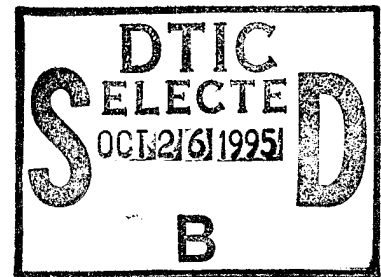AD_____

GRANT NO: DAMD17-94-J-4142

TITLE: Functions of Wild-type and Mutant Forms of p53 in Breast
Cancer

PRINCIPAL INVESTIGATOR(S):   Doctor XinBin Chen

CONTRACTING ORGANIZATION: Columbia University in the
                                City of New York
                            New York, New York   10027

REPORT DATE: August 17, 1995

TYPE OF REPORT: Annual

DTIC
SELECTED
OCT 26 1995
B

PREPARED FOR: U.S. Army Medical Research and Materiel Command
                   Fort Detrick, Maryland   21702-5012

DISTRIBUTION STATEMENT: Approved for public release;
                          distribution unlimited

The views, opinions and/or findings contained in this report are
those of the author(s) and should not be construed as an official
Department of the Army position, policy or decision unless so
designated by other documentation.

19951024 195

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE August 17, 1995	3. REPORT TYPE AND DATES COVERED Annual August 1, 1994 – July 31, 1995

4. TITLE AND SUBTITLE
Functions of Wild-Type and Mutant Forms of p53 in Breast Cancer

5. FUNDING NUMBERS
DAMD17-94-J-4142

6. AUTHOR(S)
Dr. Xinbin Chen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Columbia University
New York, New York 10027

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Cells induced to accumulate the p53 tumor suppressor protein have been shown to arrest in G1. This arrest is characterized by accumulation of the cyclin dependent kinase (CDK) inhibitor p21 (WAF1/CIP1) and of underphosphorylated forms of retinoblastoma protein (pRB). We show here that accumulation of the wild-type p53 protein in either human or murine cells markedly increases expression of cyclin D1. The induction of cyclin D1 can also be mediated by a target of p53, the p21 (WAF1/CIP1) inhibitor of cyclin-dependent kinases. The relationship between the induction of cyclin D1 and G1 arrest defines a new cellular response to p53.

14. SUBJECT TERMS
p53; cyclin D1; p21 (WAF1/CIP1); cell cycle control

15. NUMBER OF PAGES
24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

FOREWORD

Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the US Army.

_____ Where copyrighted material is quoted, permission has been obtained to use such material.

_____ Where material from documents designated for limited distribution is quoted, permission has been obtained to use the material.

_____ Citations of commercial organizations and trade names in this report do not constitute an official Department of Army endorsement or approval of the products or services of these organizations.

_____ In conducting research using animals, the investigator(s) adhered to the "Guide for the Care and Use of Laboratory Animals," prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Resources, National Research Council (NIH Publication No. 86-23, Revised 1985).

_____ For the protection of human subjects, the investigator(s) adhered to policies of applicable Federal Law 45 CFR 46.

X In conducting research utilizing recombinant DNA technology, the investigator(s) adhered to current guidelines promulgated by the National Institutes of Health.

X In the conduct of research utilizing recombinant DNA, the investigator(s) adhered to the NIH Guidelines for Research Involving Recombinant DNA Molecules.

X In the conduct of research involving hazardous organisms, the investigator(s) adhered to the CDC-NIH Guide for Biosafety in Microbiological and Biomedical Laboratories.

Accession For

NTIS GRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	

By_____
Distribution/_____

Availability Codes

| Dist | Avail and/or Special |

A-1

_____ _____
PI - Signature   Date

8/10/95

TABLE OF CONTENTS

Introduction

In response to both intrinsic and environmental DNA damage agents, the steady-state level of the p53 protein is post-transcriptionally elevated (Maltzman and Czyzyk 1984; Kastan et al. 1992; Perry et al. 1993). It has been well established that accumulation of the wild-type p53 protein results in two pathways: cell cycle arrest and programmed cell death or apoptosis, which together carry out the p53 tumor suppressor function (see reviews by Prives 1993; Levine 1993). What pathway the DNA damaged cells undergo depends on both the extracellular signals, the threshold of different cell types for apoptotic inducers, and expression of other cellular and viral proteins (see review by Fisher 1994). Therefore, mutation of p53, which may be the most common event in human cancers, leads to disruption of these pathways, resulting in a selective growth advantage of tumor cells, generally observed as tumor progression.

It is now fairly well established that p53-induced cell growth arrest is due to the ability of p53 as a transcriptional activator to regulate one or more cell cycle checkpoint-related genes. Among the genes which were shown to be induced by p53 in cells are mdm-2, GADD45 and p21 (WAF1/CIP1). Of these three, the p21 gene is the most likely to directly regulate the cell cycle. p53-regulated p21/WAF1 (El-Deiry et al. 1993) was found to be a potent cyclin dependent kinase (CDK) inhibitor (Harper et al. 1993; Xiong et al. 1993b; Gu et al. 1993), and also to inhibit DNA replication (Waga et al, 1994) but not PCNA-dependent DNA repair (Li et al, 1994) through its physical interaction with PCNA. Therefore, p21 can disrupt the normal progression of DNA-damaged eukaryotic cells through the cell cycle. These findings provide a direct link between p53 tumor suppressor protein and cell cycle control.

Accumulation of the wild-type p53 protein primarily arrests cells at G1/S (Lin et al. 1992a; Michalovitch et al. 1990; Martinez et al. 1991; Bischoff et al. 1992; Kuerbitz et al. 1992; Nigro et al. 1992). Cell cycle transition from G1 to S phases requires sequential events involving the formation, activation, and subsequent inactivation of a series of cyclins/CDKs complexes. Inhibition of CDK4 synthesis by transforming growth factor β (TGF-β1) is linked to cell cycle arrest (Ewen et al. 1993). Additionally, regulation of the synthesis and activity of the other cyclins and the activity of cyclin/CDK complexes has been shown to play a major role in cell cycle control (see reviews by Sherr 1993; Hunter and Pines 1994).

As part of an effort to identify important cell cycle-related genes that are potentially regulated by p53, we used immunoprecipitation analysis and examined the effect of p53 on various cyclins and CDKs for which antibodies were available. While we have been in the process of developing breast cell lines expressing inducible p53 (both wild-type and mutant), initial experiments were carried out using cell lines to which we have access: human glioblastoma GM 47-23 (expressing inducible wild-type p53), Del 4A (expressing deletion mutant p53) and murine 3-4 (expressing temperature-sensitive p53). We have found that cyclin D1 expression is induced by the wild-type p53 protein. This induction is at least

partially mediated by p21.

Body

    Accumulation of the wild-type p53 protein leads to increased cyclin D1 expression.
Several studies have provided evidence that cyclin D1 is a key regulator of the G1 phase of
the cell cycle (see review by Sherr 1993). We therefore considered the possibility that cyclin
D1 may be regulated by p53. A p53-inducible system was used to analyze effects of the
wild-type p53 protein on cyclin D1 expression. The glioblastoma cell line T98G, which was
the parental cell line used to establish the p53-inducible cell line GM47-23, contains an
endogenous mutant p53 (met237 to ile) (Ullrich et al., 1992). GM47-23 cells contain the
same endogenous mutant p53 gene and an exogenously introduced wild-type p53 gene under
the control of a steroid responsive promoter (Mercer et al., 1990a). The related line,
Del4A, contains the same endogenous mutant p53 and an additional dexamathasone-
inducible deletion mutant p53 gene (Mercer et al. 1990b; Lin et al., 1992a). In the presence
of dexamathasone, a moderate amount of inducible p53 was expressed (Fig. 1, compare
lanes 4 and 6 with lanes 3 and 5, respectively) as previously reported (Mercer et al., 1990a).
We confirmed that the inducible wild-type p53 protein adopts a unique conformational state
in vivo which retains the p53-specific antibody PAb1801 epitope but very little or no PAb421
and PAb122 epitopes (Fig. 1, compare lanes 4 and 6; Ullrich et al., 1992). This unique
conformation and phosphorylation state presumably enables the inducible wild-type p53
protein to escape from the dominant negative effect of the endogenous mutant p53 (Milner
and Mecalf 1991). To ascertain that the inducible wild-type p53 protein can transactivate
its target gene in the GM47-23 cell line, expression of p21, a known p53-responsive gene
(El-Deiry et al. 1993), was determined by immunoprecipitation. The p21 protein was
detected only after dexamathasone treatment (Fig. 1, compare lanes 7 and 8). Note that
there was a substantial amount of cyclin D1 detected in the p21 immunoprecipitate after
induction.

    We then examined the effect of p53 on various cyclins and CDKs for which
antibodies were available. When the steady-state levels of these cell cycle-related proteins
were determined by immunoprecipitation and Western blot analyses, it was clear that the
wild-type p53 protein either inhibited expression of CDK4, CDK2, cdc2, or cyclins A and
B1, or had no significant effect on PCNA (data not shown). However, unexpectedly, we
observed that p53 strongly stimulated the induction of cyclin D1 (Fig. 2A, lanes 1-2). Indeed,
there was also a substantial amount of cyclin D1 detected in the p21 immunoprecipitate
after induction of p53 (Fig. 2A, lanes 3-4). To confirm the cyclin D1 response to wild-type
p53 we also examined the effects of dexamethasone on T98G and Del4A cells. Both in
T98G cells which express only endogenous mutant p53 protein (Fig. 2B, lanes 1-2), and in
Del4A cells which express endogenous mutant p53 and inducible deletion mutant p53 (Fig.
2C, lanes 1-2), p21 was not induced in the presence of dexamethasone treatment (Fig. 2B
and 2C, compare lanes 3 and 4). Similarly, the amount of cyclin D1 protein was unchanged
or even slightly decreased in the presence compared with that in the absence of
dexamethasone treatment (Fig. 2B and 2C, compare lanes 5 and 6).

    To further analyze the kinetics of cyclin D1 induction GM47-23 cells were [^{35}S]-
methionine labeled at 0, 4, 8, 12, 24, and 48 h after treatment with dexamethasone and the
amount of cyclin D1 protein was determined by either immunoprecipitation using a specific

anti-cyclin D1 antibody or coimmunoprecipitation using a specific antibody directed against p21. The amount of cyclin D1 protein was markedly increased over the time course examined, peaking at 24h (Fig. 3A, compare lanes 1 and 7 with lanes 2-6 and 8-12, respectively). A similar kinetic pattern was observed for p21 expression (Fig. 3A, compare lane 1 with lanes 2-6). Induction of wild-type p53 in GM47-23 cells treated with dexamethasone was determined over a similar time course by immunoblot analysis (Fig. 3B). Inducible wild-type p53 was detected between 8 to 12 h following treatment, consistent with the timing of both cyclin D1 and p21 induction.

We also asked whether the induction of cyclin D1 expression by p53 is evolutionarily conserved by comparing human and rodent cell lines. A mouse cell line (3-4) was generated by cotransfection of mouse p53-null embryo fibroblasts (10-1) with the temperature sensitive mutant murine (ala 135 to val) p53 and *ras* oncogene. At 37^0C, the murine (val135) p53 is in mutant conformation and the cells grow, while at 32^0C, it is in wild-type conformation and the cells are arrested (Michalovitz et al. 1990; and data not shown). Significantly more cyclin D1 protein was detected at 32^0C than at 37^0C (Fig. 3C). No increase in cyclin D1 was observed at 32^0C in 10-1 cells (the parental cell line from which 3-4 cells were derived) (Fig. 3D). Thus, cyclin D1 induction by p53 occurs in both human and rodent cells.

A DNA damaging agent causes increased levels of p53, p21 and cyclin D1. To further characterize the role of cyclin D1 in p53-dependent cell growth control, we asked whether cyclin D1 is a part of the p53-dependent DNA damage response pathway. RKO cells contain wild-type p53 which arrest in G1 following γ-irradiation (Kastan et al. 1992). Camptothecin, a topoisomerase inhibitor which induces strand breaks, has been shown to induce p53 in RKO cells (Nelson and Kastan 1994). After treatment with camptothecin (300nM) for 24h, cells were ^{35}S-labeled and the amounts of the p53, p21 and cyclin D1 proteins were determined by immunoprecipitation. Fig. 4A shows that DNA damage resulted in a 5 to 10-fold increase of the wild-type p53 protein. An increase of wild-type p53 in the DNA damaged cells was commensurate with induced p21 and cyclin D1 expression (Fig. 4B, compare lanes 1 and 3 with lanes 2 and 4, respectively). These observations are consistent with the results obtained above (Fig. 2 and 3) from GM47-23 cells in that accumulation of wild-type p53 increased both p21 and cyclin D1 synthesis.

p53-dependent induction of cyclin D1 is at the transcriptional level. To determine whether accumulation of the wild-type p53 protein stabilizes the cyclin D1 protein, the half-life of the cyclin D1 protein in GM47-23 cells and the normal human cell line WI-38 were determined. From the results obtained it was clear that the cyclin D1 protein has same half-life (approximately 15-30 min) both in GM47-23 cells either in the presence or in the absence of the wild-type p53 protein and also in another human cell line (WI-38 cells) (data not shown). Thus, induction of cyclin D1 by p53 is not due to protein stabilization.

To analyze whether induction of cyclin D1 expression is at the transcriptional level, cyclin D1 mRNA was quantitated by Northern blot analysis. Poly(A)$^+$ RNAs were isolated from GM47-23 and T98G cells in the presence or absence of dexamethasone treatment. Using a labeled human cyclin D1 cDNA as probe, it was determined that the amount of

8

cyclin D1 mRNA was actually slightly decreased in the first 8 h following dexamethasone treatment, but then increased significantly between 8 and 12 h and peaked at 24 h (Fig. 5, top panel, compare lane 1 with lanes 2-6). PhosphorImage quantitation of several experiments showed that there was at least an over-all four-fold increase of cyclin D1 mRNA following dexamethasone treatment after normalization with glyceraldehyde-3-phosphate-dehydrogenase (GAPDH) mRNA levels (Fig. 5, top and bottom panel, compare lane 1 with lanes 2-6). This is consistent with the increase in protein levels observed. As a positive control, when the same blot was probed with human p21 cDNA p21 mRNA was shown to be gradually induced and peaked sharply at 24 h (Fig. 5, middle panel, compare lane 1 with lanes 2-6). No induction of either cyclin D1 or p21 mRNA was observed in T98G cells (Fig. 5, all panels, compare lane 7 with lanes 8-11).

Since p53 induction of cyclin D1 synthesis is apparently transcriptionally regulated, we asked whether the cyclin D1 promoter contains a p53-responsive element. Our experiments showed that a 104-bp fragment [from -1236 to -1133 upstream of the first methionine (Herber et al. 1994)] contains a potential weak p53 binding site. The efficiency of p53 binding to this fragment was approximately 10-20% of that observed with a comparable fragment containing the p53 binding site response element from the gadd45 gene (Kastan et al). This binding appears to be specific as determined by both competition gel-shift assay, in which it was shown that a wild-type p53 DNA binding oligo (RGC) but not mutant oligo (mRGC) competed away p53 binding to the cyclin D1 promoter DNA fragment, and by DNaseI protection. However, when a 1.3kb cyclin D1 promoter DNA fragment containing the p53 site was cloned upstream of a promoterless luciferase gene (CYCD1-LUC) and tested for transcriptional activity in dexamethasone treated and untreated GM47-23 cells we observed that this promoter-reporter construct was induced only very slightly (2-4-fold) when compared to a positive control reporter with a 100-bp fragment containing the p53 DNA binding site from the GADD45 gene, whose expression was stimulated by approximately 30-fold under the same conditions. It remains possible that p53 can directly, albeit weakly, activate expression of the cyclin D1 promoter. However, an alternative explanation is that cyclin D1 induction by p53 may be mediated by one or more p53 responsive genes.

p21 expression induces cyclin D1. Since the p21 gene, itself a target of p53, is involved in cell cycle regulation, we asked whether p21 can mediate the p53-dependent induction of cyclin D1 expression. To this end, the human p21 cDNA was cloned downstream of a cytomegalovirus (CMV) immediate early gene promoter producing a p21 expression vector (pcDNA3-p21). Following transient transfection with pcDNA3-p21, T98G cells were ^{35}S-labeled and the amounts of the p21 and cyclin D1 proteins were determined by immunoprecipitation. As expected, with increasing amounts of transfected pcDNA3-p21 DNA, p21 protein was detected in a dose-dependent manner (Fig. 6, lanes 6-7), although the highest amount of transfected DNA reduced somewhat the transfection efficiency (Fig. 6, lanes 7-8). This increase in p21 was commensurate with a significant increase in the amount of the cyclin D1 protein in the transfected cells (Fig. 6, compare lane 1 with lanes 2-4). Furthermore, there were markedly greater quantities of cyclin D1 in the p21 immunoprecipitates (Fig. 6, compare lane 5 with lanes 6-8). The fact that the cyclin D1

9

stimulation by p21 was relatively modest compared to what was observed with GM47-23 or 3-4 cells is most likely due to the fact that the efficiency of transient transfection is relatively low (around 5% of total cells). Therefore, it is probable that the induction of cyclin D1 was significantly greater than what we detected. We conclude that p21 mediates the induction of cyclin D1 expression by p53.

Conclusions

We have provided evidence that accumulation of the wild-type p53 protein leads to induction of cyclin D1 expression. This induction is mediated at least in part by the p21 gene product. As a p53-regulated gene (El-Deiry el al, 1993), p21 was found to be a potent cyclin/CDK inhibitor (Harper et al, 1993; Xiong et al, 1993b; Gu et al, 1993). While it has been shown to physically interact with PCNA, CDKs and cyclin D1 (Xiong et al, 1993a; Harper et al, 1993; Waga et al, 1994; Zhang et al, 1994; and this report), p21 is unlikely to be a transcriptional activator. How does p21 mediate p53-dependent induction of cyclin D1 synthesis? Muller et al. (1994) showed that cyclin D1 expression is regulated by pRB in pRB-deficient cell lines (BT549 and C33A). It is likely that p53-induced expression of p21 leads to inhibition of cyclins/CDKs activity, resulting in underphosphorylation of pRB. The underphosphorylated pRB then activates expression of cyclin D1. Indeed, our preliminary results are that p21 fails to induce cyclin D1 synthesis in the pRB-null cell line (Saos-2) (unpublished observation).

Cyclin D1 is a component of G1-checkpoint and a potential mediator of p53 tumor suppression. As a G1 cyclin, cyclin D1 was originally identified by very different approaches: as a suppressor of yeast G1 cyclin mutations (Xiong et al., 1991; Lew et al., 1991), as a delayed early response gene induced by colony-stimulating factor 1 (Matsushime et al., 1991) and as a putative pro-oncogene BCL1/PRAD1 (Lammie et al, 1991; Motokura et al., 1991; Withers et al., 1991; Rosenberg et al., 1991; Seto et al., 1992; Schuuring et al., 1992; Williams et al., 1992). It has been reported that overexpression of cyclin D1 promotes cell progression and differentiation, generally observed as shortened G1-S transition (Baldin et al., 1993; Quelle et al., 1993; Resnitzky et al., 1994; Musgrove et al., 1994) and oncogenesis (Bodrug et al., 1994; Wang et al., 1994). In addition, both activated ras and myc oncogenes induce cyclin D1 expression (Filmus et al. 1994; Daksis et al. 1994), suggesting that cyclin D1 is one of the mediators of oncogenic transformation. However, in some cases, increased levels of cyclin D1 have been a characteristic of arrested cells. Pagano et al. (1994) showed that transient overexpression of cyclin D1 in fibroblasts arrests cells in G1 phase. Furthermore, Dulic et al (1993) and Lucibello et al (1993) have found that levels of cyclin D1 are increased in senescent cells, corresponding to the presence of non-functional CDKs. Thus, it appears that increased levels of cyclin D1 can be found in two opposing aspects of cell cycle control: growth promoting and growth arresting.

Future work. In breast cancer cells, cyclin D1 was found to be amplified and overexpressed at a frequency up to at least 45% (Buckley et al. 1993; Lammie et al. 1991). While cyclin D1 induction by p53 occurs in both human and murine cells, we are currently testing whether introducing wild-type p53 into breast cell lines might increase cyclin D1 expression. The intriguing question is why and how the p53-induced cyclin D1 in the wild-type p53 containing cells and overexpressed cyclin D1 in certain tumor cells (including breast tumor cell lines) have two opposing effects: growth arresting and growth promoting. In murine cells, cyclin D1 exists in two forms that differ in their electrophoretic mobility: slow and fast migrating species (Matsushime et al. 1991). Accumulation of the slowly

11

migrating form correlates with the cell cycle transition from G1 to S, suggesting that this form is an active partner of CDKs. Our preliminary results show that wild-type p53 in murine cells preferentially stimulates the fast migrating form of cyclin D1, which is likely an inactive form of this cyclin. Hypothetically, the p53-induced form of cyclin D1 may antagonize the slowly migrating active form, resulting in growth arrest. In human cells our preliminary evidence suggests that human cyclin D1 also comprises two forms and wild-type p53 only stimulates one of them (the fast migrating form). Currently, we are in the process of confirming these initial observations and determining what the precise physical and functional differences are between the two species of cyclin D1.

References

Baldin, V., J. Likas, M. J. Marcote, M. Pagano, J. Bartek, and G. Draetta. 1993. Cyclin D1 is a nuclear protein required for cell cycle progression in G1. Gene & Dev. 7:812-821.

Bischoff, J. R., D. Casso, and D. Beach. 1992. Human p53 inhibits growth in *Schizosaccharomyces pombe.* Mol. Cell. Biol. 12:1405-1411.

Bodrug, S. E., B. J. Warner, M. L. Bath, G. J. Lindeman, A. W. Harris, and J. M. Adams. 1994. Cyclin D1 transgene impedes lymphocyte maturation and collaborates in lymphomagenesis with the *myc* gene. EMBO J. 13:2124-2130.

Buckley, M. F., K. J. E. Sweeney, J. A. Hamilton, R. L. Sini, D. L> Manning, R. I. Nicholson, A. deFazio, C. K. W. Watts, E. A. Musgrove, and R. L. Sutherland. 1993. Expression and amplification of cyclin genes in human breast cancer. Oncogene 8:2127-2133.

Daksis, J. I., R. Y. Lu, L. M. Facchini, W. W. Marhin, and L. J. Z. Penn. 1994. Myc induces cyclin D1 expression in the absence of de novo protein synthesis and links mitogen-stimulated signal transduction to the cell cycle. Oncogene 9:3635-3645.

Dulic, V., L. F. Drullinger, E. Lee, S. I. Reed, and G. H. Stein. 1993. Altered regulation of G1 cyclins in senescent human fibroblasts: Accumulation of inactive cyclinE-cdk2 and cyclin D1-cdk2 complexes. Proc. Natl. Acad. Sci. USA 90:11034-11038.

El-Deiry, W. S., T. Tokino, V. E. Velculescu, D. B. Levy, R. Parsons, J. M. Trent, D. Lin, W. E. Mercer, K. W. Linzer, and B. Vogelstein. 1993. *WAF1,* a potential mediator of p53 tumor suppression. Cell 75:817-825.

Ewen, M. E., H. K. Sluss, C. J. Sherr, H. Matsushime, J.-y. Kato, and D. M. Livingston. 1993. Functional interactions of the retinoblastoma protein with mammalian D-type cyclins. Cell 73:487-498.

Filmus, J., A. I. Robles, W. Shi, M. J. Wong, L. L. Colombo, and C. J. Conti. 1994. Induction of cyclin D1 overexpression by activated ras. Oncogene 9:3627-3633.

Fisher, D. E. 1994. Apoptosis in cancer therapy: crossing the threshold. Cell 78:539-542.

Gu, Y., C. W. Turck, and D. O. Morgan. 1993. Inhibition of CDK2 activity *in vivo* by an associated 20K regulatory subunit. Nature 366:707-710.

Harper, J. W., G. R. Adami, N. Wei, K. Keyomarsi, and S. J. Elledge. 1993. The p21 cdk-interacting protein Cip1 is a potent inhibitor of G1 cyclin-dependent kinases. Cell 75:805-816.

Herber, B., M. Truss, M. Beato, and R. Muller. 1994. Inducible regulatory elements in the human cyclin D1 promoter. Oncogene 9:1295-1304.

Hunter, T., and J. Pines. 1994. Cyclins and cancer II: cyclin D and CDK inhibitors come of age. Cell 79:573-582.

Kastan, M. B., Q. Zhan, W. S. El-Deiry, F. Carrier, T. Jacks, W. V. Walsh, B. S. Plunkett, B. Vogelstein, and A. J. Fornace Jr. 1992. A mammalian cell cycle checkpoint pathway utilizing p53 and GADD45 is defective in ataxia-telangiectasia. Cell 71:587-597.

Kuerbitz, S. J., B. S. Plunkett, W. V. Walsh, and M. B. Kastan. 1992. Wild-type p53 is a cell cycle checkpoint determinant following irradiation. Proc. Natl. Acad. Sci. USA. 89:7491-7495.

Lammie, G. A., V. Fantl, R. Smith, E. Schuuring, S. Brookes, R. Michalides, C. Dickson, A. Arnold, and G. Peters. 1991. D11s287, a putative oncogene on chromosone 11q13, is amplified and expressed in squamous cell and mammary carcinomas and linked to BCL-1. Oncogene 6:439-444.

Levine, A. J. 1993. The tumor suppressor genes. Annu. Rev. Biochem. 62:623-651.

Lew, D. J., V. Dulic, and S. I. Reed. 1991. Isolation of three novel cyclins by rescue of G1 cyclin (Cln) function in yeast. Cell 66:1197-1206.

Li, R., S. Waga, G. J. Hannon, D. Beach, and B. Stillman. 1994. Differential effects by the p21 CDK inhibitor on PCNA-dependent DNA replication and repair. Nature 371:534-537.

Lin, D., M. T. Shields, S. J. Ullrich, E. Appella, and W. E. Mercer. 1992. Growth arrest induced by wild-type p53 protein blocks cells prior to or near the restriction point in late G1 phase. Proc. Natl. Acad. Sci. USA. 89:9210-9214.

Lucibello, F. C., A. Sewing, S. Brusselbach, C. Burger, and R. Muller. 1993. Deregulation of cyclins D1 and E and suppression of cdk2 and cdk4 in senescent human fibroblasts. J. Cell Sci. 105:123-133.

Maltzman, W., and L. Czyzyk. 1984. UV irridiation stimulates levels of p53 cellular tumor antigen in nontransformed mouse cells. Mol. Cell. Biol. 4:1689-1694.

Martinez J., I. Georgoff, J. Martinez, and A.J. Levine. 1991. Cellular localization and cell cycle regulation by a temperature-sensitive p53 protein. Genes & Dev. 5:151-159.

Matsushime, H., M. F. Roussel, R. A. Ashmun, and C. J. Sherr. 1991. Colony-stimulating factor 1 regulates novel cyclins during the G1 phase of the cell cycle. Cell 65:701-713.

Mercer, W. E., M. T. Shields, M. Amin, G. J. Sauve, E. Appella, J. W. Romano, and S. J. Ullrich. 1990a. Negative growth regulation in a glioblastoma tumor cell line that conditionally expresses human wild-type p53. Natl. Acad. Sci. USA. 87:6166-6170.

Mercer, W. E., M. Amin, G. J. Sauve,, E. Appella, S. J. Ullrich, and J. W. Romano. 1990b. Wild type human p53 is antiproliferative in SV40-transformed hamster cells. Oncogene 5:973-980.

Michalovitz, D., O. Halevy, and M. Oren. 1990. Conditional inhibition of transformation and of cell proliferation by a temperature-sensitive mutant of p53. Cell 62:671-680.

Milner, J. and E. Madcalf. 1991. Cotranslation of activated mutant p53 with wild-type drives the wild-type p53 into the mutant conformation. Cell 65:765-774.

Motokura, T. T. Bloom, H. G. Kim, H. Juppner, J. V. Kronenberg, A. Arnold. 1991. A novel cyclin encoded by bcl1-linked candidate oncogene Nature 350:512-515.

Muller, H., J. Lukas, A. Schneider, P. Warthoe, J. Bartek, M. Eilers, and M. Strauss. 1994. Cyclin D1 expression is regulated by the retinoblastoma protein. Proc. Natl. Acad. Sci. 91:2945-2949.

Musgrove, E. A., C. S. L. Lee, M. F. Buckley, and R. L. Sutherland. 1994. Cyclin D1 induction in breast cancer cells shortens G1 and is sufficient for cells arrested in G1 to complete the cell cycle. Proc. Natl. Acad. Sci. USA. 91:8022-8026.

Nelson, W. G., and M. B. Kastan. 1994. DNA strand breaks: the DNA template alterations that trigger p53-dependent DNA damage response pathways. Mol. Cell. Biol.

14:1815-1823.

Nigro, J. M., R. Sikorski, S. I. Reed, and B. Vogelstein. 1992. Human p53 and *CDC2Hs* genes combine to inhibit the proliferation of *Saccharomyces cerevisiae*. Mol. Cell. Biol. 12:1357-1365.

Pagano, M., A. M. Theodoras, S. W. Tam, and G. F. Draetta. 1994. Cyclin D1-mediated inhibition of repair and replicative DNA synthesis in human fibroblasts. Gene & Dev. 8:1627-1639.

Perry, M. E., J. Piette, J. A. Zawadzki, D. Harvey, and A. J. Levine. 1993. The mdm-2 gene is induced in response to UV light in a p53-dependent manner. Proc. Natl. Acad. Sci. USA 90:11623-11627.

Prives, C. 1993. Doing the right thing: feedback control and p53. Current Biol. Cell Biol. 5:214-218.

Quelle, D. E., R. A. Ashmun, S. A. Shurtleff, J.-y. Kato, D. Bar-Sagi, M. F. Roussel, and C. J. Sherr. 1993. Overexpression of mouse D-type cyclins accelerates G1 phase in rodent fibroblasts. Gene & Dev. 7:1559-1571.

Resnitzky, D., M. Gossen, H. Bujard, and S.I. Reed. 1994. Acceleration of the G1/S phase transition by expression of cyclin D1 and E with an inducible system. Mol. Cell. Biol. 14:1669-1679.

Rosenberg, C. L., E. Wong, E. M. Petty, A. E. Bale, Y. Tsujimoto, N. L. Harris, and A Arnold. 1991. *PRAD1*, a candidate *BCL1* oncogene: mapping and expression in centrocytic lymphoma. Proc. Natl. Acad. Sci. USA. 88:9638-9642.

Schuuring, E. E., E. Verhoeven, W. J. Mooi, and R. J. A. M. Michalides. 1992. Identification and cloning of two overexpressed genes, U21B31/*PRAD1* and *EMS1,* within the amplified chromosome 11q13 region in human carcinomas. Oncogene 7:355-361.

Seto, M., K. Yamamoto, S. Lida, Y. Akao, K. R. Utsumi, I. Kubonishi, I. Miyoshi, T. Ohtsuki, Y. Yawata, M. Namba, T. Motokura, A. Arnold, T. Takahashi, and R. Ueda. 1992. Gene rearrangement and overexpression of PRAD1 in lymphoid malignancy with t(11;14)-(q13;q32) translocation. Oncogene 7:1401-1406.

Sherr, C. J. 1993. Mammalian G1 cyclins. Cell 73:1059-1065.

Ullrich, S. J., W. E. Mercer, and E. Appella. 1992. Human wild-type p53 adopts a unique conformational and phosphorylation state *in vivo* during growth arrest of glioblastoma cells. Oncogene 7:1635-1643.

Waga, S., G. J. Hannon, D. Beach, and B. Stillman. 1994. The p21 inhibitor of cyclin-dependent kinases controls DNA replication by interaction with PCNA. Nature 369:574-578.

Wang, T. C., R. D. Cardiff, L. Zukerberg, E. Lees, A. Arnold, and E. V. Schmidt. 1994. Mammary hyperplasia and carcinoma in MMTV-cyclin D1 transgenic mice. Nature 369:669-671.

Williams, M. E., S. H. Swerdlow, C. L. Rosenberg, and A. Arnold. 1992. Characterization of chromosome 11 translocation breakpoints at the *bcl1* and *PRAD1* loci in centrocytic lymphoma. Cancer Res. (Suppl.) 52:5541-5544.

Withers, D. A., R. C. Harvey, J. B. Faust, O. Melnyk, K. Carey, and T. C. Meeker. 1991. Charaterization of a candidate *bcl1* gene. Mol. Cell. Biol. 11:4846-4853.

Xiong, Y., T. Connolly, B. Futcher, and D. Beach. 1991. Human D-type cyclin. Cell

15

65:691-699.

Xiong, Y., H. Zhang, and D. Beach. 1993a. Subunit rearrangement of the cyclin-dependent kinases is associated with cellular transformation. Gene & Dev. 7:1572-1583.

Xiong, Y., G. J. Hannon, H. Zhang, D. Casso, R. Kobayashi, and D. Beach. 1993b. p21 is a universal inhibitor of cyclin kinases. Nature 366:701-704.

Zhang, H., G. J. Hannon, and D. Beach. 1994. p21-containing cyclin kinases exist in both active and inactive states. Gene & Dev. 8:1750-1758.

Figure Legends

Fig. 1. p53-dependent transactivation of p21 in GM47-23 cells. GM47-23 cells were [^{35}S]-methionine labeled in the presence or absence of dexamethasone (1 μM) treatment for 24 h. The ^{35}S-labeled extracts were immunoprecipitated with a control antibody PAb419 (lanes 1-2), anti-p53 antibodies PAb1801 (lanes 3-4) and PAb122 (lanes 5-6), and anti-p21 antibody (lanes 7-8). Dexamethasone treatment is indicated by + or -, respectively, at the top of each lane. Proteins that can be identified are marked at right, and molecular weight markers are indicated at left.

Fig. 2. p53-dependent induction of cyclin D1 synthesis. (A) GM47-23 cells treated with dexamethasone for 0 or 24 h were ^{35}S-methionine labeled. The labeled cell extracts were subject to immunoprecipitation with antibodies against cyclin D1 (lanes 1-2) and p21 (lanes 3-4). (B) and (C) T98G cells (B) or Del4A cells (C) treated with dexamethasone for 0 or 24 h were ^{35}S-methionine labeled. The labeled cell extracts were subject to immunoprecipitation with antibodies against p53 (PAb1801) (lanes 1-2), p21 (lanes 3-4), and cyclin D1 (lanes 5-6). The cyclin D1, p21, and inducible and endogenous mutant p53 proteins are indicated at right.

Fig. 3. Kinetics of p53-dependent cyclin D1 induction. (A) GM47-23 cells treated with dexamethasone for 0-48 h as indicated at the top of each lane were ^{35}S-methionine labeled. The labeled cell extracts were subject to immunoprecipitation with antibodies against p21 (lanes 1-6) and cyclin D1 (lanes 7-12). (B) An immunoblot was prepared using extracts from GM47-23 cells treated with dexamathasone for 0-36 as indicated at the top of each lane. The blot was probed with anti-p53 monoclonal antibody PAb1801. The inducible and endogenous p53 proteins are indicated at right. (C) and (D) Mouse 3-4 cells (C) and 10(1) cells (D) grown at 32°C for 0-48 h and 0-24 h, respectively, as indicated at the top of each lane, were ^{35}S-methionine labeled. The labeled cell extracts were subject to immunoprecipitation with anti-cyclin D1 antibody.

Fig. 4. p53-dependent cyclin D1 induction following DNA damage. ^{35}S-labeled extracts from RKO cells untreated or treated with camptothecin were subjected to immunoprecipitation with anti-p53 antibody PAb1801 (A), anti-cyclin D1 (B; lanes 1-2) and anti-p21 (B; lanes 3-4) as indicated at the top of each lane. The p53, cyclin D1 and p21 proteins are indicated at right.

Fig. 5. p53-dependent transcriptional induction of cyclin D1. A Northern blot was prepared using 0.5 μg of poly(A)$^+$ RNA samples isolated either from GM47-23 cells treated with dexamethasone for 0-48 (lanes 1-6) or from T98G cells treated with dexamethasone for 0-24 h (lanes 7-11) at the times indicated. The blot was probed sequentially with cyclin D1 cDNA (top panel), p21 cDNA (middle panel), and GAPDH cDNA (bottom panel). The identities of cyclin D1, p21, and GAPDH mRNAs are marked at right.

Fig. 6. p53-dependent induction of cyclin D1 is mediated by p21. Subconfluent T98G

17

cells in 10-cm dishes were transiently transfected with 0 μg (lanes 1 and 5), 5 μg (lanes 2 and 6), 15 μg (lanes 3 and 7), 30 μg (lanes 4 and 8) of pcDNA3-p21 DNA and the transfected cells were ^{35}S-methionine labeled. The labeled extracts were subject to immunoprecipitation with anti-cyclin D1 (lanes 1-4) or anti-p21 (lanes 5-8) antibodies.
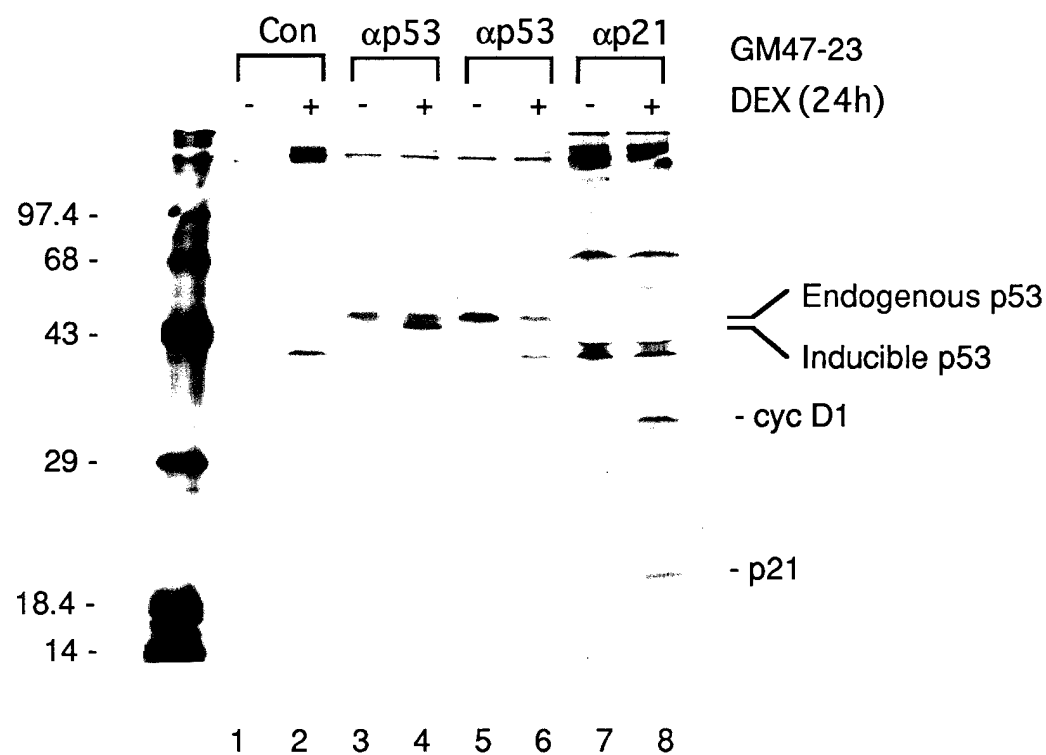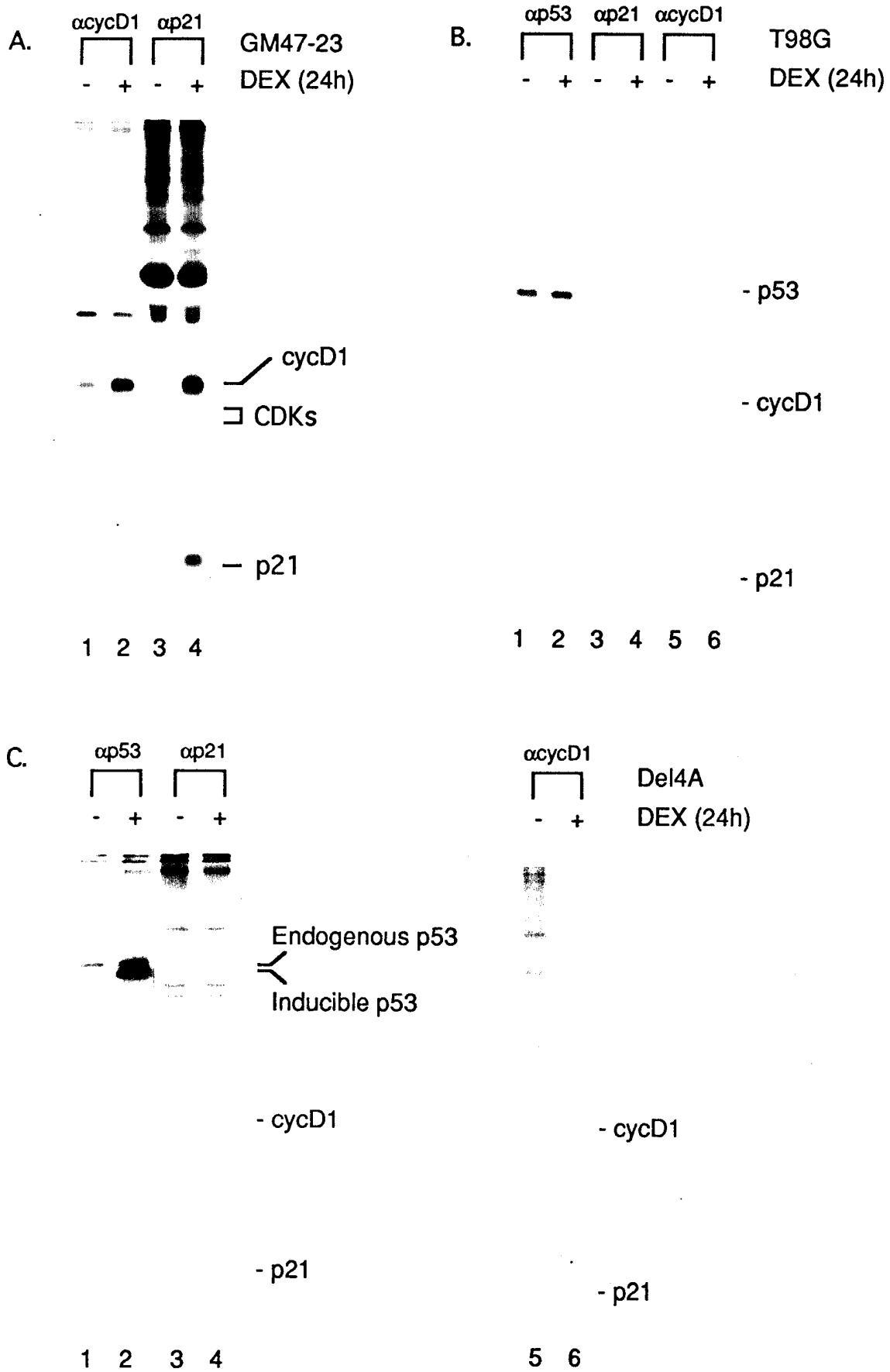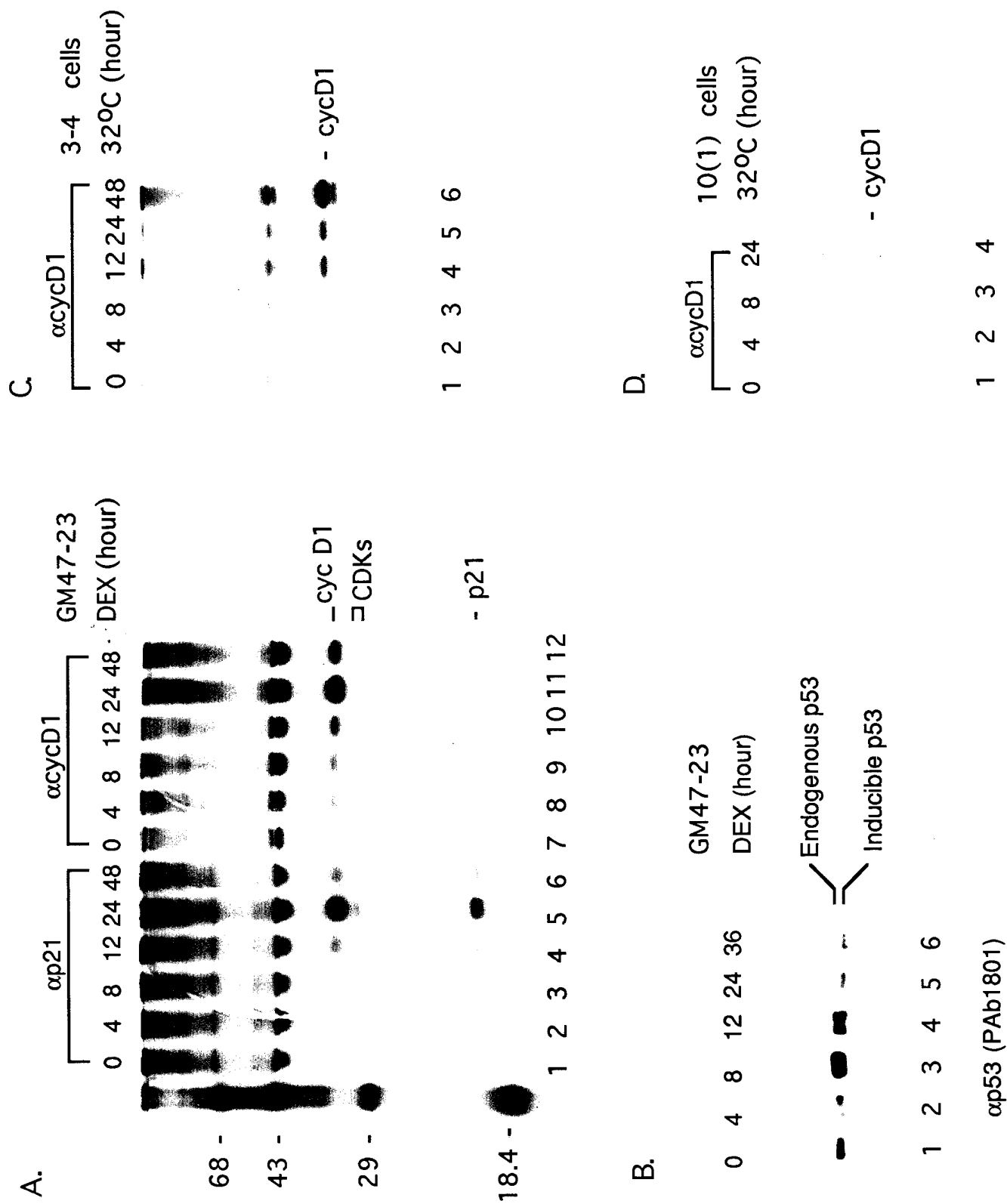
Fig. 1

Con   αp53   αp53   αp21   GM47-23
-   +   -   +   -   +   -   +   DEX (24h)

97.4 -
68 -
43 -

Endogenous p53

Inducible p53

- cyc D1

29 -

- p21

18.4 -
14 -

1   2   3   4   5   6   7   8

Fig. 2

A.

αcycD1 αp21   GM47-23

- + - +   DEX (24h)

cycD1
CDKs

— p21

1 2 3 4

B.

αp53 αp21 αcycD1   T98G

- + - + - +   DEX (24h)

- p53

- cycD1

- p21

1 2 3 4 5 6

C.

αp53   αp21

- +   - +

Endogenous p53

Inducible p53

- cycD1

- p21

1 2   3 4

αcycD1   Del4A

- +   DEX (24h)

- cycD1

- p21

5 6

Fig. 3

Fig. 4
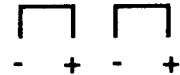
A.

αp53

RKO cells

CPT (24h)

  - +

- p53

1   2

B.

αcycD1 αp21

RKO cells

CPT (24h)

- + - +

97.4 -

68 -

43 -

- cycD1

29 -

- p21

18.4 -

14 -

1 2 3 4

Fig. 5

Fig. 6