Involvement of Parp1 in the downstream of p53 dependent signaling pathway induced after gamma-irradiation

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Abstract

It has been previously reported that G1 arrest after gamma-irradiation is suppressed by inhibitor of poly (ADP-ribose) polymerase (Parp1), 3-aminobenzamide (3-AB) in C3D2F1 3T3-a cells, which has no mutation in exon 5 to exon 9 of the p53 gene. To elucidate the mechanisms that Parp1 is involved in G1 arrest through the p53 pathways after gamma-irradiation, we investigated the effect of 3-AB on downstream following p53 protein accumulation in the p53-dependent signaling pathway at G1 arrest. The transactivation activity of p53 was assessed by the binding activity of p53 to its consensus binding sequence by gel shift assay. The expression of Waf1/Cip1/p21 and Mdm2 mRNA was analyzed by Northern blot. The DNA binding activity of p53 after gamma-irradiation was increased dose dependent manner and moreover the increase of the activity was enhanced in the presence of 3-AB. The expression of Waf1/Cip1/p21 and Mdm2, which are downstream factors of p53, was induced by approximately 8- and 12-fold at 2.5 h after 8 Gy irradiation in the absence of 3-AB, respectively. These expressions were suppressed in the presence of 3-AB. In present study, the possibility has been shown that Parp1 participates in the regulation of Waf1/Cip1/p21 and Mdm2, which are transcriptionally activated by p53, suggesting that Parp1 is involved in the downstream of p53 dependent signal transduction after DNA damage.

Introduction

Multiple lines of evidence point to poly (ADP-ribose) polymerase (Parp1) being involved in cellular DNA damage repair. Cytotoxicity induced by DNA damaging factors like gamma-irradiation is worsened in the presence of 3-AB. In present study, the possibility has been shown that Parp1 participates in the regulation of Waf1/Cip1/p21 and Mdm2, which are transcriptionally activated by p53, suggesting that Parp1 is involved in the downstream of p53 dependent signal transduction after DNA damage.

Materials and methods

Cell culture

C3D2F1 3T3-a cell line, a fibroblast cell line that was established from 14-day-old embryos of C3H/HeJ and DBA/2J mice, was used in...
this study [15]. The cells were established and provided by Professor Katsuhiro Ogawa and his collaborators at Ashikawa Medical University. Cells were seeded at 3 x 10^5 cells per 10-cm dish and cultured in DMEM (ICN Biochemical Inc. Costa Mesa, CA, USA) containing 10% fetal bovine serum (FBS). The cells were passaged every 3 days. The doubling time was approximately 17 hours. This cell line has been reported to have no mutation in exon 5 to exon 9 of the p53 gene [15].

**Inhibitor of the Parp**

3-AB was purchased from Tokyo Chemical Industry Co., Ltd. (Tokyo, Japan).

**Gel shift assay**

Upon stabilization, p53 regulates the transcription of genes having p53 recognition sequences. As an index for measuring the transcriptional activation ability of intracellular p53, a gel shift assay that measures its binding activity towards an oligo-DNA probe having p53 recognition sequences is used. As a p53 binding consensus sequence, the self-complementary double stranded DNA 5'-GGACATGCTCGTCAACTCGGCACTAACGCTACGCGAGTA-3' has been reported [16]. The 20-mer DNA was synthesized, heated in an annealing buffer solution [20 mM Tris-Cl (pH 7.5), 10 mM MgCl2, 0.1 M NaCl] at 95°C for 10 min and further at 65°C for 90 min, cooled until room temperature, and annealed. This DNA was isolated by 15% polyacrylamide gel electrophoresis. The gel was dried and analyzed with an image analyzer (BAS2000, FUJIFIRM, Tokyo, Japan).

**Northern blot analysis**

From the Northern translation initiation codon of mouse Waf1/ Cip1/p21 cDNA, the following two oligonucleotides namely, a 64-mer and a 62-mer oligonucleotides, sense 5'-ATGTTGCAATCCCTCTGTGA TGTCGCCATGTTCGCCACAGGACAAATGGTGCCGTCTGC TC-3'(64-mer) and antisense 5'-ACGGCAACAGAGAAGCAGGG CACCCTGCTACCTGCACCTGGACTAAGCTACCCGAGTA- 3'(62-mer) were set in 110 bases [17] and prepared by the solid phase phosphoramidite method using the Applied Biosystems 392 DNA/RNA synthesizer. After heating 150 ng each of these two oligonucleotides at 95°C for 5 min and 65°C for 2 min, they were gradually cooled to room temperature and annealing was carried out. Thereafter, it was labeled with DNA polymerase I (Klenow fragment) by an extension reaction using [α-^32P]dCTP. A region having 100% homology between human and mouse was used as a primer for Mdm2 [18]. In other words, a sense primer 5'-TGTGCTAACTCCACTGCTG-3' (21-mer) and an anti-sense primer 5'-TCTCAATTGTGCTAAGG-3' (19-mer) were defined for amino acids 1 to 7 and amino acids 298 to 304 respectively of the human MDM2 cDNA and isolated using the Reverse-Transcriptase Polymerase Chain Reaction (RT-PCR) method. The 0.8-kbp HindIII and SacI fragments sub-cloned into pBluescript SK(+) vector (Stratagene, La Jolla, CA, USA) were used as probes. With 50 ng of DNA labeled using the multi-prime method as the template, [α-^32P]dCTP labeling was carried out using the Megaprime DNA labeling system (Amersham, BUCKS, UK) and using the Sephadex G-50 (Pharmacia Biotech, Uppsala, Sweden) spin column method, the free nucleotides were excluded leaving labeled probes. The specific activity was 1.0 x 10^5 cpm/ng.

**Results**

**Effect of 3-AB on p53 transcriptional activity after gamma-irradiation**

The effect of 3-AB on the downstream of p53 accumulation stage in the G1 arrest signaling pathway after DNA damage was analyzed using the electrophoretic gel shift assay. In the nuclear extracts derived from C3D2F1 3T3-a cells, the DNA binding activity of p53 was detected. In accordance with the method of Zauberman et al. [19] the antibody Ab421 against the C-terminus of p53 protein, which is known to interfere the specific DNA binding activity of p53, was added in the reaction mixture, and the p53 protein-DNA complex band was further super-shifted to obtain a clearer signal [19]. To compare to the signal, purified human p53 protein expressed using a baculovirus expression system was used as a control (Figure 1A). The binding activity of p53 was observed with the dose dependence of gamma rays. The binding activity 1 hour after 12 Gy irradiation was 6-times higher than that without irradiation (Figure 1B). In the presence of 3-AB at 4 mM, we noted that basal DNA binding activity of p53 was slightly increased. In the presence of 3-AB, the increase in the DNA binding activity of p53 was further enhanced 1 hour after 8 Gy irradiation (Figure 2), suggesting the 3-AB did not inhibit the p53 DNA binding and rather it enhanced.
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Figure 1. Specific DNA binding activity of p53 protein after gamma-irradiation
The specific DNA binding activity of p53 to DNA one hour after gamma-irradiation is shown by gel shift assay. (A) Purified human p53 protein and the nuclear extract solution of C3D2F1 3T3-a cells were prepared. Arrows indicate the bands super-shifted by the p53 antibody (Ab421). (B) The specific DNA binding activity of nuclear extract p53 following irradiation 1 hour after gamma-irradiation doses of 0, 0.5, 2, 4, 8, and 12 Gy is shown.

Figure 2. Effect of 3-AB on the specific DNA binding activity of p53 protein after gamma-irradiation
The effect of 4 mM 3-AB addition one hour after 8 Gy irradiation in the specific binding activity of p53 to DNA is shown. The arrow indicates the bands super-shifted by the p53 antibody (Ab421).

Effect of 3-AB on mRNA expression levels of WAF1/CIP1/p21 and Mdm2

Effect of 3-AB on mRNA expression levels of p53-responsive signaling factors was analyzed. In C3D2F1 3T3-a cells, the mRNA expression level of WAF1/CIP1/p21 transiently increased about 8 times 2.5 h after 8 Gy irradiation and gradually decreased over 5 h of irradiation. The expression was sustained to some extent even after 12.5 h and 24 h, when G1 arrest became noticeable. However, in the presence of 4 mM 3-AB, the expression of WAF1/CIP/p21 mRNA after 2.5 h was suppressed by approximately 30%, and thereafter it was suppressed by about 50% compared to non-addition condition of 3-AB (Figure 3). In C3D2F1 3T3-a cells, the expression of Mdm2 mRNA transiently increased to about 12 times 2.5 h after 8 Gy irradiation. Subsequently, it's level decreased to about 50% in 5 h, compared to the peak at 2.5 h after irradiation and the Mdm2 expression gradually decreased thereafter. In the presence of 4 mM 3-AB, the increase of Mdm2 expression was suppressed by about 75% 2.5 h after irradiation. Of note, continuous higher Mdm2 expression was observed until 24 h after irradiation when the cells were in G1 arrest (Figure 4). This higher Mdm2 expression at 10-24 hr in the presence of 3-AB may be related to higher p53 DNA binding activity in the presence of 3-AB shown in Figure 2.
There are many reports involving the G1 arrest mechanism after DNA damage. After DNA damage, the stabilization and intracellular accumulation of p53 protein occurs. Then its transcriptional activation ability increases, and it acts as a transcriptional regulator to induce the expression of proteins that suppress the activities of G1 cyclin-Cdk complex, leading to G1 arrest [11]. In C3D2F1 3T3-a cells, after gamma-irradiation, G1 arrest is suppressed by the Parp inhibitor, 3-AB, and G2-phase arrest is accelerated [20]. Given this, we examined the effect of 3-AB on the p53-dependent G1 arrest signaling pathway. It is known that after DNA damage, the binding activity of p53 protein towards the specific DNA recognition sequence increases. In the presence of 3-AB at 4 mM, we observed that basal DNA binding activity of p53 protein is slightly increased. The addition of 3-AB further increased in the DNA binding activity of p53 protein after gamma-irradiation at 8 Gy. Therefore, the poly (ADP-ribose) synthesis reaction may be involved in the p53 DNA binding step. However, the p53 protein recognition consensus DNA sequence used was only 20 base pairs, whereas in a physiological context it is likely that additional regulatory regions exist in the promoter sequences of p53 target genes and that p53 interacts with other transcription factors, both of which can affect p53 DNA binding. Therefore, this DNA binding assay alone cannot conclusively determine the role of Parp1 in the transcriptional activation ability of p53. We examined the influence of 3-AB on the mRNA expression levels of Waf1/Cip1/p21 and Mdm2, two genes that are known to be induced by p53 following gamma-irradiation. WAF1/C1P1/p21 has been isolated and analyzed as an inhibitor of cyclin dependent kinase. The presence of p53 recognition sequences in the region upstream of the human Waf1/C1P1/p21 gene has been reported [17], and induction of mRNA expression is observed at about 2 h after gamma-ray irradiation [11]. MDM2 forms a complex with p53 protein and it is known as a protein that negatively regulates the function of p53 as a ubiquitin ligase [21]. Two p53 binding sequences are present upstream of the Mdm2 gene [22], and the expression of mRNA is very strongly induced by p53 protein after p53 stabilization following gamma-irradiation [9]. In this present study, the increase in the transient expression of mRNA was observed in the Waf1/C1P1/p21 and Mdm2 genes 2.5 h after gamma-irradiation with 8 Gy. The transient increase in expression of both mRNA was reduced in the presence of 3-AB. Thus, the inhibition of Parp1 activity was shown to antagonize in the radiation dependent increase in mRNA levels of these genes. The inhibitory effect at this early time point varied for the two transcripts and was more clearly observed for Mdm2 mRNA. This may be due to differences in the contribution of p53 protein as a transcription factor in the regulatory region of each gene. Under the same experimental conditions, even at 12 h after irradiation when G1 arrest was observed, expression of the mRNA of Waf1/C1P1/p21 was continuously suppressed to about 50% in the presence of 3-AB. The continuous suppression of the expression level of genes directly involved in cell cycle progression, through the inhibition of cyclin-dependent kinase, is considered an important factor that causes the suppression of G1 arrest in the presence of 3-AB. On the contrary, Mdm2 mRNA expression after 10 h of gamma-irradiation was about two-times higher in the presence of 3-AB than that in its absence. Kastan et al. reported that over-expression of Mdm2 suppressed G1 arrest after gamma-irradiation [18]. Therefore, the increase in Mdm2 expression levels after 10 h of gamma-irradiation may also contribute to the G1 arrest suppression seen following 3-AB treatment. Since Mdm2 is a repressor of p53 protein, Mdm2 functions to terminate the G1 arrest [23], and there has been no evidence for its involvement in the induction of G1 arrest. However, this study has indicated that the transient expression of Mdm2 may be involved for the induction of G1 arrest. In order to confirm the importance of changes in expression of these mRNAs as a factor for G1 arrest suppression in the presence of 3-AB, it is necessary to examine whether the changes in expression of Waf1/C1P1/p21 and Mdm2 also occur at the protein level.
The results gleaned from our analysis of p53 binding and transcriptional regulation following 3-AB treatment suggest that Parp1 is involved in the transcriptional activation and regulation of Waf1/Cip1/p21 and Mdm2 involving the p53-dependent signaling pathway after gamma irradiation. In mouse C3D2F1 3T3-a fibroblast cells. In human MCF-7 cells and BJ/TERT cells, another Parp inhibitor 1,5-dihydroxyisoquinoline also suppressed Waf1/Cip1/p21 and Mdm2 mRNA expression after gamma-irradiation, suggesting that a conserved role of Parp1 in G1 arrest regulation after gamma-irradiation [24].

The changes in mRNA expression by 3-AB could be due to the alteration of mRNA half-life or changes in the p53 transcriptional activation ability for mRNA expression. These possibilities can be examined by measuring the half-life of each mRNA and studying the transcriptional activation ability of each gene by nuclear run-on assays. There is also a possibility that the poly (ADP-ribose) synthesis reaction induces G1 arrest by directly inhibiting the activity of cyclin-dependent kinase or the activity of the target protein of the downstream cyclin-dependent kinase. Alternatively, a p53-independent G1 arrest mechanism could exist, which involves cross-talk with the p53-dependent pathway. Therefore, it is necessary to consider the possibility of Parp1 involvement in this alternative pathway. It is considered that Parp1 likely functions promptly as a signal of DNA strand breakage and accurately transmits quantitative information regarding DNA strand breakage.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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References

1. Nduka N, Skidmore CJ, Shall S (1980) The enhancement of cytotoxicity of N-methyl-N-nitrosourea and of gamma-irradiation by inhibitors of poly(ADP-ribose) polymerase. Eur J Biochem 105: 525-530. [Crossref]
2. Molinet M, Vermeulen W, Burkel A, Menissier-de Murcia J, Kupper HJ, et al. (1993) Overproduction of the poly(ADP-ribose) polymerase DNA-binding domain blocks alklylation-induced DNA repair synthesis in mammalian cells. EMBO J 12: 2109-2117.
3. Ding R, Pommier Y, Kang VH, Smulson M (1992) Depletion of poly(ADP-ribose) polymerase by antisense RNA expression results in a delay in DNA strand break rejoining. J Biol Chem 267: 12804-12812. [Crossref]
4. Satoh MS, Lindahl T (1992) Role of poly(ADP-ribose) formation in DNA repair. Nature 356: 356-358. [Crossref]
5. Creissen D, Shall S (1982) Regulation of DNA ligase activity by poly(ADP-ribose). Nature 296: 271-272. [Crossref]
6. Realini CA, Althaus FR (1992) Histone shuttling by poly(ADP-riboseylation). J Biol Chem 267: 18858-18865. [Crossref]
7. Tischler RB, Calderwood SK, Coleman CN, Price BD (1993) Increases in sequence specific DNA binding by p53 following treatment with chemotherapeutic and DNA damaging agents. Cancer Res 53: 2212-2216. [Crossref]
8. MalHotra W, Czynski L, (1984) UV irradiation stimulates levels of p53 cellular tumor antigen in nontransformed mouse cells. Mol Cell Biol 4: 1689-1694.
9. Price BD, Park SJ (1994) DNA damage increases the levels of MDM2 messenger RNA in wt/p53 human cells. Cancer Res 54: 896-899. [Crossref]
10. Deb SP, Munoz RM, Brown DR, Shuler MA, Deb S (1994) Wild-type human p53 activates the human epidermal growth factor receptor promoter. Oncogene 9: 1341-1349.
11. el-Deiry WS, Harper JW, O'Connor PM, Veleculescu VE, Canman CE, et al. (1994) WAF1/CIP1 is induced in p53-mediated G1 arrest and apoptosis. Cancer Res 54: 1169-1174. [Crossref]
12. Perry ME, Piette J, Zawadzki JA, Harvey D, Levine AJ (1993) The mdm-2 gene is induced in response to UV light in a p53-dependent manner. Proc Natl Acad Sci U S A 90: 11623-11627. [Crossref]
13. Zambetti GP, Barjonnet J, Walker K, Prives C, Levine AJ (1992) Wild-type p53 mediates positive regulation of gene expression through a specific DNA sequence element. Genes Dev 6: 1143-1152.
14. Kastan MB, Zhan Q, El-Deiry WS, Carrier F, Jacks T, et al. (1992) A mammalian cell cycle checkpoint pathway utilizing p53 and GADD45 is defective in ataxia-telangiectasia. Cell 71: 587-597.
15. Tokumitsu M, Kadomama T, Ogawa K (1994) Infrequent loss of heterozygosity and mutation of the p53 gene in immortal and transformed mouse embryo fibroblasts. Mol Carcinog 10: 52-57. [Crossref]
16. Funk WD, Pak DT, Karas RH, Wright WE, Shay JW (1992) A transcriptionally active DNA-binding site for human p53 protein complexes. Mol Cell Biol 12: 2866-2871. [Crossref]
17. el-Deiry WS, Tokino T, Veleculescu VE, Levy DB, Parsons R, et al. (1993) WAF1, a potential mediator of p53 tumor suppression. Cell 75: 817-825. [Crossref]
18. Chen CY, Olifer JD, Zhan Q, Fornace AJ Jr, Vogstein B, et al. (1994) Interactions between p53 and MDM2 in a mammalian cell cycle checkpoint pathway. Proc Natl Acad Sci U S A 91: 2684-2688. [Crossref]
19. Zauberman A, Barak Y, Ragimov N, Levy N, Oren M (1993) Sequence-specific DNA binding by p53: identification of target sites and lack of binding to p53 - MDM2 complexes. EMBO J 12: 2799-2808. [Crossref]
20. Nozaki T, Masutani M, Akagawa T, Sugimura T, Esumi H (1994) Suppression of G1 arrest and enhancement of G2 arrest by inhibitors of poly(ADP-ribose) polymerase: possible involvement of poly(ADP-ribosylation) in cell cycle arrest following gamma-irradiation. Jpn J Cancer Res 85: 1094-1098. [Crossref]
21. Fuch SY, Adler V, Buschmann T, Wu X, Ronai Z (1998) MDM2 association with p53 targets its ubiquitination. Oncogene 17: 2543-2547. [Crossref]
22. Juven T, Barak Y, Zauberman A, George DL, Oren M (1993) Wild type p53 can mediate sequence-specific transactivation of an internal promoter within the mdm2 gene. Oncogene 8: 3411-3416.
23. Lu X, Lane DP (1993) Differential induction of transcriptionally active p53 following UV or ionizing radiation: defects in chromosome instability syndromes? Cell 75: 765-778.
24. Wieler S, Gagné JP, Vaziri H, Poirier GG, Benchimol S (2003) Poly(ADP-ribose) polymerase-1 is a positive regulator of the p53-mediated G1 arrest response following ionizing radiation. J Biol Chem 278: 18914-18921.

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