Mechanisms of selenium down-regulation of androgen receptor signaling in prostate cancer

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Abstract
Prevention trials showed that selenium reduced prostate cancer incidence by 50%, establishing selenium as a promising chemopreventive agent for prostate cancer. Selenium inhibited human prostate cancer cell growth, blocked cell cycle progression at multiple transition points, and induced apoptotic cell death. Previous studies showed a novel mechanism of selenium anticancer action in which selenium markedly reduces androgen signaling and androgen receptor (AR)–mediated gene expression, including prostate-specific antigen (PSA), in human prostate cancer cells. The molecular mechanisms of selenium-mediated down-regulation of AR signaling are not clear. In this study, a systemic approach was taken to examine the modification of androgen signaling by selenium in human prostate cancer cells. In addition to reduced AR mRNA expression, selenium was found to initially increase the stability of AR mRNA within 6 hours while decreasing the stability of AR mRNA after 8 hours. Selenium increased AR protein degradation and reduced AR nuclear localization. Scatchard analysis indicated that selenium did not affect ligand binding to AR in LNCaP cells. Chromatin immunoprecipitation analyses showed that DHT increased the recruitment of AR and coactivators, such as SRC-1 and TIF-2, to the promoter of the PSA gene, and that recruitment was greatly diminished in the presence of 5 μmol/L selenium. On the other hand, selenium enhanced the recruitment of corepressors, such as SMRT, to the promoter of the PSA gene. Taken together, these results suggest that selenium disrupts AR signaling at multiple stages, including AR mRNA expression, mRNA stability, protein degradation, nuclear translocation, and recruitment of coregulators. [Mol Cancer Ther 2006;5(4):913–8]

Introduction
The growth of prostate epithelial cells requires physiologic levels of androgen, both to stimulate proliferation and inhibit apoptotic death (1). Androgen binds to the androgen receptor (AR), which causes AR to bind to androgen-responsive elements in the promoters of androgen-regulated genes. This interaction is affected by many other transcription coregulators. These complex interactions among AR, androgen-responsive elements, and coregulators facilitate the activation or repression of genes regulating development, differentiation, and proliferation of target cells. Several androgen-responsive genes have been identified, including prostate-specific antigen (PSA) and human glandular kallikrein 2 (2).

Selenium is an essential nutrient that has a chemopreventive effect against a variety of malignancies, including prostate cancer. A number of case-controlled epidemiologic studies have shown an inverse relationship between selenium status and prostate cancer risk (3–7). One of the most important studies of selenium as a chemopreventive agent is the Nutritional Prevention of Cancer study initiated by Clark et al. (8). Supplementation of people with selenized yeast was capable of reducing the overall cancer morbidity by nearly 50% (8). Although selenium treatment did not significantly affect the incidence of nonmelanoma skin cancers, patients receiving the supplement showed a significantly lower prevalence of developing lung (relative risk, 0.54), colon (relative risk, 0.42), or prostate cancer (relative risk, 0.37). Further analysis (9) reaffirmed the significant reduction in prostate cancer incidence by selenium (relative risk, 0.48; 95% confidence interval, = 0.28–0.80). The promising epidemiologic and prevention studies on selenium in prostate cancer provide the basis for the current Selenium and Vitamin E Chemoprevention Trial (10).

The biological activity of selenium is dependent on its chemical form. In general, inorganic selenium compounds, such as selenite or selenite, are known to produce genotoxic effects. Organic selenium-containing compounds, such as selenomethionine and methylselenocysteine, are better tolerated and exhibit anticarcinogenic activity. Methylseleninic acid (CH$_3$SeO$_2$H) was developed specifically for in vitro studies (11) because cultured cells respond poorly to selenomethionine (a commonly used selenium reagent) due to very low levels of β-lyase activity,
which is required for conversion of selenomethionine to the active methylselenol (12). The effect of physiologic concentrations of methylseleninic acid on cultured cells has been documented in several studies (11, 13–15).

Cell culture studies showed that selenium inhibited the growth of prostate cancer cell lines, including androgen-sensitive LNCaP and androgen-insensitive DU145 and PC3 cells (14–17). In vivo studies also support the antitumorigenic role of selenium in prostate cancer. Dietary supplementation of selenium resulted in reduction of tumor growth in PC3 tumors in mice (18). There are a number of potential mechanisms proposed for the antiproliferative effects of selenium, including antioxidant effects, enhancement of immune function, stimulation of apoptosis, and induction of cell cycle arrest (16). We recently showed that methylseleninic acid is able to decrease markedly AR transcript and protein levels (14). The expression of PSA, a well-known androgen-regulated gene, is also inhibited by methylseleninic acid (13, 14).

The down-regulation of AR signaling by selenium provides an important mechanism for selenium prostate cancer chemoprevention. However, the molecular mechanisms of selenium-mediated down-regulation of AR signaling are not clear. AR is a ligand-dependent transcription factor. The activation of AR requires binding to its ligand, translocation to the nucleus, and interaction with coregulators, including coactivators and corepressors, in the AR target genes. In this study, a systemic approach was taken to examine the modification of androgen signaling by selenium in human prostate cancer cells. The results suggest that selenium affects AR signaling at multiple levels, including AR mRNA expression, mRNA stability, protein degradation, nuclear translocation, and recruitment of coregulators.

Materials and Methods

Selenium Reagent and Cell Culture

Methylseleninic acid was synthesized as described previously (11). Human LNCaP prostate cancer cells were obtained from the American Type Culture Collection (Manassas, VA) and maintained in RPMI 1640 supplemented with 10% fetal bovine serum. The cells were grown at 37°C in 5% CO₂ and 95% air.

Cytosolic and Nuclear Protein Preparation

LNCaP cells were cultured in charcoal-stripped fetal bovine serum for 3 days. The cells were treated with 10 nmol/L DHT in the absence or presence of 10 μmol/L methylseleninic acid for 2 hours. Cells were harvested, washed with PBS twice, and resuspended in a hypotonic buffer [10 mmol/L HEPES-KOH (pH 7.9), 1.5 mmol/L MgCl₂, 10 mmol/L KCl, and 0.1% NP40] and incubated on ice for 10 minutes. Nuclei were precipitated by 3,000 × g centrifugation at 4°C for 10 minutes. The supernatant was collected as the cytosolic fraction. After washing once with the hypotonic buffer, the nuclei were lysed in a lysis buffer [50 mmol/L Tris-HCl (pH 8), 150 mmol/L NaCl, 1% Triton X-100] and incubated on ice for 30 minutes. The nuclear lysate was preleared by 10,000 rpm centrifugation at 4°C for 15 minutes. Protein concentration was determined using the Coomassie Plus protein assay kit (Pierce, Rockford, IL).

Northern Blot Analysis

Total RNA was extracted from cells with TRIzol reagent (Life Technologies, Rockville, MD). Twenty micrograms of each sample were electrophoresed on 1.2% denaturing agarose gels and transferred to a nylon membrane (MSI, Costa Mesa, CA) using the Ready-To-Go DNA Labeling Beads (Amersham Pharmacia Biotech, Piscataway, NJ). Hybridization was carried out during 3 hours at 65°C in Rapidhyb buffer (Amersham, Arlington Heights, IL). Membranes were washed for 15 minutes at 65°C in 2× SSC, 0.1% SDS (twice), 0.5× SSC, 0.1% SDS and 0.1× SSC, and 0.1% SDS. Radioactivity in the membranes was analyzed with a Storm Phosphoimager System.

Western Blot Analysis

The protein extracts were resolved on 12.5% SDS-PAGE. Proteins were then transferred to nitrocellulose membrane. After blocking overnight at 4°C in 5% milk in PBS/0.1% Tween 20, membranes were incubated for 1 hour at room temperature with anti-AR rabbit polyclonal antibody (Santa Cruz Biotechnology, Santa Cruz, CA) or anti-α-actin (Sigma, St. Louis, MO), anti-RNA polymerase II (Fromega, Madison, WI), or anti-Hsp90 (Sigma) diluted in 1% milk in PBS/Tween 20. Following secondary antibody incubation, immunoreactive proteins were visualized with an enhanced chemiluminescence detection system (Amersham Pharmacia Biotech, Buckinghamshire, England).

In vitro AR Ligand-Binding Assay

Ligand-binding assay was done as previously described (19). LNCaP prostate cancer cells were plated at 1 × 10⁶ per plate in 10-cm plates and allowed to grow to confluency for 3 days. Cells were treated with 10 μmol/L methylseleninic acid for 4 hours before harvesting and homogenization in TEDG buffer [10 mmol/L Tris (pH 7.4), 1.5 mmol/L EDTA, 10% glycerol, and 1 mmol/L DTT added immediately before use]. The cell suspension was passed through a 26-gauge needle (10–15 times) to homogenize. The homogenate was incubated on ice for 10 minutes and centrifuged at 13,000 rpm for 30 minutes at 4°C. The supernatant was collected and used as the cytosolic fraction. Total protein was estimated in the extracts from both untreated and methylseleninic acid–treated cells, and equal amounts of protein were used in the subsequent assay. The extracts were incubated with 0.01, 0.05, 0.1, 0.25, 0.5, 0.75, and 1 mmol/L ³H-R1881 either in the presence or absence of 100 mmol/L (excess) unlabeled (cold) R1881 in a total reaction volume of 250 μL (made up with TEDG buffer). The reaction mixtures were incubated on ice throughout the assay. Dextran-coated charcoal suspension (500 μL; 0.25% charcoal, 0.025% dextran in 1× PBS) was added to each sample and incubated at 4°C with vigorous shaking for 10 minutes. The samples were centrifuged at 3,000 rpm...
for 10 minutes at 4°C. The supernatant (500 μL) was added to 5 mL of scintillation fluid and counted in a liquid scintillation counter. The amount of the radio-labeled ligand bound to the receptor in the presence and absence of competing unlabeled ligand was calculated and expressed as fmol/mg protein. The difference between count per minute with ³²H-R1881 only and count per minute with ³²H-R1881 + cold R1881 was calculated and taken as the amount of bound ³²H-R1881. The data were analyzed by Scatchard analysis as described previously (19).

**AR mRNA Stability Assay**

Equal numbers of LNCaP cells were plated in 10-cm plates and incubated at 37°C until they reached 70% confluence. Cells were either pretreated with 5 μg/mL actinomycin D before treatment with 10 μmol/L methylseleninic acid, or they were treated with 5 μg/mL actinomycin D and 10 μmol/L methylseleninic acid together for 0, 4, 8, 12, 24, 36, and 48 hours. Total RNA was extracted with TRIzol reagent (Invitrogen, San Diego, CA), and 20 μg of total RNA from each sample were run on a 1.2% formaldehyde-agarose gel. The membrane was hybridized with the AR cDNA probe labeled with ³²P-dCTP. After hybridization and washing, radioactivity in the membranes was analyzed with a Storm Phosphorimager System, and the levels of AR mRNA were quantified by Phosphorimager. The turnover of AR mRNA was determined by comparing mRNA levels over time in cells treated with or without methylseleninic acid.

**AR Protein Stability Assay**

Equal numbers of LNCaP cells were plated in 60-mm plates and incubated at 37°C until they reached 70% confluence. Cells were either pretreated with 50 μg/mL cycloheximide before treatment with 10 μmol/L methylseleninic acid, or they were treated with 50 μg/mL cycloheximide and 10 μmol/L methylseleninic acid simultaneously for 0, 4, 8, 12, 24, 36, and 48 hours. Cells were homogenized in high salt buffer [10 mmol/L HEPES (pH 7.5), 0.4 mol/L NaCl, 1 mmol/L EDTA, 1% NP40], and the supernatants were used as the whole-cell lysates. Equal amounts of protein were run on 10% SDS-PAGE and probed with anti-AR rabbit polyclonal antibody (Santa Cruz Biotechnology) or antibody that specifically recognize coactivator TIF-2, SRC-1, or corepressors, such as SMRT or NCoR (Santa Cruz Biotechnology), overnight at 4°C with rotation. Chromatin-antibody complexes were isolated from solution by incubation with protein G-Sepharose beads for 1 hour at 4°C with rotation. The Sepharose-bound immune complexes were washed and eluted from beads with elution buffer (1% SDS and 0.1 mol/L NaHCO₃), and DNA was extracted. DNA samples from chromatin immunoprecipitation preparations were analyzed by PCR using primers spanning the PSA gene in the region of promoter (forward, 5'-CCTAGATGAGGTCTTCATGAGCTACA; reverse, 5'-GGGACGGAGAGC-TAGCATTG).

**Results**

**Methylseleninic Acid Decreases AR mRNA Stability**

Our results suggest that whereas methylseleninic acid decreased AR mRNA levels at the transcriptional level (14), AR mRNA expression can also be regulated at post-transcriptional level. To examine whether methylseleninic acid affects AR mRNA stability, LNCaP cells that express functional AR were treated with or without 5 μmol/L methylseleninic acid in the presence of actinomycin D (5 μg/mL) to stop de novo mRNA synthesis. The total RNA was isolated at different time points, and AR mRNA levels were measured by Northern blot analysis. The half-life of AR mRNA was determined by comparison of mRNA levels over time between cells treated with or without actinomycin D, either in the presence or absence of methylseleninic acid. Because actinomycin D is capable of inducing cell death, we monitored cell growth for a period of 24 hours and did not observe cell death or growth inhibition with the concentration of actinomycin D used (5 μg/mL). We did not observe significant cell death or growth inhibition at 5 μmol/L methylseleninic acid over a period of 24 hours in LNCaP cells (14). Methylseleninic acid treatment initially enhanced AR mRNA levels within 6 hours. However, AR mRNA levels were significantly decreased by methylseleninic acid compared with the control at 8 hours. Figure 1 shows on the semilog plot, the mean values of percentage of AR mRNA levels over time relative to respective time 0 AR mRNA value as 100%. In methylseleninic acid–treated cells, AR half-life was reduced to about 7 hours from 12 hours in the control cells, suggesting that AR mRNA degradation was greatly accelerated in the presence of methylseleninic acid after 6 hours.

**Methylseleninic Acid Increases AR Protein Turnover**

We have shown that methylseleninic acid decreased the levels of AR mRNA and protein in LNCaP cells (14). We
next examined the effect of methylseleninic acid on AR protein degradation after new protein synthesis was blocked by cycloheximide as a potential mechanism for down-regulation of AR protein level. The protein synthesis inhibitor cycloheximide (50 \( \mu \)g/mL) was added with or without 5 \( \mu \)mol/L methylseleninic acid (MSA) at time 0. At specified time points, cells were harvested, and the levels of AR protein were measured by Western blot using anti-AR antibody. In methylseleninic acid–treated cells, the half-life of AR protein was reduced to 6 hours from 21 hours in the control cells (Fig. 2A), suggesting that AR protein degradation was greatly enhanced in the presence of methylseleninic acid. Systematic protein degradation by the ubiquitin-proteasome system plays an important role in the maintenance of protein stability. Protein ubiquitination provides the recognition signal for the 26S proteasome, leading to protein degradation (20, 21). Studies showed that AR protein level in cells is regulated by systemic protein degradation pathways (22, 23). To examine whether selenium induced AR protein degradation via ubiquitin-proteasome system, the 26S proteasome inhibitor MG132 was added to the cells treated with methylseleninic acid. MG132 was able to retard methylseleninic acid effect on AR protein levels (Fig. 2B), suggesting that methylseleninic acid induced AR degradation via a proteasome-dependent pathway.

**Selenium Inhibits AR Nuclear Translocation**

AR typically translocates to the nucleus to exert its function on gene expression. To examine whether selenium affects the translocation of AR, Western blot analysis was done using cell extracts from either cytosolic or nuclear extracts. LNCaP cells were cultured in charcoal-stripped fetal bovine serum for 3 days before adding 10 nmol/L of DHT in the absence or presence of 10 \( \mu \)mol/L methylseleninic acid for 2 hours. Nuclear and cytosolic fractions were prepared and used for Western blot analysis using the anti-AR antibody. DHT treatment increased the levels of AR protein expression in the nucleus, which were reduced by the treatment with methylseleninic acid (Fig. 3). In contrast, methylseleninic acid had little effect on AR protein expression in the cytosol. The expression of RNA polymerase II and Hsp90 were used as markers for the integrity of the nuclear and cytosolic fractions, respectively. These results suggest that methylseleninic acid suppresses AR signaling in part via interruption of AR nuclear translocation.

**Selenium Inhibits the Recruitment of Coactivators and Enhances the Recruitment of Corepressors to AR Target Genes**

AR interacts with coregulators to achieve maximal transactivation activity. To examine the effects of selenium on the recruitment of coregulators to the promoters of AR target genes, chromatin immunoprecipitation analysis was done. DHT increased the recruitment of AR and TIF-2 and SRC-1 to the promoter of the PSA gene in the absence of methylseleninic acid, and this recruitment was greatly diminished in the presence of 5 \( \mu \)mol/L methylseleninic acid (Fig. 4). On the other hand, methylseleninic acid treatment prevented the nuclear translocation of AR in the presence of hormone; thus, the corepressors, including SMRT and NcoR, remain bound to the promoter of the PSA gene (Fig. 4). These results suggest that methylseleninic acid–mediated reduction of AR activation may be due, at least in part, to a decrease in the recruitment of AR and its coactivators to the promoter of the AR target gene PSA, while maintaining corepressors bound to the promoter.

**Figure 1.** Effect of MSA on AR mRNA stability in LNCaP cells. The mRNA synthesis inhibitor antinomycin D (5 \( \mu \)g/mL) was added with or without 5 \( \mu \)mol/L methylseleninic acid (MSA) at time 0. At specific time points, cells were harvested, and total RNA was isolated by Northern blots. Points, means of three independent experiments plotted on semilog scale relative to respective time 0 AR mRNA value as 100%; bar, SD.

**Figure 2.** A, effect of methylseleninic acid (MSA) on AR protein turnover in LNCaP cells. The protein synthesis inhibitor cycloheximide (50 \( \mu \)g/mL) was added with or without 5 \( \mu \)mol/L methylseleninic acid at time 0. At specific time points, cells were harvested, and cell lysates were prepared. AR protein levels were determined by Western blot analysis using antibody specifically against AR and normalized to \( \alpha \)-actin control. Points, means of three independent experiments plotted on semilog scale relative to respective time 0 AR value as 100%; bars, SD. B, effect of MG132 on methylseleninic acid–induced AR protein degradation. MG132 (5 \( \mu \)mol/L) was added to LNCaP cells together with cycloheximide (50 \( \mu \)g/mL) in the presence and absence of 5 \( \mu \)mol/L methylseleninic acid. The cell lysates were prepared at 24 h. AR protein levels were determined by Western blot analysis using antibodies specifically against AR and \( \alpha \)-actin as a control.
Selenium is an important trace element exhibiting anticancer activity. There are a number of potential mechanisms proposed for the anticancer effects of selenium, including antioxidant effects, enhancement of immune function, stimulation of apoptosis, and induction of cell cycle arrest (16). We previously showed a novel mechanism of selenium action in which selenium disrupts androgen signaling by inhibiting AR mRNA and protein expression and reducing the expression of AR target genes (14). These studies provide an important molecular mechanism of selenium chemoprevention and potential therapy for prostate cancer. In the present study, the mechanisms of selenium-mediated AR signaling down-regulation were examined. Selenium decreased AR mRNA stability, accelerated AR protein degradation, and blocked AR nuclear translocation. In addition, selenium inhibited the recruitment of coactivators and maintained corepressors bound to the promoters of AR target genes.

AR is a ligand-dependent transcription factor whose activation is initiated by its binding to androgen and subsequent translocation to the nucleus, where it binds to the promoters and activates the transcription of AR target genes. Any interruption of this process may alter AR function. Coregulators such as TIF-2 and SRC-1 interact with AR to enhance ligand-dependent transactivation of AR. The expression of TIF-2 and SRC-1 is increased in cancer and recurrent prostate cancer after medical or surgical castration (25), suggesting that TIF2 and SRC-1 may be involved in the development and progression of prostate cancer. Our findings showed that selenium can interrupt the interaction between AR and coregulators by blocking the recruitment of coactivators (SRC-1 and TIF-2) while maintaining corepressors (SMRT and NCoR) bound to the promoters of AR target genes. These findings suggest that selenium not only disrupts AR signaling, but also interrupts the interaction of coregulators with AR to achieve maximal effect on androgen function.

A common treatment modality for prostate cancer is androgen deprivation, which can be achieved by surgical...
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castration, chemical castration, or a combination of surgical and chemical castrations. The goal of these androgen deprivation treatments is either to block androgen-AR binding or to reduce the levels of androgen. Although antiandrogen treatment is effective, the antitumor effects may be temporary. Virtually, every patient will relapse due to the growth of androgen-independent prostate cancer cells. There is an urgent need for testing new therapies based on different mechanisms to target AR signaling for androgen-independent prostate cancer. AR signaling is often hyperactive in androgen-independent prostate cancer and plays a critical role in the growth and progression of prostate cancer. A treatment aiming at reducing AR expression may represent an attractive approach to target androgen signaling in prostate cancer. Our findings show that selenium disrupts androgen signaling at multiple stages of AR signaling pathways, including AR mRNA expression, mRNA stability, protein degradation, nuclear translocation, and interaction with coregulators in prostate cancer (14). This unique antiandrogen activity suggests that selenium may serve as a therapeutic agent, in addition to a chemopreventive agent, for prostate cancer.

Understanding the molecular mechanism of selenium-mediated down-regulation of AR signaling may aid in the development of effective treatments aimed at targeting AR signaling for prostate cancer. We are currently testing the combination treatment to more effectively target AR signaling in prostate cancer using antiandrogen agents (flutamide or Casodex, blocking ligand binding to AR) and selenium (reducing AR expression) based on our understanding of the mechanisms of their action.

References

Molecular Cancer Therapeutics

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