Identification of an Activator Required for Elevation of Maturation-promoting Factor (MPF) Activity by γ-S-ATP

Shigeru Yamashita and James L. Maller

Department of Pharmacology, University of Colorado School of Medicine, Denver, Colorado 80262

Abstract. Maturation-promoting factor (MPF) is a cell cycle control element able to cause cells to enter M-phase upon microinjection and will induce metaphase in nuclei incubated in cell extracts. Previous work has shown that MPF is composed of a complex between p34$^{cdc\ 2}$ protein kinase and a B-type cyclin. In the present work γ-S-ATP was found to cause activation of MPF activity in partially purified preparations, but this activation was lost upon chromatography on Matrex Green gel A. Readdition of other Matrex Green fractions to purified MPF restored the ability of γ-S-ATP to activate MPF for nuclear breakdown as well as phosphorylation of histone H1. Use of the system described here will facilitate study of p34$^{cdc\ 2}$ kinase activation and identification of elements involved in MPF regulation.

MATURATION-promoting factor (MPF)[1] was first described in 1971 as a cytoplasmic activity appearing during meiosis in amphibian oocytes that could cause maturation when injected into resting oocytes, even in the absence of protein synthesis (Masui and Markert, 1971; Smith and Ecker, 1971). Subsequently, a similar activity was found in meiosis and mitosis in other cells, leading to the concept that MPF was a universal regulator of M-phase in eucaryotic cells (Kishimoto et al., 1982). Although MPF was believed to be a protein kinase or an activator of a kinase, little progress was made in its characterization until recently, with the development of a cell-free system from unfertilized eggs that could carry out early mitotic events in vitro (Lohka and Masui, 1983; Lohka and Maller, 1985; Miake-Lye and Kirschner, 1985). Using this system, Lohka et al. (1988) purified MPF to near homogeneity and showed that it consisted of a 32–34-kD protein kinase complexed with a 45-kD substrate. Subsequently, Gautier et al. (1988) showed that the 34-kD protein kinase component was a *Xenopus* homologue of the *cdc* 2$^+$ gene product, designated p34$^{cdc\ 2}$, which had been identified in fission yeast as a crucial regulator of the $G_2 \rightarrow M$ transition in the cell cycle (Lee and Nurse, 1988). In addition, Dunphy et al. (1988) found that the product of the *Schizosacchanomyces pombe suc I* gene, which binds p34$^{cdc\ 2}$, blocked MPF action in cell-free extracts. Human p34$^{cdc\ 2}$ was already known to complement mutations in *cdc* 2$^+$ in fission yeast, demonstrating its important function was conserved in mitosis from yeast to man (Lee and Nurse, 1987).

Recently, we demonstrated that the 45-kD component of *Xenopus* MPF was a B-type cyclin, as shown by immunoprecipitation and immunoblotting by specific *Xenopus* cyclin antibodies (Gautier et al., 1990). MPF from starfish oocytes has also been found to be a heterodimer of a B-type cyclin with p34$^{cdc\ 2}$ (Labbé et al., 1989*a*). Cyclins are proteins that are continuously synthesized and accumulate during interphase but that undergo degradation at the metaphase → anaphase transition (Evans et al., 1983; Pines and Hunt, 1987; Pines and Hunter, 1989). Cyclins are homologous to the *cdc 13*$^+$ gene in *S. pombe*, which is required for *cdc 2* kinase activation (Solomon et al., 1988; Goebl and Byers, 1988; Booher and Beach, 1988). Several investigators have found that cell-free extracts of *Xenopus* eggs are able to synthesize and degrade cyclin between S- and M-phase. Moreover, cyclin synthesis alone (Minshull et al., 1989; Murray and Kirschner, 1989) or addition of purified fractions containing only cyclin (Lohka et al., 1988), has been reported to drive nuclei in extracts into M-phase, and cyclin degradation is required for the M → S transition (Murray et al., 1989). Cyclin is phosphorylated by p34$^{cdc\ 2}$ in the MPF complex (Lohka et al., 1988; Gautier et al., 1988), and exogenous bacterially produced cyclin is a substrate for phosphorylation and thiophosphorylation by purified MPF (Gautier et al., 1990). The thiophosphorylation of cyclin is of particular interest because γ-S-ATP addition to crude fractions was essential in the purification of *Xenopus* egg MPF (Lohka et al., 1988) and Cyert and Kirschner (1988) reported that addition of γ-S-ATP to crude fractions of oocytes stimulated activation of "pre-MPF." Moreover, they also reported that antibodies to thiophosphate were able to deplete partially purified MPF treated with γ-S-ATP (Cyert et al., 1988). However, at present it is not known if the thiophosphorylation of cyclin has any functional effect on MPF.

At present two different changes in the p34$^{cdc\ 2}$ kinase component of MPF have been demonstrated to occur during M-phase in different cell types. In HeLa cells, Draetta and

1. *Abbreviations used in this paper*: MG, Matrex Green; MPF, maturation-promoting factor; NEBD, nuclear envelope breakdown.

Beach (1988) showed that in late G_2 phase a minor fraction of $p34^{cdc\ 2}$ entered a high molecular mass complex with a 62-kD protein and the 13-kD product of the *suc I* gene. Formation of this complex was associated with elevated protein kinase activity, but it is not known if this complex represents MPF in HeLa cells. In the budding yeast *Saccharomyces cerevisiae*, a small fraction of the *CDC 28* gene product, a functional homologue of *cdc 2*$^+$, enters a high molecular mass complex with a 40-kD substrate and exhibits elevated protein kinase activity (Wittenberg and Reed, 1988). It is not known if this complex represents MPF in *S. cerevisiae*. An M-phase-activated H1 kinase has also been identified in several cell types as a complex of $p34^{cdc\ 2}$ with other proteins (Arion et al., 1988; Labbé et al., 1989*b*; Langan et al., 1989).

In addition to association with other components, phosphorylation of $p34^{cdc\ 2}$ has been identified as a regulatory mechanism controlling its protein kinase activity. Gautier et al. (1989) showed that in interphase *Xenopus* oocytes and activated eggs, $p34^{cdc\ 2}$ was highly phosphorylated, and its histone H1 kinase activity was low, whereas upon entry into M-phase in either meiosis or mitosis, $p34^{cdc\ 2}$ was dephosphorylated and its histone H1 protein kinase activity became activated. Dorée and co-workers also reported apparent dephosphorylation of starfish oocyte $p34^{cdc\ 2}$ upon entry into M-phase (Labbé et al., 1989*b*). The phosphorylation occurs on both tyrosine and threonine residues, although quantitative removal of tyrosine phosphate does not activate mouse $p34^{cdc\ 2}$ (Dunphy and Newport, 1989; Morla et al., 1989). However, Gould and Nurse (1989) identified the phosphotyrosine site in *S. pombe cdc 2* and showed mutation in that site caused mitotic catastrophe. In both frog and starfish, the kinetics of H1 kinase activity changes are very similar to changes in MPF activity monitored by injection of oocytes. During these changes in protein kinase activity of MPF, no important change occurs in the amount of $p34^{cdc\ 2}$ present in the cell (Gautier et al., 1989; Labbé et al., 1989*a*). This suggests that the disappearance of MPF kinase activity during interphase represents inactivation of the kinase component, not its destruction.

Consistent with this concept, Dunphy and Newport (1988) found that MPF activity could be recovered from ammonium sulfate fractions of interphase egg extracts in the presence of adenosine (3′-*O*-thio)-triphosphate (γ-S-ATP) and a small amount of crude active MPF. In this paper we have investigated the activation of MPF by γ-S-ATP at different stages of purification and identified a protein activator required for activation by γ-S-ATP.

Materials and Methods

Materials

γ-S-ATP and histone H1 were from Boehringer Mannheim Diagnostics, Inc., Houston, TX. DEAE-Sephacel and heparin-Sepharose were from Pharmacia Inc., Piscataway, NJ, and Matrex Green gel A was from Amicon Corp., Danvers, MA.

Preparation of Metaphase MPF and Latent MPF

Metaphase MPF was prepared as described by Lohka et al. (1988) except that the heparin-Sepharose column was eluted with 600 mM NaCl instead of 400 mM NaCl when γ-S-ATP was omitted from the preparation as indicated in the figure legends. A unit of MPF is defined as that amount in a volume of 50 μl that causes at least 20% of newly assembled pronuclei to undergo nuclear envelope breakdown (NEBD) within 2 h in a final volume of 75 μl containing 2×10^6 sperm nuclei/ml (Lohka et al., 1988). Latent MPF was prepared as described by Dunphy and Newport (1988) except that eggs were activated by treatment with the calcium ionophore A23187 (5 μg/ml in 50% medium OR2 for 10 min), followed by washing, and incubation in 10% OR2 until 30 min, at which point eggs were crushed by centrifugation at 10,000 *g* for 15 min. Pronuclear extracts for assaying MPF were prepared as described by Lohka and Maller (1985).

Preparation of Activator Fraction

The activator fraction was eluted in the 600–1,200 mM NaCl fraction from the Matrex Green gel A column used in MPF purification. Proteins in the pooled fractions derived from ~100 ml of eggs were precipitated by addition of an equal volume of 3.8 M ammonium sulfate, collected by centrifugation, dissolved in 0.5 ml of dialysis buffer, and dialyzed overnight. Dialysis buffer was 100 mM β-glycerophosphate, 5 mM EGTA, 15 mM $MgCl_2$, 1 mM DTT, 20 mM Hepes, pH 7.5. The activator was stored at −70°C in small aliquots.

Activation of Latent and Metaphase MPF

60 μl of latent MPF was mixed with 3 μl of active, metaphase MPF containing 1 unit of activity and 3 μl of 6.6 mM γ-S-ATP. After incubation for 2 h at 22°C, MPF activity was assayed as described by Lohka et al. (1988). Controls were carried out with γ-S-ATP with latent or metaphase MPF alone or latent and metaphase MPF mixed without any γ-S-ATP. Activation of metaphase MPF was performed by incubating 18 μl of Matrex Green–purified MPF containing 1 U of activity with 45 μl of the activator fraction and 3 μl of 6.6 mM γ-S-ATP for 90 min at 22°C. Controls were carried out by incubation of MPF and activator without γ-S-ATP. MPF activity was then assessed under standard conditions as described above. In some experiments activation mixtures also contained 1×10^8 cpm of γ-^{35}S-ATP and the products of the reaction were analyzed by SDS gel electrophoresis and autoradiography. H1 histone kinase assays were carried out as described previously (Gautier et al., 1988).

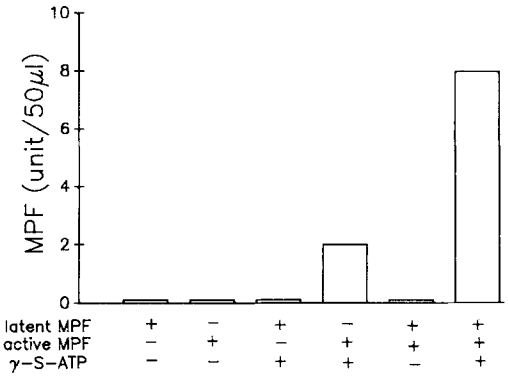

Figure 1. Activation of metaphase MPF or latent MPF by γ-S-ATP. Latent MPF was isolated as described in Materials and Methods from unfertilized eggs activated for 30 min by treatment with the calcium ionophore A23187. Active metaphase MPF was purified from nonactivated eggs through ammonium sulfate precipitation by the method of Lohka et al. (1988) and diluted to 0.7 U per addition so that it alone had no ability to cause NEBD in the absence of γ-S-ATP. Units less than one are depicted as zero in the graph. After the indicated components were incubated in a final volume of 25 μl at 22°C for 120 min, various dilutions were added to 12.5 μl of cell-free extracts containing newly assembled nuclei and the extent of nuclear breakdown assessed by phase contrast and fluorescence microscopy. A unit of MPF activity was defined as the reciprocal of the highest dilution of MPF that caused at least 20% of nuclei to undergo NEBD. The data show crude active MPF can be further activated twofold by γ-S-ATP alone and latent MPF activation requires both active MPF and γ-S-ATP.

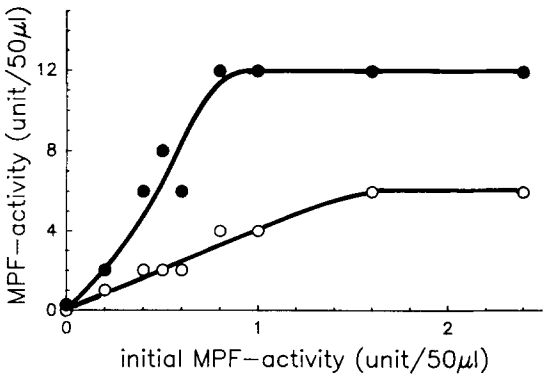

Figure 2. Dose-dependence for metaphase MPF activation of latent MPF. Different amounts of metaphase MPF were used in the activation of latent MPF as described in Fig. 1. The data show 0.8 U of metaphase MPF in combination with γ-S-ATP is sufficient to cause maximal activation of latent MPF. (●) γ-S-ATP plus latent MPF; (○) γ-S-ATP alone.

Results

In initial investigations, we carried out experiments similar to those described by Dunphy and Newport (1988). Ammonium sulfate fractions were prepared from unfertilized eggs in interphase after activation by treatment with the calcium ionophore A23187 (latent MPF). These fractions were then incubated with γ-S-ATP and a small amount of an ammonium sulfate fraction of MPF from metaphase-arrested unfertilized eggs (active metaphase MPF but an amount insufficient to cause any NEBD by itself in vitro). After 60 min, sperm pronuclei assembled in the cell-free system were added and NEBD was assessed after an additional 60 min by fluorescence microscopy. As reported originally by Dunphy and Newport (1988), we observed elevated MPF activity in the cell-free system when these three components were incubated together (Fig. 1). However, we carried out an additional control experiment not reported by Dunphy and Newport (1988) and found that γ-S-ATP alone was able to activate ammonium-sulfate purified metaphase MPF itself (Fig. 1). This indicated that the elevated MPF activity in the system reported by Dunphy and Newport (1988) was a mixture of effects of γ-S-ATP on the active metaphase MPF component itself as well as on the latent MPF component from interphase eggs. Therefore, subsequent experiments focussed on the activation of metaphase MPF from M-phase eggs. The dose dependence of γ-S-ATP-dependent activation of metaphase MPF was compared in the presence and absence of latent MPF as shown in Fig. 2. Consistent with Fig. 1, substantial activation of metaphase MPF by γ-S-ATP alone was evident at different metaphase MPF concentrations, but maximal activation of metaphase MPF by γ-S-ATP occurred at higher MPF concentrations than were required for maximal activation of latent MPF (Fig. 2). The extent of activation of metaphase MPF by γ-S-ATP alone varied considerably from one preparation to another, ranging from 1.5- to 4-fold with an initial MPF activity of 1 U/50 μl.

The metaphase MPF used by Dunphy and Newport (1988) and also in Figs. 1 and 2 is a crude ammonium sulfate preparation that is <10-fold purified over cytosol. In an attempt to analyze the system more rigorously, we have examined the activation of metaphase MPF itself in fractions from various steps of the MPF purification procedure that we have reported previously (Lohka et al., 1988). As shown in Fig. 3, metaphase MPF purified through TSK3,000SW chromatography was no longer able to be activated by γ-S-ATP alone, although it would still support activation of latent MPF from interphase eggs in the presence of γ-S-ATP. Subsequent experiments demonstrated the activating component was removed at the Matrex Green chromatography step. Whether the latent MPF preparation also contains the activating component removed from metaphase MPF by Matrex Green chromatography will require purification of the latent form of MPF.

The active metaphase MPF used in Figs. 1–3 was prepared according to the procedure of Lohka et al. (1988) that uses addition of γ-S-ATP to crude extracts and after ammonium sulfate precipitation. The γ-S-ATP-dependent activation of metaphase MPF in Figs. 1–3 was thus superimposed on a preparation that had already been incubated with γ-S-ATP. To maximize the effect of γ-S-ATP, we investigated the activation of metaphase MPF in ammonium sulfate preparations made without addition of γ-S-ATP. Although the recovery of metaphase MPF in such preparations was only 50% of that seen when γ-S-ATP was included, addition of γ-S-ATP caused a greater increase in MPF activity than when a γ-S-ATP incubation had occurred earlier in the purification (data not shown). Therefore, subsequent experiments used MPF preparations that had not been previously treated with γ-S-ATP. The time course of activation of such a metaphase MPF preparation and its dependence on γ-S-ATP concentration were analyzed, as shown in Fig. 4. The activating effect was maximal after 15 min of incubation and ~150 μM γ-S-ATP was required for maximal activation.

Because the component required for activation of MPF was separated from MPF by Matrex Green (MG) gel A chromatography (Fig. 3), we assessed the ability of fractions from the MG column to reconstitute the ability of metaphase MG MPF to be activated further by γ-S-ATP. As shown in

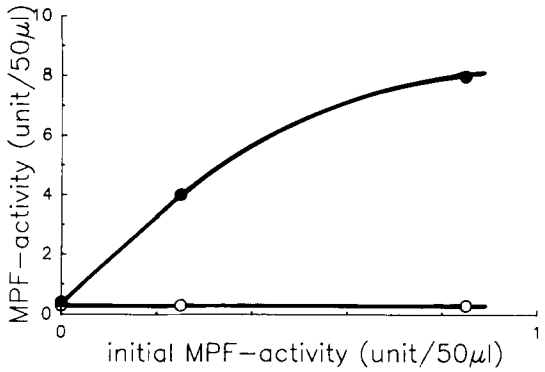

Figure 3. Removal of an activating component during MPF purification. Metaphase MPF was purified through TSK3,000SW chromatography, and analyzed for ability to activate latent MPF. (●) γ-S-ATP plus latent MPF; (○) ATP-γ-S alone. The data show the more highly purified MPF is not activated by γ-S-ATP alone (compare with Fig. 2) but can still activate latent MPF in the presence of γ-S-ATP.

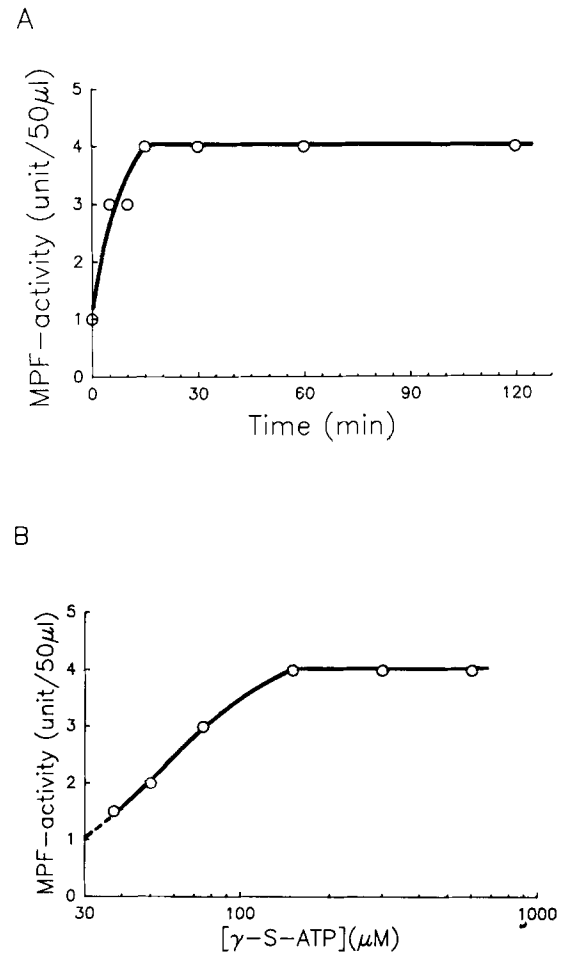

Figure 4. Dependence of metaphase MPF activation on time and γ-S-ATP. (*A*) γ-S-ATP (300 μM) was mixed with metaphase MPF (0.8 U) prepared without γ-S-ATP for the indicated times at 22°C and then MPF activity was assayed in the cell-free system. The data show γ-S-ATP-dependent activation is maximal by 15 min. (*B*) γ-S-ATP concentration dependence. Metaphase MPF (0.8 U) was incubated with varying concentrations of γ-S-ATP at 22°C for 2 h and then assayed as described in Materials and Methods. The data show 150 μM γ-S-ATP is sufficient for maximal activation.

Fig. 5, the 600–1,200 mM eluate of the MG column was able to restore the ability of γ-S-ATP to activate active MG MPF, but no MPF activity was evident in this fraction alone even when incubated with γ-S-ATP.

These results indicate that a thiophosphorylated component is necessary for activation of metaphase MPF. To assess whether MPF itself might be thiophosphorylated under these conditions, we incubated extracts of M-phase eggs with ^{35}S-γ-SATP or microinjected ^{35}S-γ-S-ATP into oocytes undergoing germinal vesicle breakdown and analyzed both total thiophosphorylation and the level of radiolabel into the 34-kD subunit of MPF after immunoprecipitation with the PSTAIR antibody against p34$^{cdc\ 2}$. Although a number of proteins were labeled in vivo or in vitro with γ-S-ATP, after immunoprecipitation no radiolabel was detected in the immunoprecipitate (data not shown), most likely because thio-ATP competes very poorly with ortho-ATP for phosphorylation (Erikson and Maller, 1989). Further analysis of thiophosphorylated proteins was evaluated in assays involving addition of ^{35}S-γ-S-ATP to the activator fraction in the presence and absence of metaphase MPF. A thiophosphorylated band of M_r = 45 kD is evident in both the metaphase MPF alone and the activator fraction alone, but the number of thiophosphorylated proteins visible when the two fractions are mixed is too great to permit identification of specifically enhanced thiophosphoproteins (not shown). Purified MPF contains a subunit of M_r = 45 kD (Lohka et al., 1988) which has been identified as a B-type cyclin and which can be thiophosphorylated by γ-S-ATP (Gautier et al., 1990). Preliminary experiments indicate that antibody to either cyclin B1 or B2, both of which are present in Mono S purified MPF (Gautier et al., 1990), can immunoprecipitate a 45-kD thiophosphorylated band in these extracts (Yamashita, S., and J. Gautier, unpublished results). However, under conditions where MPF is activated, the amount of radiolabeled thiophosphate in the 45-kD protein is unchanged.

These results demonstrate the presence of an activator of MPF in the cytoplasm of metaphase-arrested eggs. This activator is necessary for activation of partially purified MPF from metaphase-arrested eggs. The reaction is unlikely to represent an autoactivation because no MPF activity was evident in the activator fraction in the presence or absence of γ-S-ATP, and increasing the amount of MG-purified MPF in the system could not substitute for the activator fraction (data not shown). Dunphy and Newport (1988) reported and we have confirmed here that interphase eggs contain a latent form of MPF that conceivably could also be present in the activator fraction. To address this possibility, MPF activated by γ-S-ATP and the activator was diluted to give the same MPF concentration as initially (1 U/50 μl), and then fresh activator plus γ-S-ATP was added. No further increase in MPF activity was evident (data not shown), eliminating the possibility that latent MPF was present in the activator fraction.

Discussion

Two general approaches to study of the cell cycle have been productive to date. One approach has used the power of mo-

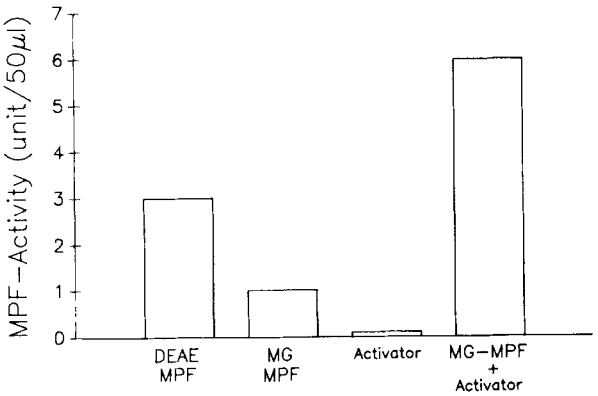

Figure 5. Loss and restoration of MPF activation by γ-S-ATP. Aliquots of MPF fractions containing 1 U of activity from various stages of purification without initial γ-S-ATP treatment were incubated with γ-S-ATP, and assayed for activity as in Fig. 1. Purification from DEAE to MG revealed a loss of ability to be activated. However, readdition of the 0.6–1.2 M eluate from the MG column to MG-MPF restored the ability of γ-S-ATP to activate MPF (MG-MPF/activator). This material is referred to as the "activator" fraction. Incubation of the activator alone with γ-S-ATP did not produce any MPF activity.

lecular genetics in both fission and budding yeast to identify genes critical for cell cycle control (see Lee and Nurse, 1988 for review). This work has identified p34$^{cdc\ 2}$ as a central regulator involved in the $G_2 \rightarrow M$ transition and uncovered a network of other cell cycle control genes that regulate *cdc 2*$^+$ activity, including the products of the *wee 1*$^+$, *nim 1*$^+$, *suc I*$^+$, *cdc 25*$^+$, and *cdc 13*$^+$ genes (Russell and Nurse, 1987*a*, *b*; Solomon et al., 1988; Goebl and Byers, 1988; Hayles et al., 1986; Simanis and Nurse, 1985). A limitation to the genetic approach is that it is often difficult to obtain the functionally active protein products of the genes. This limitation is absent in the biochemical approach to the cell cycle, which has been used to purify MPF as a major cell cycle control element in the $G_2 \rightarrow M$ transition (Lohka et al., 1988). Both the genetic and biochemical approaches have converged on MPF in the light of evidence that MPF is a complex of p34$^{cdc\ 2}$ and p45^{cyclin}, homologues of two cell cycle control genes identified in yeast. In this paper we have continued the biochemical approach to cell cycle control, investigating in particular the mechanism of activation of MPF. We have identified in metaphase MPF an "activator" component that is required for activation of MPF by γ-S-ATP.

Recent studies have shown that the activation of MPF by the activator fraction is also correlated with activation of the histone H1 kinase activity of *cdc 2*, as might be expected. In terms of kinase activation, p34$^{cdc\ 2}$ kinase activity in MPF has been found by several laboratories to be activated by dephosphorylation during the cell cycle both in vivo and in vitro (Gautier et al., 1989; Morla et al., 1989; Labbé et al., 1989*a*; Dunphy and Newport, 1989; Gould and Nurse, 1989). This biochemical finding is consistent with the genetic evidence in *S. pombe* that the function of the *cdc 2*$^+$ gene is inhibited by the product of the *wee 1*$^+$ gene, which is predicted to encode a serine/threonine protein kinase (Russell and Nurse, 1987*a*). The inhibitory function of this gene is itself inactivated by the product of another gene called *nim 1*$^+$, which also is predicted to encode a serine/threonine protein kinase (Russell and Nurse, 1987*b*). Given the high degree of conservation of mitotic controls it is therefore tempting to speculate that the requirement for γ-S-ATP for activation of MPF reflects the irreversible inactivation of *wee 1*$^+$ due to thiophosphorylation by a homologue of the *nim 1*$^+$ gene. Alternatively, the activator could be a p34$^{cdc\ 2}$ phosphatase that was itself activated by thiophosphorylation. Finally, the product of the *cdc25*$^+$ gene is involved in the timing of p34$^{cdc\ 2}$ activation and could potentially be involved here. These possibilities cannot be rigorously evaluated until the activator protein has been purified and characterized and the protein kinase that phosphorylates it identified.

We thank Jean Gautier for stimulating discussions and for immunoprecipitating cyclins from the activator fraction.

This work was supported by a grant to J. L. Maller from the National Institutes of Health (GM26743). S. Yamashita was supported by a fellowship from the Uehara Memorial Foundation, and is on leave from the Department of Pharmacology, Faculty of Medicine, University of Tokyo, Japan.

Received for publication 23 August 1989 and in revised form 21 December 1989.

References

Arion, D., L. Meijer, L. Brizuela, and D. Beach. 1988. *cdc 2* is a component of the M-phase-specific H1 kinase: evidence for identity with MPF. *Cell.* 55:371–378.

Booher, R., and D. Beach. 1988. Involvement of *cdc 13*$^+$ in mitotic control in *Schizosaccharomyces pombe*: possible interaction of the gene product with microtubules. *EMBO (Eur. Mol. Biol. Organ.) J.* 7:2321–2327.

Cyert, M., and M. W. Kirschner. 1988. Regulation of MPF activity *in vitro*. *Cell.* 53:185–195.

Cyert, M. S., T. Scherson, and M. W. Kirschner. 1988. Monoclonal antibodies specific for thiophosphorylated proteins recognize *Xenopus* MPF. *Dev. Biol.* 129:209–216.

Draetta, G., and D. Beach. 1988. Activation of *cdc 2* protein kinase during mitosis in human cells: cell cycle-dependent phosphorylation and subunit rearrangement. *Cell.* 54:17–26.

Dunphy, W. G., and J. W. Newport. 1988. Mitosis-inducing factors are present in a latent form during interphase in the *Xenopus* embryo. *J. Cell Biol.* 106:2047–2056.

Dunphy, W. G., and J. W. Newport. 1989. Fission yeast p13 blocks mitotic activation and tyrosine dephosphorylation of the *Xenopus cdc 2* protein kinase. *Cell.* 58:181–191.

Dunphy, W. G., L. Brizuela, D. Beach, and J. Newport. 1988. The *Xenopus cdc 2* protein is a component of MPF, a cytoplasmic regulator of mitosis. *Cell.* 54:423–431.

Erikson, E., and J. L. Maller. 1989. Biochemical characterization of the p34$^{cdc\ 2}$ protein kinase component of purified maturation-promoting factor from *Xenopus* eggs. *J. Biol. Chem.* 264:19577–19582.

Evans, T., E. Rosenthal, J. Youngblom, D. Distel, and T. Hunt. 1983. Cyclin: a protein specified by maternal mRNA that is destroyed at each cleavage division. *Cell.* 33:389–396.

Gautier, J., C. Norbury, M. Lohka, P. Nurse, and J. Maller. 1988. Purified maturation-promoting factor contains the product of a *Xenopus* homolog of the fission yeast cell cycle control gene *cdc 2*$^+$. *Cell.* 54:433–439.

Gautier, J., T. Matsukawa, P. Nurse, and J. Maller. 1989. Dephosphorylation and activation of *Xenopus* p34^{cdc2} protein kinase during the cell cycle. *Nature (Lond.).* 339:626–629.

Gautier, J., J. Minshull, M. J. Lohka, M. Glotzer, T. Hunt, and J. L. Maller. 1990. Cyclin is a component of maturation-promoting factor from *Xenopus*. *Cell.* 60:487–494.

Goebl, M., and B. Byers. 1988. Cyclin in fission yeast. *Cell.* 54:738–740.

Gould, K., and P. Nurse. 1989. Tyrosine phosphorylation of the fission yeast *cdc 2* protein kinase regulates entry into mitosis. *Nature (Lond.).* 342:39–45.

Hayles, J., D. Beach, B. Durkacz, and P. Nurse. 1986. The fission yeast cell cycle control gene *cdc 2*; isolation of a sequence *suc I* that suppresses *cdc 2* mutant function. *Mol. Gen. Genet.* 202:291–293.

Kishimoto, T., R. Kuriyama, H. Kondo, and H. Kanatani. 1982. Generality of the action of various maturation-promoting factors. *Exp. Cell Res.* 137:121–126.

Labbé, J. C., J.-P. Capony, D. Caput, J. C. Cavadore, J. Derancourt, M. Kaghad, J. -M. Lelias, A. Picard, and M. Dorée. 1989*a*. MPF from starfish oocytes at first meiotic metaphase is a heterodimer containing one molecule of *cdc 2* and one molecule of cyclin B. *EMBO (Eur. Mol. Biol. Organ.) J.* 8:3053–3058.

Labbé, J. C., A. Picard, G. Peaucellier, J. C. Cavadore, P. Nurse, and M. Dorée. 1989*b*. Purification of MPF from starfish: identification as the H1 histone kinase p34$^{cdc\ 2}$ and a possible mechanism for its periodic activation. *Cell.* 57:253–263.

Langan, T. A., J. Gautier, M. Lohka, R. Hollingsworth, S. Moreno, P. Nurse, J. Maller, and R. Sclafani. 1989. Mammalian growth-associated H1 histone kinase: a homolog of *cdc 2*$^+$/*CDC28* protein kinases controlling mitotic entry in yeast and frog cells. *Mol. Cell. Biol.* 9:3860–3868.

Lee, M. G., and P. Nurse. 1987. Complementation used to clone a human homologue of the fission yeast cycle control gene *cdc 2*. *Nature (Lond.).* 327:31–35.

Lee, M. G., and P. Nurse. 1988. Cell cycle control genes in fission yeast and mammalian cells. *Trends Genet.* 4:287–290.

Lohka, M. J., and Y. Masui. 1983. Formation *in vitro* of sperm pronuclei and mitotic chromosomes induced by amphibian ooplasmic contents. *Science (Wash. DC).* 220:719–721.

Lohka, M. J., and J. L. Maller. 1985. Induction of nuclear envelope breakdown, chromosome condensation, and spindle formation in cell-free extracts. *J. Cell Biol.* 101:518–523.

Lohka, M. J., M. K. Hayes, and J. L. Maller. 1988. Purification of maturation-promoting factor, an intracellular regulator of early mitotic events. *Proc. Natl. Acad. Sci. USA.* 85:3009–3013.

Masui, Y., and C. L. Markert. 1971. Cytoplasmic control of nuclear behavior during meiotic maturation of frog oocytes. *J. Exp. Zool.* 177:129–146.

Miake-Lye, R., and M. W. Kirschner. 1985. Induction of early mitotic events in a cell-free system. *Cell.* 41:165–175.

Minshull, J., J. Blow, and T. Hunt. 1989. Translation of cyclin mRNA is necessary for extracts of activated *Xenopus* eggs to enter mitosis. *Cell.* 56:947–956.

Morla, A. O., G. Draetta, D. Beach, and J. Y. J. Wang. 1989. Reversible tyrosine phosphorylation of *cdc 2*: dephosphorylation accompanies activation during entry into mitosis. *Cell.* 58:193–203.

Murray, A. W., and M. Kirschner. 1989. Cyclin synthesis drives the early embryonic cell cycle. *Nature (Lond.).* 339:275–280.

Murray, A. W., M. J. Solomon, and M. Kirschner. 1989. The role of cyclin synthesis and degradation in the control of MPF activity. *Nature (Lond.).*

339:280–286.
Pines, J., and T. Hunt. 1987. Molecular cloning and characterization of the mRNA for cyclin from sea urchin eggs. *EMBO (Eur. Mol. Biol. Organ.) J.* 6:2987–2995.
Pines, J., and T. Hunter. 1989. Isolation of a human cyclin cDNA: evidence for cyclin mRNA and protein regulation in the cell cycle and for interaction with $p34^{cdc\ 2}$. *Cell.* 58:833–846.
Russell, P., and P. Nurse. 1987*a*. Negative regulation of mitosis by *wee* 1^+, a gene encoding a protein kinase homolog. *Cell.* 49:559–567.
Russell, P., and P. Nurse. 1987*b*. The mitotic inducer *nim* 1^+ functions in a regulatory network of protein kinase homologs controlling the initiation of mitosis. *Cell.* 49:569–576.
Simanis, V., and P. Nurse. 1986. The cell cycle control gene *cdc* 2^+ of fission yeast encodes a protein kinase potentially regulated by phosphorylation. *Cell.* 45:261–268.
Smith, D., and R. E. Ecker. 1971. The interaction of steroids with *Rana pipiens* oocytes in the induction of maturation. *Dev. Biol.* 25:232–247.
Solomon, M., R. Booher, M. Kirschner, and D. Beach. 1988. Cyclin in fission yeast. *Cell.* 54:738–739.
Wittenberg, C., and S. I. Reed. 1988. Control of the yeast cell cycle is associated with assembly/disassembly of the *CDC 28* protein kinase complex. *Cell.* 54:1061–1072.