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**The inhibition of radiation-induced mutagenesis by the
combined effects of selenium and the aminothiols
WR-1065**

**Alan M. Diamond^{1,4}, Phylis Dale^{1,2}, Judith L. Murray¹
and David J. Grdina^{1,2}**

¹Department of Radiation and Cellular Oncology, University of Chicago, Chicago, Illinois 60637
and ²Center for Mechanistic Biology and Biotechnology, Argonne National Laboratory, Argonne,
Illinois 60439-4833.

⁴To whom reprint requests should be addressed

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***Abbreviations:** GPx, glutathione peroxidase; CHO, Chinese Hamster Ovary; WR-1065, 2-[(aminopropyl)amino]ethanethiol; FBS, fetal bovine serum; WR-2721, S-2-(3-aminopropylamino)ethylphosphorothioic acid; GSH, glutathione; BSO, buthionine sulfoximine; *hprt*, hypoxanthine-guanine phosphoribosyl transferase.

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In order to evaluate the anti-mutagenic effects of the potential chemoprotective compounds selenium and S-2-(3-aminopropylamino)ethylphosphorothioic acid (WR-1065), CHO AA8 cells were exposed to both compounds either individually or in combination prior to irradiation. Mutation frequency following exposure to 8 Gy was evaluated by quantitation of the mutations detected at the *hprt* locus of these cells. Protection against radiation-induced mutation was observed for both 30 nM sodium selenite or 4 mM WR-1065. In addition, the protection against mutation induction provided by the combination of these agents appeared additive. In contrast, sodium selenite did not provide protection against radiation toxicity when provided either alone or in conjunction with WR-1065. In order to evaluate the possible mechanisms of the anti-mutagenic effects observed in these cells, glutathione peroxidase (GPx) activity was evaluated following exposure to the chemopreventative compounds. The addition of sodium selenite to the culture media resulted in a 5-fold increase in GPx activity, which was unaltered by the presence of the WR-1065. Northern analysis of RNA derived from these cells indicated that selenium supplementation resulted in a marginal increase in the mRNA for the cytosolic GPx (GSHPx-1) which was insufficient to account for the stimulation of GPx activity observed in cellular extracts. These results suggest that selenium and WR-1065 offer protection via independent mechanisms and that GPx stimulation remains a possible mechanism of the anti-mutagenic effect of selenium.

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Introduction

A large body of experimental evidence has demonstrated the chemopreventative role of selenium in carcinogenesis. Animal studies have indicated that dietary supplementation with low, non-toxic levels of selenium can inhibit tumor formation following insult with a wide variety of carcinogens (1-3). These include chemicals having diverse modes of action, exposure to different qualities of radiation, and oncogenic viruses (1-3). Protection can be observed for most organ systems with a typical reduction in tumor incidence ranging from 40%-80%. Numerous *in vitro* studies have likewise indicated the protective effects of selenium with regard to both mutagenesis and toxicity (4-8). Collectively, scientific data indicate the promise of selenium as both a chemoprotective and chemopreventative agent and provide the impetus to study and understand the mechanism of action of selenium-containing compounds.

In protein, selenium exists predominately in the form of selenocysteine. This amino acid is encoded by the UGA codon, which more typically signals the termination of translation (9). In mammalian cells, several dozen selenoproteins have been observed, only a few of which have been characterized in detail (10). The best studied of these is the glutathione peroxidase (GPx*) family of proteins. These important anti-oxidant enzymes contain a single UGA-encoded selenocysteine moiety and utilize reducing equivalents from glutathione to detoxify both hydrogen and lipid peroxides (11). The cytosolic GPx, GSHPx-1, is the best characterized of these proteins. It is expressed at varying levels in most tissue types and, unlike catalase, is not sequestered in any particular subcellular compartment. It is also distinguished from catalase in its ability to detoxify both hydrogen and lipid peroxides. Given the role for GSHPx-1 in the elimination of reactive oxygen species, it might follow that the

chemopreventative properties described above for selenium may, at least in part, be mediated via its effects on GPx proteins. However, this is often regarded as not to be the case as older studies have indicated that chemopreventative doses of selenium did not cause a measurable change in GPx activity (12,13). In addition to GPx effects, it has been speculated that selenium may exert its protective effects by altering carcinogen metabolism (14), influencing the cell cycle (15) and the induction or inhibition of apoptosis (16,17).

The radioprotective compound WR-2721 has been shown to be both anti-mutagenic and anti-carcinogenic in animal model systems (18-21). It is activated in biological systems by dephosphorylation to its thiol form, referred to as WR-1065. This activated form has been shown to be protective against cytotoxicity when administered to cells just prior to exposure to radiation or chemotherapeutic drugs (22-25). In contrast, the anti-mutagenic properties of WR-1065 can be exhibited when the drug is added after exposure to these toxic agents, suggesting that the effects on toxicity and mutagenesis may occur by distinct mechanisms (21,24). Possible mechanisms proposed include free radical scavenging, modifications of repair processes and alterations of chromatin structure (26).

Given the similarities between the properties of selenium and WR-1065, we investigated their combined *in vitro* effects on cells exposed to ionizing radiation. It is reported that both sodium selenite and WR-1065 are effective individually in reducing mutation frequency at the *hprt* locus and that this effect is additive when both reagents are provided simultaneously. Only WR-1065 was protective against radiation toxicity. It is also observed that the low levels of sodium selenite which provide protection against radiation-induced mutation significantly induced glutathione peroxidase enzyme indicating that the activity of GPx's may contribute to the radioprotection offered by selenium supplementation.

Material and methods

Cells and culture conditions

The Chinese hamster ovary (CHO) cell line CHO-AA8 was grown in a-minimal essential medium (a-MEM; Gibco, Grand Island, NY) with 10% fetal bovine serum (Biologos, Naperville, IL) in a humidified atmosphere containing 5% CO₂ and 95% air at 37°C. WR-1065 was supplied by the Drug Synthesis and Chemistry Branch, Division of Cancer Treatment (National Cancer Institute) and was dissolved in phosphate-buffered saline (PBS) (8.1 mM Na₂HPO₄, 1.5 mM KH₂PO₄, 0.14 M NaCl, 2.6 mM KCl) at a 1.0 M concentration and sterilized by filtration prior to use. Sodium selenite (Sigma Chemical Co., St. Louis, MO) was prepared in H₂O as a 3 μ M stock solution sterilized by filtration. For studies including selenium in the culture medium, cells were maintained in 30 nM sodium selenite for at least three days prior experimental manipulation and maintained at this concentration throughout all manipulations. Cells were exposed to 4 mM WR-1065 for thirty minutes prior to irradiation after which the WR-1065 was removed by resuspension in standard medium.

Irradiation Conditions

Cell suspensions were irradiated at ice bath temperatures. Cells were irradiated with ⁶⁰Co γ -rays from a γ -beam 650 irradiator (Atomic Energy of Canada).

Survival and mutation analysis

All cell cultures were grown in a-MEM medium containing hypoxanthine (10 μ g/ml), aminopterin (0.4 μ l/ml) and thymidine (5 μ g/ml) for 24 h to reduce the background of spontaneous *hprt* mutants. The mutation frequency at the *hprt* locus was determined by seeding at least 10⁶ surviving cells per experiment. Cells were grown in non-selective medium for 8 days to allow for the expression of the induced mutations. 8 X 10⁴ cells were seeded into each of 20 plates and exposed to 5 μ g/ml 6-thioguanine (Sigma Chemical Co., St. Louis, MO) in standard growth medium for 7 days and then stained with 0.5% methylene blue. Mutation frequency is expressed as mutants/10⁶ viable cells. Radiation induced mutation frequencies were corrected for the

appropriate background and experiments were performed in triplicate. For survival studies, cells were exposed to g-rays as described above and survival was determined by plating the appropriate numbers of cells to give between 80 and 200 colonies/dish after 10 days incubation.

GPx assay

GPx activity was measured by a standard assay which spectrophotometrically measures the oxidation of NADPH in a coupled system containing reduced glutathione, glutathione reductase, cellular extracts and hydrogen peroxide as the substrate as described elsewhere (27). The rate of oxidation of NADPH is measured at 339 nm in a Beckman DU 540 spectrophotometer at 30 second intervals over 5 minutes. The background rate of oxidation is determined without lysate. GPx activity is determined as:

$$\frac{\Delta 339\text{-Background}}{0.00625} \times 1000$$

$$\text{X } \mu\text{g protein}$$

and is expressed as the nmoles of NADPH oxidized per minute per μg protein. At least 4 assays were performed on independent cultures.

Northern Blot analysis

Total RNA was isolated using the RNeasy Total RNA Kit (Qiagen) and electrophoresed in 1% formaldehyde/agarose gels and transferred to Gene Screen Plus hybridization membranes (DuPont) as described by the vendor. ^{32}P -labelled bovine GSHPx-1 cDNA was prepared by random oligo-labeling. Filters were washed with 0.2X SSC and 1% SDS at 65° C twice for 1 hour each at which time the filters were dried and exposed to X-ray film at -85° C using an intensifying screen. Filters were rehybridized with a chicken 7S RNA gene (28) probe as an indicator of equal loading of RNA onto the gels.

Results

Mutation induction at the *hprt* locus is a generally used method for assessing potentially carcinogenic DNA damage that arises after exposure of mammalian cells to a variety of insults (29). Because dietary supplementation with low levels of selenium have been reported to inhibit carcinogenesis and DNA damage (3-8,30), we

assessed whether exposure to sodium selenite could reduce the incidence of radiation-induced mutations at the *hprt* locus. CHO-AA8 cells were incubated in 30 nM sodium selenite for at least three days prior to exposure to 8 Gy of ^{60}Co γ -rays and compared to cells grown under identical conditions without selenite supplementation. As seen in Figure 1, exposure of AA8 cells to this amount of radiation resulted in an average mutation frequency of 116 ± 10 mutations per 10^6 surviving cells as determined by the ability of cells to grow in 6-thioguanine. As presented in the Figure, the mutation frequency in the absence of exposure to radiation was negligible ($< 2 \pm 0.6$ mutations/ 10^6 cells). When CHO-AA8 cells were preincubated with low levels of sodium selenite, a 37% decline in mutation frequency was observed (73 ± 6 mutations/ 10^6 cells), indicating the efficacy of sodium selenite as an anti-mutagenic agent in this system. Similar results were obtained when cells were exposed to 40 mM WR-1065 for 30 minutes just prior to irradiation (64 ± 4 mutations/ 10^6 cells). Under these conditions, the mutation frequency was reduced by 45%. In order to assess the combined effects of selenium and WR-1065 with regard to the protection from radiation-induced mutation, cells were treated with both agents and the mutation frequency at the *hprt* locus was determined. Under these conditions, a decline in mutation frequency of 68% to 38 ± 4 mutations/ 10^6 cells was observed (Figure 1). Thus, the exposure of AA8 cells to both selenium and WR-1065 resulted in levels of protection against radiation-induced mutation that were similar to the sum of the protection offered by the two individual agents.

The effects of selenium and WR-1065 on radiation toxicity were also examined. Exposure of CHO-AA8 to 8 Gy of γ -rays resulted in a surviving fraction of under 10%. These results and the survival of these cells incubated with 30 nM sodium selenite

and/or 4 mM WR-1065 are presented in Figure 2. As previously reported, exposure to WR-1065 significantly increased the survival of cells exposed to this dose of radiation (31). In contrast to the data obtained regarding radiation-induced mutations, incubation of these cells with sodium selenite did not significantly increase the survival of exposed cells. Similarly, incubation of CHO-AA8 cells with both WR-1065 and sodium selenite did not result in an increase in survival above that seen with WR-1065 alone. Therefore, selenium supplied in the form of sodium selenite was able to protect irradiated cells from mutation but not from toxicity in this system.

In order to evaluate possible mechanisms of the anti-mutagenic effects observed for selenium in CHO-AA8, the effects of sodium selenite supplementation on GPx enzyme activity were investigated. CHO-AA8 cells were incubated with sodium selenite and WR-1065 either alone or in combination as described above. The resulting GPx activities were compared to control cells incubated in the standard medium. GPx activity was determined by a coupled spectrophotometric assay which quantitates the amount of this enzyme from sonicated extracts (27). These results are presented in Table 1 and indicate that low-level supplementation of the culture medium with sodium selenite significantly induced GPx activity by approximately 5-fold. Incubation of these cells with WR-1065 did not result in any stimulation of GPx activity and incubation with both sodium selenite and WR-1065 did not result in stimulation above that seen with the sodium selenite alone. Stimulation of GPx activity by selenium supplementation has been reported to occur by transcriptional and/or post-transcription mechanisms (32-36). In order to evaluate the mechanism of GPx stimulation in CHO-AA8 cells, the cells were treated as described above with sodium selenite, WR-1065 or both. Total RNA was prepared and analyzed by Northern analysis using a cDNA for the cytosolic glutathione peroxidase GSHPx-1. As presented in Figure 3, GSHPx-1 mRNA levels are somewhat stimulated by exposure to sodium selenite, but to insufficient levels to account for the observed

increment in enzyme activity. As in the case of the GPx enzyme assays, no increase in steady state levels of GSHPx-1 mRNA were observed when cells were incubated with WR-1065.

Discussion

In this manuscript, the effects of selenium and WR-1065 on radiation-induced mutation induction and toxicity were examined. Both selenium and WR-1065 were effective to a similar degree in reducing the frequency of γ -ray induced mutations at the *hprt* locus, as indicated by survival in 6-thioguanine. When CHO-AA8 cells were incubated in both selenium and WR-1065, the protection observed was significantly more than either agent alone. In contrast, only WR-1065 protected these same cells against radiation toxicity. When the effects of radioprotective doses of selenium on GPx activity were examined, there was an approximately 5-fold increase in the activity of this anti-oxidant enzyme in selenium-supplemented cells. This observed stimulation of GPx enzyme activity could not be accounted for by increased GSHPx-1 transcription as indicated by only marginal increment in the steady state levels of GSHPx-1 mRNA. While it is possible that the elevation in GPx activity observed following media supplementation is due to the stimulation of GPx genes other than GSHPx-1, the post-transcriptional effects of selenium on GSHPx-1 enzyme activity has been documented for several cell types (32-36).

While there has been a large number of reported studies indicating the efficacy of selenium in the reduction of chemical carcinogenesis, only a few manuscripts have evaluated the radioprotective effects of selenium. Borek et al. have demonstrated a significant reduction in the X-ray-induced transformation of C3H/10T $\frac{1}{2}$ cells when the culture media is supplemented with non-toxic levels (2.5 μ M) of sodium selenite (30). This result is consistent with data presented in this manuscript indicating low

levels of selenium are capable of reducing the the mutation frequency at the *hprt* locus of γ -irradiated cells. In contrast, others have failed to detect a protective effect for selenium following irradiation of animals or cells in culture (37,38). The mechanism by which selenium protects against mutation in this study remains unknown. The stimulation of GPx activity following selenium supplementation indicates the possibility that the anti-oxidant function of this enzyme directly reduces the the levels of oxidative DNA damage associated with radiation exposure. However, Se⁷⁵-labelling experiments have indicated that there are several selenium-containing proteins in a mammalian cell (10), any of which might contribute to radioprotection. In addition, selenoprotein-independent mechanisms of mutation reduction are also possible (14-17).

As seen here and in previously published reports, the aminothiols WR-1065 was effective in the protection of CHO-AA8 cells from both the mutagenic and toxic effects of radiation (31). Possible mechanisms of action of this compound have included effects on cell cycle, endogenous nuclease activity, and topoisomerase I and II activities (32). Significantly, the radioprotective effects of WR-1065 are apparent even when administered at low doses up to three hours following radiation exposure (21-25). This observation argues against a simple model of radioprotection involving only free radical scavenging. Recently, it has been demonstrated that the the protein synthesis inhibitor, cyclohexamide, can eliminate the post-exposure radioprotective effects of WR-1065 (26). These results are consistent with a model of WR-1065 action functioning by enhancing the fideleity of an error-prone inducible DNA repair process.

The additive effect of selenium and WR-1065 in the prevention of γ -ray induced mutation suggests that these two agents are functioning by distinct mechanisms. The thiol has been shown previously to significantly increase the levels

of glutathione (GSH) in exposed cells grown under *in vitro* conditions by stimulating the conversion of cystine in the media to cysteine and subsequent transport into the cell where it stimulates GSH biosynthesis (26,39). However, this cellular response to WR-1065 has been shown not to contribute to the radioprotective properties as pretreatment of the cells with BSO, a GSH synthesis inhibitor, had no effect on either enhanced survival or reduced mutagenesis (26). Although WR-1065 exposure did not result in enhanced GPx activity in cellular extracts, it remains possible the elevation of the synthesis of GSH, the hydrogen donor for GPx-mediated detoxification, influences the efficacy of GPx enzyme activity *in vivo*. The coupled assay used in this study only quantitates the amount of GPx protein in the extract as it is performed under conditions where GPx is limiting and the other components are in excess (27). Therefore, elevated GSH may have a stimulatory effect on GPx enzyme kinetics.

In this study, selenium was shown to neither protect CHO-AA8 from radiation toxicity nor potentiate the protection provided by WR-1065. This in contrast to a previous report indicating that selenium could enhance the radioprotective effects of the WR-1065 precursor, WR-2721, with regard to survival-enhancing and hematopoietic-regenerating effects when these compounds were provided to mice prior to exposure to ^{60}Co radiation (40). The difference between these experiments may be due to the form of the thiol or tissue specific consequences of selenium supplementation.

In conclusion, the data presented indicated that low level supplementation of culture media with selenium in the form of sodium selenite could significantly protect CHO-AA8 cells from radiation-induced mutagenesis and that this is associated with a significant elevation of GPx activity. The additive radioprotective effects of selenium and WR-1065 suggest that these agents may function by independent mechanisms and further suggest that the combined administration of non-toxic levels of these compounds may be useful in enhancing their chemopreventative effectiveness.

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References

1. Ip,C (1986) Selenium and experimental cancer. *Ann. Clin. Res.*, 18, 22-29.
2. Medina,D. and Morrison,D.G. (1988) Current ideas on selenium as a chemopreventative agent. *Pathol. Immunopathol. Res.*, 7, 187-199.
3. El-Bayoumy,K. The role of selenium in cancer prevention. In: Cancer Prevention (DeVita, V.T.Jr., Hellman, S. and Rosenberg, S.A., eds.) J.B. Lippincott Co. Philadelphia, Pa., pp 1-15, 1991.
4. Sato,M., Nunoshiba,T., Nishioka,H., Yagi,T. and Takebe, H. (1991) Protective effects of sodium selenite on killing and mutation by N-methyl N'-nitro-nitrosoguanidine in *E. coli*. *Mut. Res.*, 250,73-77.
5. Rosin, M.P. (1981) Inhibition of spontaneous mutagenesis in yeast cultures by selenite, selenate and selenide. *Cancer Lett.*, 13,7-14.
6. Lin,J.K. and Tzeng,S.F. (1992) Chromosomal aberrations and sister chromatid exchanges by N-nitroso-2-aminoflourene and their modification by arsenite and selenite in Chinese Hamster Ovary cells. *Mut. Res.*, 265,203-210.
7. Fico,M.E., Poirer,K.A., Watrach,A.M., Watrach,M.A. and Milner,J.A. (1986) Differential effects of selenium on normal and neoplastic canine mammary cells. *Cancer Res.*, 46, 3384-3388.
8. Ejadi,S., Bhattacharya,,I.D., Voss,K., Singletary,K. and Milner,J.A. (1989) *In vitro* and *in vivo* effects of sodium selenite on 7,12-dimethylbenz[*a*]anthracene-DNA adduct formation in isolated rat mammary epithelial cells. *Carcinogenesis*, 10, 823-826.
9. Hatfield,D. and Diamond,A.M. (1993) UGA: A split personality in the universal genetic code. *TIGS*, 9,69.

10. Behne,D., Weissnowak,C., Kalcklosch,M., Westphal,C., Gessner,H. and Kyriakopolos,A. (1995) Studies on the distribution and characteristics of new mammalianselenium-containing proteins. *Analyst* ,**120**, 823-825.
11. Mullenbach,G.T., Tabrizi,A., Irvine,B.D., Bell,G.T.,Tainerf,J.A. and Hallewell, R.A. (1988) Selenocysteine's mechanism of incorporation revealed in cDNAs of three glutathione peroxidases. *Prot. Engineer.* ,**2**,239--246.
12. McConnell,K.P., Broghamer,W.L., Blotcky,A.J. et al. , (1975) Selenium levels in human blood and tissues in health and disease. *J. Nutr.*, **105**,1026-1031.
13. Horvath,P. and Ip,C. (1975) Synergistic effect of vitamin E and selenium in the chemoprevention of mammary carcinogenesis in rats. *Cancer Res.*, **43**,5335-5341.
14. Liu,J., Gilbert,K., Parker,H.M., Haschek,W.M. and Milner,J.A. (1991) Inhibition of 7,12-dimethylbenz[a]anthracene-induced mammary tumors and DNA adducts by dietary selenite. *Cancer Res.*, **51**,4613-4617.
15. Jiang,X.-R., Macey,M., Lin,H.-X. and Newland, A.C. (1992) The anti-leukemic effects and the mechanism of sodium selenite. *Leuk. Res.*, **16**, 347-352.
16. Lu,J., Kaeck,M., Jiang,C., Wilson,A.C. and Thompson,H.J. (1994) Selenite induction of DNA strand breaks and apoptosis in mouse leukemic L1210 cells. *Biochem. Pharmacol.*, **47**, 1531-1535.
17. Hockenbery,D.M., Oltvai,Z.N., Yin,X.-M., Milliman,C.L. and Korsmeyer,S.J. (1993) Bcl-2 functions in an anti-oxidant pathway to prevent apoptosis. *Cell*,**75**,241-251.
18. Milas,L., Hunter,N., Stephens,C.L.,and Peters,,L.J. (1984) Inhibition of radiation carcinogenesis by S-2-(3-aminopropylamino)ethylphosphothioic acid. *Cancer Res.*, **44**, 5567-5569.
19. Grdina, D.J., Carnes,B.A., Grahm, D. and Sigdestad,C.P. (1991) Protection against late effects of radiation by S-2-(3-aminopropylamino)ethylphosphothioic acid. *Cancer Res.*, **51**, 4125-4130.
20. Kataoka,Y., Basic,I., Perrin,J. and Grdina,D.J. (1992) Anti-mutagenic effects of radioprotector WR-2721 against fission-spectrum neutrons and ⁶⁰Co gamma rays in mice. *Int. J. Radiat. Biol.*, **61**, 387-392.
21. Grdina,J.L., Kataoka,Y., Basic,I.,and Perrin,J. (1992) The radioprotector Wr-2721 reduces neutron-induced mutations at the hypoxanthine-guanine phosphoribosyl transferase locus in

- mouse splenocytes when administered prior to or following irradiation. *Carcin.*, **13**, 811-814.
22. Schwartz, J.L., Giovanazzi, S.M., Karrison, T., Jones, C. and Grdina, D.J. (1988) 2-[(aminopropyl)amino]ethanethiol mediated reduction in ^{60}Co gamma ray and fission-spectrum neutron-induced chromosome damage in V79 cells. *Radiat. Res.*, **113**, 145-154.
 23. Littlefield, L.G., Joiner, E.E., Coolyer, S.P., Sallam, F. and Frome, E.L. (1993) Concentration-dependent protection against X-ray-induced chromosome aberrations in human lymphocytes by the aminothiols WR-1065. *Radiat. Res.*, **133**, 88-93.
 24. Grdina, D.J., Nagy, B., Hill, C.K., Wells, R.L. and Peraino, C. (1985) The radioprotector WR-1065 reduces radiation-induced mutation at the hypoxanthine-guanine phosphoribosyl transferase locus in V79 cells. *Carcin.*, **6**, 929-931.
 25. Grdina, D.J., Nagy, B., Hill, C.K. and Sigdestad, C.P. (1989) Protection against radiation-induced mutagenesis in V79 cells by 2-[(aminopropyl)amino]ethane-thiol under conditions of acute hypoxia. *Radiat. Res.*, **117**, 251-258.
 26. Murley, J.S. and Grdina, D.J. (1995) The effects of cyclohexamide and WR-1065 on radiation-induced repair processes: A mechanism for chemoprevention. *Carcin.*, (In press).
 27. Samuels, B.L., Murray, J.L., Cohen, M.B., Safa, A.R., Sinha, B.K., Townsend, A.J., Beckett, M.A. and Weichselbaum, R.R. (1991) Increased glutathione peroxidase activity in a human sarcoma cell with inherent doxorubicin resistance. *Cancer Res.*, **51**, 521-527.
 28. Balmain, A., Krumlauf, R., Vass, J.K. and Birnie, G.D. (1982) Cloning and characterization of the abundant 7S RNA from mouse cells. *Nucleic Acids Res.*, **10**, 4259-4277.
 30. Borek, C., Ong, A., Mason, H., Donahue, L. and Biaglow, J.E. (1986) Selenium and vitamin E inhibit radiogenic and chemically induced transformation *in vitro* via different mechanisms. *Proc. Natl. Acad. Sci. USA*, **83**, 1490-1494.
 31. Grdina, D.J., Shigematsu, N., Dale, P., Newton, G.L., Aguilera, J.A. and Fahey, R.C. (1995) Thiol and disulfide metabolites of the radiation protector and potential chemopreventative agent WR-2721 are linked to both its anti-cytotoxic and anti-mutagenic mechanisms of action. *Carcin.*, **16**, 767-774.
 32. Toyoda, H., Himeno, S.-i. and Imura, N. (1989) The regulation of glutathione peroxidase gene expression relevant to species difference and the effects of dietary selenium

- manipulation. *Biochem. Biophys. Acta*, **1008**, 301-308.
33. Chada,S., Whitney,C. and newburger,P.E. (1989) Post-transcriptional regulation of glutathione peroxidase gene expression by selenium in the HL-60 human myeloid cell line. *Blood*, **74**, 2535-2541.
 34. Christensen,M.J. and Burgener,K.W. (1992) Dietary selenium stabilizes glutathione peroxidase mRNA in rat liver. *J. Nutr.*, **122**, 1620-1626.
 35. Saedi,M.S., Smith,C.G., Frampton,G., Chambers,I., Harrrison,P.R. and Sunde, R.A. (1988) Effect of selenium status on mRNA levels for glutathione peroxidase in rat liver. *Biochem. Biophys. Res. Commun.*, **153**, 855-861.
 36. Yoshimura,S., Takekoshi,S., Wanatabe,K. and Fujii-Kuriyama, Y. (1988) Determination of nucleotide sequence of cDNA coding for rat glutathione peroxidase and diminished expression of the mRNA in selenium-deficient rat liver. *Biochem. Biophys. Res. Commun.*, **154**, 1024-1028.
 37. Zackheim,H.S., Fu,K.K., and Chan, A.S. (1993) Lack of effect of supplemental dietary selenium on time to development of radiation-induced cutaneous tumors in rats. *Cancer Lett.*, **70**, 123-127.
 38. Sandstrom,B.E., Grankvist,K. and Marklund,S.L. (1989) Selenite induced increase in glutathione peroxidase activity protects human cells from hydrogen peroxide induced DNA damage but not from damage inflicted by ionizing radiation. *Int. J. Rad. Biol.*, **56**, 837-841.
 39. Wardman,P., Dennis,M.F., Stratford,M.R.L. and White,J. (1992) Extracellular, intracellular and subcellular concentration gradients of thiols. *Int. J. Radiat. Oncol. Biol. Phys.*, **22**, 751-754.
 40. Weiss,J.F., Hoover,R.L and Sree Kumar,K. (1987) Selenium pretreatment enhances the radioprotective effect and reduces the lethal toxicity of WR-2721. *Free Rad. Res. Comms.*, **3**, 33-38.

Table 1. GPx activity in CHO-AA8 cells exposed to selenium and/or WR-1065

<u>Cells</u>	<u>30 nM NaSelenite</u>	<u>4 mM WR-1065</u>	<u>GPx Activity*</u>
CHO-AA8	-	-	20.7±9.5
CHO-AA8	+	-	84.8±16.7
CHO-AA8	-	+	19.9±7.5
CHO-AA8	+	+	84.5±9.4

*Activity expressed in nmoles NADPH oxidized/min/mg protein and presented ± S.D.
Data obtained from four independent experiments.

Figure Legends

Fig. 1. Effects of 30 nM sodium selenite and 40 mM WR-1065 or the combination of both agents on mutation induction at the *hprt* locus in CHO AA8 cells exposed to 8 Gy ^{60}Co γ -rays. The data presented is from three independent experiments and the error bars represent the standard error of the mean (SEM).

Fig. 2. Effects of 30 nM sodium selenite and 40 mM WR-1065 or the combination of both agents on the survival of CHO AA8 exposed to 8 Gy ^{60}Co γ -rays. The data presented is from three independent experiments and the errors represent the SEM.

Fig. 3. Northern analysis of GSHPx-1 expression following exposure of CHO AA8 cells to 30 nM sodium selenite and WR-1065 or the combination of both agents. Total RNA was prepared and electrophoresed on a 1% agarose/formaldehyde gel. The gel was transferred to a Gene Screen Plus hybridization membrane and probed with a 32 -labelled bovine GSHPx-1 cDNA and exposed overnight to X-ray film at -85°C . MCF-7 human breast carcinoma total RNA (which does not express detectable levels of GSHPx-1 transcripts) and RNA from an adriamycin resistant derivative were included as negative and positive hybridization controls. The same filter was re-hybridized with a mouse 7S RNA probe as a control for equal loading of RNA onto the gel. The lines to the right of the autoradiograph indicate the mobility of the 18S and 28S ribosomal RNAs.

MCF-7
MCF-7 (ADR)
CHO-AA8
CHO-AA8 + Se
CHO-AA8 + WR-1065
CHO-AA8 + WR-1065 + Se

-7S