Suppression of cell proliferation and regulation of estrogen receptor α signaling pathway by arsenic trioxide on human breast cancer MCF-7 cells

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Abstract

In recent years, breast cancers have aroused much concern. Together with a growing incidence all over the world, the development of drug resistance to tamoxifen, the most commonly prescribed chemotherapeutic drug for breast cancer patients, has highlighted the importance of developing a new chemotherapeutic drug in combating breast cancer. With the aim of treating breast cancers, the anti-tumor effects of arsenic trioxide in MCF-7 cells have been studied.

MCF-7 cells are estrogen responsive cells which mimic breast cancers at the early stage. 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2H-tetrazolium bromide (MTT) assay and direct cell counting were used to measure cell proliferation. The mechanisms of action were elucidated through the measurement of estrogen receptor (ER) binding, mRNA and protein levels of ERα and its activity.

We have demonstrated that arsenic trioxide was capable of reducing cell survival in MCF-7 cells via the suppression of the estrogen-induced growth stimulatory effects in MCF-7 cells. Arsenic trioxide was shown to suppress the action of estrogen through the regulation of the ERα signaling pathway. Arsenic trioxide could down-regulate ERα mRNA and protein levels without competing with estrogen for ERα binding. Arsenic trioxide also inhibited the transcription activity mediated by the ERα signaling pathway and ultimately it down-regulated c-myc protein expression and inhibited cell entry to S phase under estrogen’s stimulation.

In conclusion, arsenic trioxide could inhibit the growth of MCF-7 cells by reducing the growth stimulatory effect of estrogen. As estrogen is a primary risk factor in promoting the growth of breast tumor cells, the anti-estrogenicity exhibited by arsenic trioxide sheds light on the therapy of breast cancer.


Introduction

Arsenic trioxide (As2O3) is an arsenic compound existing as an odorless, tasteless, white crystal or powder. In the 1970s, the effects of As2O3 on a number of cancers were investigated and it was found to be most effective in killing acute promyelocytic leukemia (APL) cells. Later, another group from Shanghai found promising effects of As2O3 in clinical trials of APL patients. APL accounts for 10–15% of all acute myeloid leukemia in adults (Soignet et al. 1998). In earlier times, APL patients were treated with anthracyclines. This cytotoxic chemotherapy achieved 70–85% remission but also induced severe complications and drug resistance in APL patients (Warrell et al. 1993). It was not until the characterization of the molecular pathologies of APL that a group from Shanghai found that all-trans retinoic acid (ATRA) was effective in combating the disease. Clinical trials indicated a complete remission in 85–90% of cases (Huang et al. 1988). Although ATRA treatment showed improvement in coagulopathy and high complete remission in APL patients (Huang et al. 1988), adverse effects were also observed. Hyperleukocytosis developed during the second and third weeks of treatment. It is attributed to the activation of leukocytes (Castaigne et al. 1990). Together with other syndromes such as respiratory distress, pleural effusions, weight gain, fever and occasionally renal failure, these adverse effects are collectively called ‘retinoic acid syndrome’. Moreover, ATRA resistance was observed in patients following ATRA treatment. Since then, frequent clinical trials have been performed to assess the effectiveness of As2O3 in APL treatment. As2O3 achieved a complete remission rate of 57–98% in both de novo and relapsed APL patients. Moreover, patients receiving As2O3 treatment had improved disseminated intravascular coagulation, hypertrehinolysis and bleeding
symptoms (Shen et al. 1997, Guo et al. 1999). Studies in NB4 cells have shown that As2O3 induces apoptosis at concentrations of 1–2 μM. When NB4 cells were treated with low concentrations of As2O3 (0.1–0.25 μM) over 10 days, condensed chromatin, smaller nuclei, and decreased numbers of nuclei were observed. Cytoplasmic ratio and appearance of granules in the cytoplasm were also observed (Chen et al. 1996). Further investigation showed the up-regulation of CD52 and BFL-1, the down-regulation of retinoic acid receptor α, and synergistic effects in the regulation of protein kinase CB-1 and small ubiquitin-related modifier 1 (SUMO-1) (Cai et al. 2000). Recent findings showed that As2O3 induced acetylation of histones 3 and 4 resulting in transcriptional activation of downstream genes for differentiation (Wang 2001).

To date, little is known about the effect of As2O3 on human breast cancer. In fact, public concern and awareness about breast cancer have been heightened recently. At present, the cause of breast cancer is still unclear. The female hormone, estrogen, plays an essential role in the growth and differentiation of tissues in the female reproductive system. Over the past years, both in vitro and in vivo studies have provided support for the role of estrogen in the development of breast cancer. Estrogen was found to be the primary stimulant of the growth of breast cancer (Lippman et al. 1976, Henderson et al. 1982). The mechanism of action of estrogen on breast cancer involves both promotion of cell proliferation and prevention of apoptosis (Kyprianou et al. 1991). Estrogen increased the cell proliferation rate by recruiting non-cycling cells into the cell cycle, shortening the overall cell cycle time through the reduction of the length of the G1 phase and promoting cell entry to the S phase (Brunner et al. 1995). Similar studies had also shown the inhibition of p21 and p27, p21 and p27 phosphorylation, activation of caspase 9, and ultimately induction of apoptosis. The action of estrogen was mediated through the estrogen receptor (ER). Two ERs have been identified, estrogen receptor α (ERα) and estrogen receptor β (ERβ), ERβ was only identified in 1996 (Mosselman et al. 1996). At the onset of breast cancer, 46–77% of breast cancers are ERα positive (Dickson & Lippman 1995). Thus, ERα expression in human breast tumors is an important prognostic indicator and marker of the responsiveness of endocrine therapies. Studies of the regulation of ERα and its respective signaling pathway will unravel the stimulatory effects of estrogens on proliferation in breast cancer cells and thus shed light on the development of strategies in treating breast cancer.

The present study mainly focused on the estrogen receptor-dependent signaling pathway. Studies were focused on using As2O3 in concentrations below 2 μM to elucidate the mechanism of action in mediating the anti-tumor effect on MCF-7 cells.

Materials and Methods

Cell culture

MCF-7 and MDA-MB-231 cell lines were purchased from the American Type Culture Collection (Baltimore, MD, USA). They were maintained in RPMI 1640 medium supplemented with 10% dextran-coated charcoal-stripped fetal bovine serum and 1% antibiotics (v/v) at 37 °C in a humidified atmosphere of 5% CO2.

Preparation of As2O3

The stock solution of As2O3 was prepared by dissolving As2O3 powder in PBS at a concentration of 10 mM.

MTT assay

MCF-7 cells and MDA-MB-231 were seeded at $1 \times 10^4$ cells/well in 96-well plates. After treatment with the appropriate concentration of As2O3, suspension medium was removed and 30 μl MTT solution was added to each well and incubated at 37°C for 2–4 h. After that, 100 μl DMSO were added to each well and incubated for a further 15 min. Optical density (O.D.) at 540 nm was measured. Percentage survival was defined as: % survival = 100% × (O.D. of test sample/O.D. of control).

Direct cell counting by the trypan blue dye exclusion method

MCF-7 cells were seeded at $5 \times 10^4$ cells/well in 24-well plates. After treatment with the appropriate concentration of As2O3 and 17β-estradiol for 24, 48 or 72 h, the cell number in each well was counted by the trypan blue staining method using a hemacytometer.

Effect of As2O3 on estrogen binding to ERα by ERα competitive binding assay

The assay was carried out using an ERα competitive screening kit according to the manual provided by the manufacturer (Wako Chemical, Richmond, VA, USA; catalogue number 295-56301). In brief, human recombinant ERα was coated in microplates. When incubating samples with fluorescence-labeled estrogen, there is competition with estrogen for the binding sites on ERα. After removal of unbound substances or fluorescence-labeled estrogen, the retained estrogen was determined by
measuring the fluorescent intensity. A control of fluorescence-labeled estrogen alone was prepared to act as a positive control. Excitation of the sample mixture emitted high fluorescent intensity. The extent of binding depends on the capability of the substance in competing with estrogen and this is correlated to the affinity of that substance to ERα.

Assessment of the transcriptional activity of ERα

Estrogen response element (ERE) containing vector was constructed by insertion of a single stranded ERE oligonucleotide into pGL3 basic vector at NheI site upstream of the luciferase gene. The sequence of ERE oligonucleotide was constructed according to the previous report (Cullen et al. 2001).

The sequence is: 5′-CCAGGTCAGGTACGGAGCTAAAATAACACATTCAAG-3′. pGL3–control vector was used as a positive control which emitted strong luminescence upon activation. pGL3–basic vector was used as a negative control which is lacking in promoter and enhancer sequences. Renilla luciferase reporter plasmid was prepared to act as an internal control for the determination of transfection efficiency. The treatment scheme was as follows. Cells were seeded at 5 × 10^4 cells/well in 24-well plates until confluence at 40–60%. Four wells were prepared for each treatment. Experimental medium without serum supplement (50 µl) was transferred to microtubes to which 300 ng ERE luciferase reporter plasmid, 100 ng Renilla luciferase reporter plasmid and 1 µg Fugene 6 transfection reagent were added. The mixture was incubated at room temperature for 30 min. Next, the cells were incubated with transfection mixture for 6 h at 37°C. After that, the mixture was discarded. The transfected cells were then treated with 10 nM 17β-estradiol, As2O3 at 1 µM, As2O3 at 2 µM or As2O3 plus 17β-estradiol. The cells were treated for either 48 or 72 h. Luciferase assay was carried out using the Dual-Luciferase Reporter Assay System (Promega, Madison, WI, USA). Procedures were followed according to the manual provided by the manufacturer. The luminescence of ERE luciferase measured is proportional to the luciferase activity of the ERα complex upon treatment. The luminescence of Renilla luciferase is proportional to the amount of transfected cells.

Normalized luciferase luminescence is calculated as follows: normalized luciferase luminescence = luminescence (Firefly luciferase)/luminescence (Renilla luciferase). Normalized luciferase activity (% control) = normalized luciferase luminescence (test sample)/normalized luciferase luminescence (untreated control) * 100%.

Normalized luciferase activity of untreated control was expressed as 100%.

Figure 1 Cell survival of MCF-7 cells following 17β-estradiol treatment for various time intervals. Cells were treated with different concentrations (0–1000 nM) of 17β-estradiol for 24, 48 and 72 h. The percentage cell survival was measured by MTT assay. Data are presented as means ± s.d. of 6 replicate measurements. The percentage survival is expressed relative to control which is defined as 100%. *P<0.05 (vs. control).
Detection of expression level of ERα by RT-PCR

Cells were seeded at 3 × 10^5 cells/well in 6-well plates. Cells were treated with 10 nM 17β-estradiol, 2 µM As_2O_3 or co-treated with both drugs for 24 and 48 h. Controls were prepared by incubating with experimental medium only. After treatment, RNA was isolated using the TRIzol reagent (Invitrogen) according to the procedures suggested by the manufacturer. cDNA was then synthesized using Superscript First-Strand Synthesis System (Invitrogen). In brief, RNA samples of 5 µg were mixed in 0.5 ml microtubes with 1 µl 10 mM dNTP mix, 1 µl Oligo(dT)12–18 (0.5 µg/µl) in diethyl pyrocarbonate (DEPC) treated water to a final volume of 10 µl. The samples were incubated at 65 °C for 5 min and then placed on ice for at least 1 min. A reaction mixture composed of 1 µl RNase inhibitor, 2 µl 10 × RT buffer, 2 µl dithiothreitol (0.1 M), and 4 µl MgCl₂ (25 mM) was added to each sample and mixed gently. The samples were incubated at 42 °C for 2 min. One microliter Superscript reverse transcriptase was added and incubated for 50 min at 42 °C and then for 15 min at 70 °C. The mixture was then chilled on ice. Finally, 1 µl RNase H was added and further incubated for 20 min at 37 °C. The cDNA samples were stored at −20 °C until use. PCR was performed with primers flanking the ERα gene to produce a PCR product with a size of 490 base pairs. The sequences of the primers were as follows: forward 5’ CAG GGG TGA AGT GGG GTC TGC TC 3’; reverse 5’ ATG CGG AAC CGA GAT GAT GTA GC 3’.

As an internal control, PCR with primers specific for glyceraldehyde phosphate dehydrogenase (GADPH) was carried out. Samples (10 µl) were mixed with 2 µl 6 × loading dye and electrophoresed in 1% agarose gel electrophoresis. The band intensities of PCR products were analyzed by ImageQuant program (Amersham Biosciences).

Detection of protein expression levels of ERα and c-myc by Western blot analysis

Cells were seeded at 1 × 10^6 cells/well in 100 mm culture plates and treated with different drugs for 48 h. Treatment groups in this assay included a control group with medium only, 2 µM As_2O_3 alone, 10 nM 17β-estradiol alone and 2 µM As_2O_3 together with 10 nM 17β-estradiol. After drug treatments, cells were collected and lysed.
The protein content in each sample was determined by BCA assay (Sigma). Thirty micrograms protein of each sample were resolved by 10% SDS-PAGE. After electroblotting, the membrane was probed with anti-ERα antibody (Oncogene Science, Cambridge, MA, USA) or anti-c-myc antibody (BD Pharmingen, San Diego, CA, USA). Secondary antibody was conjugated with horseradish peroxidase. Finally, the signal was detected by an enhanced chemiluminescence (ECL) kit (Amersham Biosciences).

Effects of As$_2$O$_3$ on cell cycle distribution of MCF-7 cells under estrogen stimulation

Cells at $3 \times 10^5$ cells/well were seeded in 6-well plates and treated with different drugs for 48 or 72 h. Treatment groups in this assay included a control group with medium only, 2 µM As$_2$O$_3$ alone, 10 nM 17β-estradiol alone and 2 µM As$_2$O$_3$ together with 10 nM 17β-estradiol. After treatment, the cells were washed with PBS and stained with propidium iodide (PI) solution (2 mg/ml), RNase A (10 mg/ml) and 400 µl PBS for 30 min at 37°C under subdued light. Stained cells were analyzed using a FACSort flow cytometer (BD Biosciences, San Jose, CA, USA). With the CellQuest program, the cell population was targeted by forward light scatter (FSC) and side scatter (SSC). The fluorescence signal of PI was detected at channels of FL-2. The percentages of DNA content at different phases of the cell cycle were analyzed with Modfit software (Verity Software House, Topsham, ME, USA).

Statistical analyses

Data were expressed as means ± standard deviations (S.D.) for three replicate experiments. The Student’s $t$-test was used for statistical analyses.

Results

Effect of As$_2$O$_3$ and 17β-estradiol on cell viability of MCF-7 cells

The growth stimulatory effects of 17β-estradiol on MCF-7 cells in a range of concentrations were determined by MTT assay and direct cell counting. The percentage survival of MCF-7 cells increased upon incubation with 0·1 nM to 500 nM 17β-estradiol (Fig. 1) compared with the untreated control. Within 24 h incubation, no obvious survival stimulation was observed. It was not until 48 h
incubation that estrogen induced an increase in percentage survival from 100% in untreated controls to a maximum of 137% in 10 nM 17β-estradiol-treated cells. Increasing the incubation time to 72 h further increased the percentage survival. At this time period, 10 nM 17β-estradiol attained the maximum survival stimulation of 165% with respect to controls. On the other hand, 1000 nM 17β-estradiol reduced cell survival from 75% to 49% after 24 and 72 h treatment respectively.

To assess the effect of As2O3 on 17β-estradiol-treated MCF-7 cells, MCF-7 cells were incubated with As2O3 and 17β-estradiol simultaneously. As seen in Fig. 2, when treated together with As2O3, the percentage survival of MCF-7 cells was reduced as compared with 17β-estradiol treatment alone. The reduction was dose- and time-dependent. For concentrations between 0.25 and 0.5 µM, As2O3 did not reduce the percentage survival. At a concentration of 2 µM As2O3, 25% reduction of survival was induced after 24 h treatment, and it was maximized after 72 h treatment to 52% as compared with the untreated controls (Fig. 3).

### Effect of As2O3 on cell survival of the hormone independent breast cancer cell line, MDA-MB-231

To compare the cell survival inhibiting effects of As2O3 on MCF-7 cells and MDA-MB-231 cells, IC50 after various time treatments was obtained and the results are shown in Table 1. Higher IC50 of As2O3 was obtained in MDA-MB-231 cells as compared with MCF-7 cells. In other words, As2O3 was more potent in combating cell survival in MCF-7 cells than in MDA-MB-231 cells.

### Effect of As2O3 on estrogen binding to estrogen receptor α (ERα)

In assessing the competitive binding capacity of As2O3 on ERα, an ERα competitor screening kit was applied. The specific estradiol binding after incubation with various concentrations of 17β-estradiol, As2O3, tamoxifen and paclitaxel is shown in Fig. 4. 17β-Estradiol in concentrations of 0.1 nM to 200 nM reduced the specific estradiol binding dramatically in a concentration-dependent manner. Concentrations above 200 nM completely prevented the binding of fluorescent estradiol to ERα. The estradiol binding remained high in the presence of paclitaxel indicating that it did not compete with estradiol for ERα binding. The result was consistent with the fact that paclitaxel inhibited breast cancer survival through mechanisms other than ERα signaling. When incubated with tamoxifen in concentrations above 0.25 µM, the estradiol binding was reduced by more than 50%. Compared with As2O3, estradiol binding remained high in

### Table 1: The inhibiting effects of As2O3 on cell survival of MCF-7 and MDA-MB-231 cells after different treatment times. The results are expressed as IC50 of As2O3 (µM)

<table>
<thead>
<tr>
<th>Treatment time (h)</th>
<th>MCF-7 IC50 (µM)</th>
<th>MDA-MB-231 IC50 (µM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>48</td>
<td>1.8</td>
<td>7</td>
</tr>
<tr>
<td>72</td>
<td>1.2</td>
<td>4.8</td>
</tr>
<tr>
<td>96</td>
<td>0.8</td>
<td>3.4</td>
</tr>
<tr>
<td>120</td>
<td>0.5</td>
<td>2.1</td>
</tr>
</tbody>
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### Figure 4: A graph showing the competitive binding ability of 17β-estradiol, As2O3, tamoxifen and paclitaxel to ERα. Data shown are representative of three separate experiments in each of which triplicate wells were assayed. Error bars are S.D. of triplicate wells. The wells incubated with solvent only are considered as control whose fluorescent intensity is expressed as 100%.

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concentrations below 2 µM; higher concentrations did not increase the ability of As$_2$O$_3$ to compete with estradiol for ER$\alpha$ binding. This result suggested that As$_2$O$_3$ did not compete with 17$\beta$-estradiol for ER$\alpha$ binding.

Regulation of ER$\alpha$ mRNA levels following As$_2$O$_3$ treatment

As ER$\alpha$ is the important mediator of the estrogen-stimulated signaling pathway, the alteration of ER$\alpha$ expression level in MCF-7 cells during As$_2$O$_3$ exposure may contribute to the interference exerted by As$_2$O$_3$ on the pathway. In this sense, the effect of As$_2$O$_3$ on ER$\alpha$ RNA levels was examined. Total RNA samples from the untreated control and after treatment with 2 µM As$_2$O$_3$ alone or simultaneously with 17$\beta$-estradiol were isolated and analyzed by RT-PCR. As seen in Fig. 5, in the first 24 h treatment, 10 nM 17$\beta$-estradiol down-regulated transcription levels by 52% relative to controls and further treatment to 48 h down-regulated the level by 72%. Twenty-four- and forty-eight-hour exposure to 2 µM As$_2$O$_3$ also induced a down-regulation of ER$\alpha$ expression but to a lesser extent. When MCF-7 cells were incubated with 2 µM As$_2$O$_3$ plus 17$\beta$-estradiol, a synergistic effect was observed at both time treatments (Fig. 5).
Regulation of ERα protein levels following As$_2$O$_3$ treatment

In addition to the RNA levels, we have examined the ERα protein levels. Within 48 h of treatment, there were decreases in the ERα protein expression levels of 42% and 22% following treatment with 10 nM 17β-estradiol and 2 μM As$_2$O$_3$ when compared with controls without treatment. Co-treatment of both drugs resulted in a greater reduction in protein expression levels by 90%. This revealed that administration of 10 nM 17β-estradiol and 2 μM As$_2$O$_3$ together down-regulated ERα protein levels with greater effect than that induced by 17β-estradiol alone. Synergistic down-regulation was observed following both treatments together (Fig. 6).

Regulation of ERα transcriptional activity following As$_2$O$_3$ treatment

In this section, the regulation of the estrogen activated transcriptional activity by As$_2$O$_3$ was studied by examining the effect of As$_2$O$_3$ on ERα binding to ERE. In the study, a dual luciferase reporter system was adopted. Renilla luciferase control reporter vector and pGL3 reporter vector were co-transfected to MCF-7 cells. Results are expressed as percentage activation. The normalized luciferase activity of 10 nM 17β-estradiol, As$_2$O$_3$ at 1 μM and 2 μM concentrations, and As$_2$O$_3$ simultaneously added with 17β-estradiol are shown in Fig. 7. The luciferase activity was significantly enhanced 3-5-fold by 10 nM 17β-estradiol as compared with the controls. Upon treatment with both 1 μM and 2 μM As$_2$O$_3$, dose- and time-dependent reductions in percentage activity were observed. When exposed to both 17β-estradiol and 2 μM As$_2$O$_3$ over 72 h, the 3-5-fold induction by 10 nM 17β-estradiol was decreased to 28-77%. The results suggested that 2 μM As$_2$O$_3$ exerted an inhibitory effect on ERα-mediated luciferase activation over 48 and 72 h of treatment. In other words, As$_2$O$_3$ at 2 μM down-regulated the transcriptional activity of ERα. Most importantly, it also counteracted the transcriptional activity of ERα induced by 10 nM 17β-estradiol (Fig. 7).

Regulation of c-myc protein level by As$_2$O$_3$

By Western blot analysis, the protein expression of the c-myc gene was examined and the results are shown in Fig. 8. 17β-Estradiol up-regulated c-myc protein expression by 65% after 48 h treatment with respect to the untreated control. The up-regulation was partially suppressed by co-treatment with 2 μM As$_2$O$_3$ in MCF-7 cells over the same period of time, such that the protein level after co-treatment remained higher (131%) than that of controls (100%). After treatment with 2 μM As$_2$O$_3$ alone, the protein level of c-myc was down-regulated over 60% as compared with the controls without any treatment.

Effects of As$_2$O$_3$ on cell cycle distribution of MCF-7 cells under estrogen stimulation

The effect of As$_2$O$_3$ on cell cycle distribution of MCF-7 cells was analyzed after the cells were treated with 2 μM As$_2$O$_3$ 17β-estradiol, and 17β-estradiol simultaneously with 2 μM As$_2$O$_3$. Figure 9(A-D) shows the cell cycle distribution of MCF-7 cells after 48 h treatment. Compared with controls, 48 h treatment with 2 μM As$_2$O$_3$ markedly increased the proportion of cells in the G$_1$ phase from 46.7% to 67.4% while it reduced the proportion of cells in the S and G$_2$/M phases from 18.5% to 10.2% and from 34.6% to 22.4% respectively. Consistent results were obtained at 72 h treatment, with a greater percentage change in the phase distribution. Thus, As$_2$O$_3$ induced G$_1$ phase arrest in MCF-7 cells by inhibiting cell cycle progression to the S and G$_2$/M phases. Following incubation of MCF-7 cells with the same concentration of 17β-estradiol alone, a reduction of 35.5% of the cell population in the G$_1$ phase occurred while G$_2$/M phase and S phase cell populations were decreased by 9% and 79.8% respectively. Following incubation with 2 μM As$_2$O$_3$ together with 17β-estradiol, an increase in the cell population in the G$_1$ phase and a reduction in the cell population in the G$_2$/M phase and S phase over the same...
treatment time was also seen. This implied that As$_2$O$_3$ induced G$_1$ phase growth arrest of MCF-7 cells stimulated by 10 nM 17$\beta$-estradiol.

**Discussion**

It has been widely concluded that estrogen exposure is a prominent risk factor in breast cancer and its stimulatory effects can potentiate the growth of breast tumor cells (Henderson et al. 1988). In an attempt to treat breast cancer, estrogen withdrawal is one of the strategies used. To see whether As$_2$O$_3$ is able to block estrogen-stimulated cell growth in MCF-7 cells, the effect of As$_2$O$_3$ in estrogen withdrawal was assessed. Prior to the study, the growth stimulatory effect of estrogen was assessed in which 10 nM 17$\beta$-estradiol could induce a most dramatic cell growth stimulation. Different concentrations of 17$\beta$-estradiol have been used in studies of ER-regulated pathways or as a model for anti-estrogenicity. The concentrations range from 0.1 nM to 100 nM. Concentrations higher than this range induce toxic effects. Here, we observed that 1 nM 17$\beta$-estradiol could stimulate cell growth which was at its maximum at a concentration of 10 nM. So, 10 nM 17$\beta$-estradiol was used in the following experiments as a positive control (Fig. 1). With respect to the untreated controls, the percentage survival of MCF-7 cells was reduced from 160% with 10 nM 17$\beta$-estradiol treatment alone to 50% in co-treatment of 2 µM As$_2$O$_3$ together with 10 nM 17$\beta$-estradiol (Fig. 2). In addition, As$_2$O$_3$ was also found to suppress the stimulation of cell growth by estradiol in MCF-7 cells (Fig. 3).

The MDA-MB-231 cell line is an estrogen-independent cell line that does not depend on estrogen for growth and survival. As$_2$O$_3$ in concentrations below 2 µM was also shown to suppress the survival of MDA-MB-231 following 72 h exposure (Table 1). The lower sensitivity of MDA-MB-231 cells to As$_2$O$_3$ suggested an association of estrogen receptor status with growth inhibitory potency. Recent studies also revealed that tamoxifen induced apoptosis in both ER$^+$ and ER$^-$ cell lines via different mechanisms (Salami & Karami-Tehrani 2003). Only ER$^+$ cells could respond to low concentrations of tamoxifen. It might be concluded that there exists ER$^+$ and ER$^-$

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**Figure 3** Regulation of estrogen-activated ER$\alpha$ transcriptional activity following As$_2$O$_3$ treatment for 48 and 72 h. MCF-7 cells co-transfected with luciferase reporter plasmid were treated with various concentrations of As$_2$O$_3$ alone, 10 nM 17$\beta$-estradiol alone and 2 µM As$_2$O$_3$ simultaneously with 10 nM 17$\beta$-estradiol. Cells without any treatment (control) were prepared for comparison. Each value was normalized by Renilla luciferase control vector. The luciferase activity was expressed as the percentage of untreated control defined as 100%. The experiment was repeated three times and a single representative experiment is shown. Error bars represent the s.d. of four wells of each sample.
elucidating the mechanisms of how As$_2$O$_3$ inhibited breast cancer cell survival. The effects of As$_2$O$_3$ on ER$\beta$ need further investigation.

Anti-estrogens, such as tamoxifen, elicit an estrogen withdrawal effect mainly by competitive binding to the hormone binding domain of ER$\alpha$ and subsequent alteration of the conformation necessary for recruitment of transcription co-activators to transcription activation function 2 (AF2). Our study of the competitive binding ability of As$_2$O$_3$ on MCF-7 cells indicated that As$_2$O$_3$ did not compete with 17$\beta$-estradiol for ER binding (Fig. 4). The specific ER$\alpha$ binding required hydrogen bond formation between an aromatic ring in the ligands and residues in the domain and a water molecule. The remaining residues in the binding cavity interacted with a variety of different hydrophobic groups of ligands (Brzozowski et al. 1997, Pike et al. 2001). The structure of As$_2$O$_3$ shows that the metal elements, arsenic and oxygen, are arranged in a polar ring structure. It was believed that the inability of As$_2$O$_3$ in binding to the ER$\alpha$ ligand binding site could be attributed to its non-hydrophobic structure.

By RT-PCR and Western blot analysis, both ER$\alpha$ gene transcription and protein expression levels were down-regulated following 10 nM 17$\beta$-estradiol treatment (Figs 5 and 6). Our results are consistent with other studies in which various concentrations of 17$\beta$-estradiol were used (Berthois et al. 1990, Alarid et al. 1999). Some reports have indicated an association of ER$\alpha$ mRNA levels and protein levels after 17$\beta$-estradiol and other antiestrogen treatments (Saceda et al. 1988, Santagati et al. 1997). ER$\alpha$ protein degradation was reported to be dependent on estrogen-induced proteasome-mediated proteolysis instead of DNA transcription (Alarid et al. 1999). Here, we demonstrated the down-regulation of ER$\alpha$ mRNA levels followed by the down-regulation of ER$\alpha$ protein levels following 48 h treatment with As$_2$O$_3$. The mechanism of action remains elusive but there is no doubt that following 2 $\mu$M As$_2$O$_3$ treatment together with 10 nM 17$\beta$-estradiol, both ER$\alpha$ protein levels and mRNA levels were further down-regulated as compared with treatment with 17$\beta$-estradiol alone (Figs 5 and 6). The results might be responsible for the reduced estrogen stimulatory effect in MCF-7 cells by reducing the number of ER$\alpha$ sites available for 17$\beta$-estradiol binding and subsequent activation of the ER$\alpha$ signaling pathway.

After binding to ER$\alpha$, the estrogen–ER$\alpha$ complex will translocate to the target DNA binding site called estrogen responsive element (ERE) in the promoter region of the target gene for gene transcription activation (Klinge 2000).
Effect of As$_2$O$_3$ on ERα signaling

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% G1 : 46.69%
% G2 : 34.64%
% S phase : 18.48%
Sub-G1 : 1.91%

% G1 : 43.57%
% G2 : 36.11%
% S phase : 20.32%
Sub-G1 : 2.48%

% G1 : 67.43%
% G2 : 22.42%
% S phase : 10.15%
Sub-G1 : 6.04%

% G1 : 67.06%
% G2 : 24.04%
% S phase : 8.90%
Sub-G1 : 10.08%

% G1 : 35.95%
% G2 : 31.65%
% S phase : 32.39%
Sub-G1 : 1.18%

% G1 : 28.20%
% G2 : 35.36%
% S phase : 36.53%
Sub-G1 : 1.66%

% G1 : 57.03%
% G2 : 33.03%
% S phase : 9.94%
Sub-G1 : 5.3%

% G1 : 69.73%
% G2 : 25.41%
% S phase : 4.85%
Sub-G1 : 7.89%
Here, we showed the suppressing effect of As$_2$O$_3$ on 10 nM 17β-estradiol-stimulated transcription activation by using a luciferase reporter system containing the ERE element. Following 10 nM 17β-estradiol treatment, the activation was dramatically enhanced indicating that the action of the 10 nM 17β-estradiol dose on MCF-7 cells was mediated by the estrogen–ERα complex binding to DNA and the stimulation of target gene transcription. When treated with 2 µM As$_2$O$_3$ simultaneously with 10 nM 17β-estradiol, transcription activation was not enhanced. Instead, it was suppressed twofold and fivefold over the 48 and 72 h treatment periods respectively, as compared with that of 10 nM 17β-estradiol treatment alone (Fig. 7). Thus, As$_2$O$_3$ at 2 µM suppressed 17β-estradiol-induced transcription of ERE bearing target genes.

It is of interest to examine the mechanism of how As$_2$O$_3$ suppressed 17β-estradiol-stimulated cell growth and even elicited growth inhibition in MCF-7 cells. In the present study, c-myc protein expression was studied. c-myc is an oncogene responsible for cell growth (Escot et al. 1986, Dang 1999). Previous studies have reported that c-myc expression was elevated in estrogen-treated cells (Dubik et al. 1987, Dubik & Shiu 1988). Moreover, down-regulation of c-myc expression was sufficient to block 17β-estradiol-stimulated cell growth. This result was also observed in our study as c-myc protein expression was enhanced by 10 nM 17β-estradiol after 48 h treatment. At this time, a dramatic increase in the percentage survival of MCF-7 cells following 10 nM 17β-estradiol treatment over 48 h was observed (Fig. 8). So, c-myc was responsible for the growth stimulation of MCF-7 cells as demonstrated in the present study. Upon exposure to 2 µM As$_2$O$_3$ together with 10 nM 17β-estradiol, the expression level of c-myc was reduced as compared with that stimulated by 10 nM 17β-estradiol alone (Fig. 8). From our study, survival of MCF-7 cells under the same conditions was reduced to 70% of control. Following a longer incubation to 72 h, As$_2$O$_3$ suppressed cell survival to 48% of control (data not shown). Therefore, it was possible that the blocking of the 17β-estradiol-stimulated cell growth was associated with down-regulation of c-myc protein expression. As the promoter region upstream of c-myc gene included half the ERE, the down-regulation of c-myc protein expression might be attributed to the inhibition of ERα transcription activation.

The growth inhibition induced by As$_2$O$_3$ in MCF-7 cells was further explored by studying the effects of As$_2$O$_3$ on the estrogen-regulated cell cycle. 17β-Estradiol stimulated cell growth by accelerating G$_1$–S phase progression and recruiting cells from the G$_0$ phase to enter the cell cycle (Sutherland et al. 1983). Here, we showed that the cell population after 10 nM 17β-estradiol treatment showed an increase in numbers in the S phase and a decrease in numbers in the G$_1$ phase, i.e. the stimulatory cell cycle progression in MCF-7 cells (Fig. 9). When co-treated with 2 µM As$_2$O$_3$ and 17β-estradiol, the cell population accumulated in the G$_1$ phase, indicating that 2 µM As$_2$O$_3$ opposed 17β-estradiol-stimulated cell cycle progression to S phase in MCF-7 cells. The opposition may be due to the regulation of cell cycle proteins in the G$_1$ and G$_1$/S phases such as down-regulation of cyclin D1 mRNA and protein expression, as up-regulation of cyclin D1 levels were shown to be responsible for 17β-estradiol-stimulated cell cycle progression (Prall et al. 1997, Charpentier et al. 2000). By cDNA microarray analysis, cyclin D1 gene was found to be regulated by estrogen with the ERE sequence in the promoter regions (Gruvberger et al. 2001). So, As$_2$O$_3$ induced cell growth inhibition in MCF-7 cells by G$_1$ phase arrest in MCF-7 cells; this might be related to cyclin D1 and awaits further studies.

As estrogen is a primary risk factor of promoting the growth of MCF-7 cells and estrogen was also found to promote resistance of chemotherapeutic drugs in MCF-7 cells (Teixeira et al. 1995), our finding that As$_2$O$_3$ could exhibit anti-estrogenicity on MCF-7 cells may shed light on the therapy of breast cancer in the initial stages of tumor development.

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**References**


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