blockade of [ $^3$ H]cAMP binding is rapid, showing first-order kinetics with a half-time of 4 s. (iii) The blockade is induced by low cAMP concentrations. A half-maximal effect is induced by about 0.7 nM cAMP; at this concentration only 5% of the  $B^S$ - and  $B^{SS}$ -sites are occupied with cAMP. (iv) The cAMP-induced blockade of the binding of equimolar concentrations of [ $^3$ H]cAMP is released upon addition of a higher concentration of cAMP. The release is fast because [ $^3$ H]cAMP immediately starts to bind to  $B^{SS}$  after the increment of the cAMP concentration. (v) The cAMP-induced blockade is released slowly after removal of cAMP. Binding of equimolar concentrations of [ $^3$ H]cAMP to  $B^{SS}$  reappears with a half-time of about 90 s. (vi) Conditions that prevent full adaptation of the cGMP response result in only a partial blockade of the transition from  $B^S$  to  $B^{SS}$ .

The characteristics of the cAMP-induced blockade of cAMP binding to the  $B^{SS}$ -state of the B-receptor population are essentially identical with the cAMP-induced adaptation of guanylate cyclase. In contrast, these characteristics are quite different from those of the cAMP-induced adaptation of adenylate cyclase or the cAMP-induced modification (presumably phosphorylation) of the major cell surface receptor, which occurs with a half-time of a few minutes and takes place at 0 °C.

Although cAMP-induced adaptations of adenylate and guanylate cyclase probably occur independent of each other, they may proceed via a similar mechanism, i.e., an alteration of receptor G-protein interaction. Recently it has become possible to detect GTP-stimulated adenylate cyclase activity in *D. discoideum* membranes (Theibert & Devreotes, 1986; Van Haastert et al., 1987). In both studies it was observed that GTP stimulation of adenylate cyclase was lost in membranes that were derived from cells with an adapted adenylate cyclase.

The mechanism by which cAMP stimulates guanylate cyclase in *D. discoideum* is emerging. Recently, Europe-Finner and Newell (1985) and Small et al. (1986) have shown that  $IP_3$  and  $Ca^{2+}$  activate guanylate cyclase in permeabilized cells. Furthermore, these investigators have shown that GTP $\gamma$ S induces the accumulation of  $IP_3$  in these cells (Europe-Finner & Newell, 1987), suggesting a direct or indirect role for the G-protein-mediated activation of phospholipase C in the stimulation of guanylate cyclase in *D. discoideum*. It is tempting to suggest that adaptation of guanylate cyclase is associated with the inability to activate this G-protein, which is detected as the cAMP-induced blockade in the formation of the  $SS$ -state of the B-sites. Further work on the molecular

mechanism of adaptation of guanylate cyclase will focus on the physical identification of G-proteins and receptor subclasses and on their modification by cAMP.

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