Arsenic trioxide down-regulates antiapoptotic genes and induces cell death in mycosis fungoides tumors in a mouse model

A. Tun-Kyi¹,4, J.-Z. Qin², P. A. Oberholzer¹, A. A. Navarini³, J. C. Hassel¹, R. Dummer¹ & U. Döbbeling¹*

¹Department of Dermatology, University Hospital Zurich, Zurich, Switzerland; ²Skin Disease Research Laboratories, Oncology Institute, Loyola University Medical Center, Maywood, IL, USA; ³Institute for Experimental Immunology, University Hospital Zurich, Zurich, Switzerland; ⁴Harvard Medical School, Department of Medicine, Beth Israel Deaconess Medical Center, Harvard Institutes of Medicine, Boston, USA

Received 8 November 2007; revised 15 January 2008; accepted 7 February 2008

Background: Mycosis fungoides (MF) is the most frequent cutaneous T-cell lymphoma (CTCL). Arsenic trioxide (As₂O₃) has recently been shown to be effective against leukemias, so we studied whether As₂O₃ induces apoptosis of CTCL cells in vitro. We further investigated if As₂O₃ is effective in a MF mouse model.

Material and methods: Annexin V/7-amino-actinomycin-D stainings were carried out to investigate if As₂O₃ induced apoptosis of CTCL cell lines. To study the underlying mechanisms, the effects of As₂O₃ on various transcription factors and apoptosis regulating proteins were analyzed by western blots, electrophoretic mobility shift assays and transcription factor enzyme-linked immunosorbent assays. The ability of As₂O₃ to induce tumor regression was investigated in a MF mouse model.

Results: As₂O₃-induced apoptosis was paralleled by a reduction of the DNA-binding activities of transcription factors of the NFkB and signal transducer and activator of transcription gene families and reduced expression of the antiapoptotic proteins bcl-1, bcl-xL and mcl-1. Local injections of 200 μM As₂O₃ into tumors caused complete remissions in five of six mice and one partial remission.

Conclusions: As₂O₃ induced apoptosis of CTCL cells by the down-regulation of transcription factors that stimulate the expression of antiapoptotic genes. Local injection of As₂O₃ into MF tumor-bearing mice resulted in tumor regression.

Key words: cancer therapy, cell death/survival genes, cutaneous T-cell lymphoma, gene regulation, oncogenes, transcription factors

Introduction

Cutaneous T-cell lymphomas (CTCL) are a class of non-Hodgkin’s lymphoma and are the second most common extranodal lymphomas, characterized by a clonal proliferation of neoplastic T lymphocytes [1, 2]. The two main forms are mycosis fungoides (MF), which is the most common type of CTCL, and its leukemic form, the Sézary syndrome (SS). MF remains confined to the skin and often presents with patches and plaques or in more advanced forms with tumors and a generalized erythema (erythroderma). Most patients will only experience skin symptoms without serious complications. In early clinical stages, malignant T cells are present in the epidermis, particularly along the basal layer and adjacent to Langerhans cells. However, as disease progresses, neoplastic cells are detected within dermal infiltrates in increasing numbers, at times entailed with loss of epidermotropism. In contrast, SS patients show a generalized erythroderma, leukemic T cells in the blood and a reduced life expectancy compared with MF patients with only ~30% of patients surviving beyond 5 years after diagnosis. This is probably due to the circulating malignant T cells which produce various immunosuppressing molecules such as interleukin (IL)-10, which might lead to a down-regulation of the immunological tumor surveillance.

There are various therapeutic modalities that show activity in CTCL [3, 4]. MF patients in early stages are generally treated with glucocorticoids, retinoids, extracorporal photopheresis or more effectively with psoralen and UVA (PUVA). PUVA therapy shows complete remission for 6–30 months in >80% of the patients, but the patients relapse. Advanced MF stages and SS are treated with PUVA in combination with interferon-α, locally applied cytostatics such as 1,3-bis(2-chloroethyl)-1-nitrosourea or radiation therapy [4, 5]. Currently, no cure for either form of CTCL has been found.
As mentioned above, CTCL tumors remain restricted to the skin for most of the time as the disease progresses. The low number of mitotic cells led to the idea that the increase of the tumor mass is due to the overexpression of cell survival genes such as bcl-2 which protect tumor cells from programmed cell death (apoptosis) [6] rather than oncogenes that promote cell growth. Indeed, it has been found that the antiapoptotic genes bcl-2, bcl-xL and mcl-1 are expressed in CTCL cells and that the expression levels of the latter increase with the progression of the disease [7].

IL-7 and IL-15 are growth factors for CTCL cells that are produced by skin keratinocytes and CTCL cells themselves [8–11]. Both ILs stimulate the expression of bcl-2 [12]. CTCL cells possess also constitutive NFkB, c-myc and signal transducer and activator of transcription (STAT)5 [12–17] activities that may stimulate the transcription of the apoptosis inhibitors cAP2 [17] and bcl-2. NFkB activities may therefore also increase the survival of CTCL cells. Agents that suppress NFkB activity and/or bcl-2 expression may be good candidates for the treatment of CTCL, as they should be able to induce apoptosis in CTCL cells.

Arsenic-containing compounds like As2O3 and melarsoprol have been shown to induce bcl-2 down-regulation and apoptosis in acute promyelocytic leukemia (APL) [18, 19] and chronic B-cell leukemia [20] at nontoxic concentrations. The inhibition of bcl-2 leads to the activation of the proteolytic caspases, which regulate the further steps of cell death [21]. As2O3 has been used for APL treatment and led to complete remission in 90% of the patients and prolonged survival [19, 22]. SS patients have been treated systematically with As2O3 with little success, as the As2O3 levels in the skin have not been high enough [23].

In this study, we investigated the effects of As2O3 on the cell survival/death genes bcl-2, bcl-xL, mcl-1, bax, bad and the transcription factors NFkB and STAT5 by western blot and electrophoretic mobility shift assays (EMSA) as well as transcription factor enzyme-linked immunosorbent assays (ELISAs), using nuclear and cytoplasmatic extracts from CTCL cell lines Hut78 and MyLa 2059. We also investigated whether As2O3 leads to cell death in CTCL cell lines in vitro and whether As2O3 causes remission of human CTCL tumors in nude mice in vivo.

**material and methods**

**cells and cell culture**

The cell line Hut78 (SS) was obtained from ECACC. The cell line MyLa 2059 (MF) was a kind gift of Dr Keld Kaltoft, University of Aarhus, Denmark. Hut78 and MyLa cells were grown in Hepes-buffered RPMI-1640 medium supplemented with 2 mM glutamine, 10% fetal calf serum, 0.25 mg/ml amphotericin B, 100 U penicillin G, 100 U streptomycin and 1 mM pyruvate (all from Invitrogen, Basel, Switzerland).

**induction of apoptosis**

Apoptosis was assessed in vitro after growing 2 × 10^5 Hut78 or MyLa 2059 cells in the presence of 0.5–2 μM As2O3 for 10–14 days, depending on the sensitivity of the tested cell line to the corresponding agent. Cell death was monitored by observation of cell morphology, cell counting and trypan blue staining as well as MTT assays and flow cytometric analysis of Annexin V/7-amino-actinomycin-D (AAD)-stained cells as further described below. Fresh MF and SS cells from patients were not analyzed, as they survive only a short time in culture and do not propagate.

**MTT assay**

Cells were cultured in the presence of various concentrations of As2O3 for 3 days. Cells were thereafter washed and resuspended in DMEM containing 0.5 mg/ml MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) (Sigma, Buchs, Switzerland) and incubated for 3 h at 37°C. Cells were then washed and the converted dye solubilized with 1 ml acidic isopropanol (0.04 M HCl in absolute isopropanol). The absorbance of the converted dye was subsequently measured at a wavelength of 570 nm.

**flow cytometry**

As2O3-treated cell suspensions were stained with Annexin V-PE and 7-AAD following the manufacturer’s guidelines and analyzed on a FACS Calibur machine (both BD Biosciences, Switzerland). Annexin V-PE positive, 7-AAD negative cells were considered early apoptotic and cells that were in late apoptosis or already dead were both Annexin V-PE and 7-AAD positive.

**western blotting**

The antibodies against bcl-2 (sc-1041), bcl-x (sc-1041), mcl-1 (sc-819) and beta actin (sc-1616) were from Santa Cruz Biotechnology Inc. For western blotting, 30 μg of protein of cytoplasmatic extracts were run on a 9% sodium dodecyl sulfate polyacrylamide gel and separated by polyacrylamide gel electrophoresis. The proteins were transferred to a nitrocellulose filter using a Mini Trans Blot Cell (BioRad, Reinach, Switzerland) following the manufacturer’s guidelines. Unspecific antibody-binding sites were blocked by incubating the membrane overnight at 4°C in 2% milk in tris-buffered saline (TBS), pH 8.0 containing 0.3% Tween 20 (TBS-T). The membrane was then incubated with the corresponding first antibody (1:1000 dilution) for 4 h at room temperature in 1% milk in TBS-T. The incubation with the secondary antibody (anti-rabbit, Santa Cruz Biotechnology Inc., 1:1000 dilution) was done in TBS-T for 4 h at room temperature. The signal was detected by incubating the membrane with BM purple AP substrate (Roche Biochemicals, Rotkreuz, Switzerland) following the manufacturer’s instructions.

**nuclear and cytoplasmatic cell extracts**

Extracts were prepared by the following method. Cells (1–2 × 10^6) were swollen in 400 μl hypotonic buffer A (10 mM Hepes, pH 7.9, 10 mM KCl, 1 mM benzamidine, 1 mM EGTA, pH 8, 1 mM EDTA, pH 8) for 20 min at 4°C and thereafter passed 10 times through a 25-gauge needle. The suspensions were then centrifuged at 16,000 g for 30 s and the supernatants were used as cytoplasmatic extracts. The nuclear pellets were extracted with 60 μl hypertonic buffer C (20 mM Hepes pH 7.9, 25% glycerol 0.42 M NaCl, 1.5 mM MgCl2, 0.2 mM EDTA pH 8, 1 mM benzamidine). The supernatants were centrifuged for 5 min and then used as nuclear extracts for EMSAs.
electrophoretic mobility shift assay

We carried out EMSAs with nuclear extracts of Hut78 and MyLa 2059 cell lines as described earlier [24]. The nuclear extracts were incubated with a radioactively labeled oligonucleotide containing the binding sites for NFkB. We compared nuclear extracts from untreated Hut78 and MyLa 2059 cells and Hut78 and MyLa 2059 cells which had been treated with 1 μM (Hut 78 cells) or 2 μM As2O3 (MyLa 2059 cells) for 1, 2 and 4 days. The DNA–protein complexes were analyzed on a non-denaturating 4% polyacrylamide gel. The oligonucleotide for the DNA-binding site was synthesized by Microsynth, Balgach, Switzerland.

transcription factor ELISA

We used the NFkB family transcription factor ELISA from Active Motif, Rixenart, Belgium. A DNA oligonucleotide containing the DNA-binding sequence of NFkB was attached to the surface of a 96-well plate. After rehydration, the nuclear extracts of the MF and SS cells were added and incubated for 1 h at room temperature to let the NFkB protein bind to their DNA motifs. The plates were then washed to remove unbound proteins, and antibodies against the different proteins of the NFkB family were added. After 1 h incubation at room temperature, the first antibodies were washed away and a second antibody coupled to horseradish peroxidase (HRP) was added for 1 h at room temperature. The addition of the HRP substrate to the well started a color reaction, which allowed the measurement of the DNA-bound transcription factor. The specificity of the DNA-binding reaction was monitored by control experiments where oligonucleotides containing the wild-type or mutated DNA-binding motif of interest were added as competitors.

mice, tumor induction and As2O3 treatment

Athymic nude mice from Harlan, Oxon, UK were kept under sterile conditions in the central animal laboratory of the University Hospital Zurich; 3 × 106 MyLa 2059T cells were injected s.c. into the right flank of the mice. Tumors were visible after 2–3 weeks in 70%–80% of the mice. The tumor sizes were measured by calipers and the volumes were calculated by the formula $V = \frac{\text{length} \times \text{width} \times \text{height}}{2}$. The MyLa 2059T cells were derived from a tumor induced in athymic nude mice by standard MyLa 2059 cells. The cells were examined for the presence of murine pathogens before injection. The cells were injected s.c., since the skin of nude mice is extremely thin (3–6 cell layers) and does not allow intradermal injections. The tumors were injected with As2O3 directly, as the tail veins of mice are fragile and break down after daily repeated injections.

As2O3 treatment (50 or 200 μM in sterile PBS) was started when the tumors had reached a minimal volume of 100 mm3. Using an insulin syringe, 50 μl of As2O3 were injected when the tumor volume was <200 mm3 and 100 μl As2O3 were injected when the tumor volume was >200 mm3.

The experiments were carried out following the ethical guidelines for animal experiments of the Swiss National Fund and were approved by the Veterinary Authorities of the Kanton of Zurich, Switzerland (license no. 163/2003).

results

As2O3 causes cell death of cutaneous T cell lines in vitro

It has been shown that As2O3 concentrations of ~1 μM cause cell death of leukemia cells [20]. To investigate the effects of As2O3 on the proliferation and viability of Hut78 and MyLa 2059 cells, cells were cultured in the presence of various As2O3 concentrations.

Microscopic inspection of cell cultures showed the presence of both Hut78 and MyLa 2059 cells displaying the typical features of apoptosis such as cell shrinkage, membrane blebbing, nuclear fragmentation and cellular debris in a dose-dependent manner (data not shown). By determining the number of viable cells using the trypan blue exclusion test, we found that culturing the cells in the presence of 0.5–2 μM As2O3 significantly decreased the number of viable Hut78 and MyLa 2059 cells. Figure 1A shows that As2O3 induced cell death of most of the Hut78 cells at 0.5 μM within 8 days; 1 and 2 μM As2O3 had a comparable effect within 6 and 3 days, respectively. MyLa 2059 cells were more resistant against As2O3 (Figure 1B). In the presence of 1 μM As2O3, the number of MyLa 2059 cells remained nearly constant.

We confirmed these results by performing MTT assays which showed a dose-dependent decrease of viable Hut78 and MyLa 2059 cells after treatment with various concentrations of As2O3 for 3 days (Figure 2A).

Figure 1. Arsenic trioxide causes cell death of (A) Hut78 and (B) MyLa 2059 cells. The cells were treated with different As2O3 concentrations as indicated. The number of cells (y-axis) is given in percent (100% = 2 × 106 cells). The time of treatment is indicated on the x-axis.
To study whether the observed decrease in growth was due to necrosis or apoptosis, Hut78 and Myla 2059 cells were cultured in the presence of various concentrations of As$_2$O$_3$ for 3 days and thereafter stained with Annexin V/7-AAD and subsequently analyzed by flow cytometry. Results demonstrated that both Hut78 and MyLa 2059 cells underwent apoptosis in a dose-dependent manner. Flow cytometry showed that the cells moved from viable (Annexin V-PE and 7-AAD negative) to early (Annexin V-PE positive and 7-AAD negative) and finally late apoptosis (Annexin V-PE and 7-AAD positive) as the As$_2$O$_3$ concentration was increased (Figure 2B). These data demonstrate that apoptosis is the main reason for As$_2$O$_3$-induced cell death.

The influence of As$_2$O$_3$ on apoptosis-regulating proteins in CTCL cell lines

MF and SS cells express the antiapoptotic proteins bcl-2, bcl-xL, mcl-1 and the proapoptotic genes bad and bax [7]. To test whether As$_2$O$_3$ influences the abundance of these proteins during the induction of apoptosis, we analyzed their expression levels while culturing Hut78 and MyLa 2059 cells in the presence of 1 μM As$_2$O$_3$. Figure 3 shows that bcl-2 and mcl-1 were faster down-regulated in the presence of As$_2$O$_3$ than the beta actin control in both Hut78 and MyLa 2059 cells. The bcl-xL protein shows another kinetic since its levels increased on day 2, but subsequently dropped down to levels that are lower than those in untreated cells, indicating that there may be a defence mechanism that protects cells from low concentration and short time exposure to As$_2$O$_3$. The proapoptotic gene bax behaved similar to the beta actin control and showed only a weak decrease after prolonged As$_2$O$_3$ exposure, whereas bad was more strongly down-regulated. The data shown are representative of three independent experiments.

The influence of As$_2$O$_3$ on constitutive transcription factor activities in MF and SS cells

MF and SS cells contain constitutive NFκB activities [13, 15] that may protect them from apoptosis. When measuring the binding of NFκB to its DNA-binding sequence using EMSAs, we found that binding was strongly reduced after prolonged...
As$_2$O$_3$ treatment at 1 $\mu$M. However, the DNA-binding activity of the ubiquitous Oct-1 transcription factor remained nearly unchanged (Figure 4).

To determine the effects of As$_2$O$_3$ on the DNA-binding activities of the different members of the NFkB transcription factor family, we carried out transcription factor ELISAs using the corresponding antibodies. Since MF and SS cells have also been found to contain constitutive STAT5a and STAT5b activities that may also protect MF and SS cells from apoptosis, we also included these two proteins in our analysis as well.

Figure 5 shows that As$_2$O$_3$ strongly reduced the DNA-binding activities of all the seven tested transcription factors p50, p65 (RelA), p52, RelB, c-Rel, STAT5a and STAT5b.

de the influence of As$_2$O$_3$ on tumor growth in a mouse model for MF

A mouse model for MF has recently been established using the MyLa 2059 cell line and athymic nude mice [25]. To study whether As$_2$O$_3$ can also slow down tumor growth in vivo, 3 $\times$ 10$^6$ cells were injected into the flanks of athymic nude mice. Once the tumors reached a size of 100 mm$^3$, As$_2$O$_3$ treatment was started. Since cells in a solid tumor are much more resistant against antitumor agents, we started with the injection of 50 $\mu$M As$_2$O$_3$ into the center of the lesion. The dose was increased to 100 $\mu$l once the tumors reached a size >200 mm$^3$. Tumors <800 mm$^3$ were treated with a volume of 150 $\mu$l. In control mice that were injected with PBS alone, the tumors reached a maximal volume of 1000 mm$^3$ within 17–20 days after which they were killed (Figure 6A). The treatment with 50 $\mu$M As$_2$O$_3$ delayed the growth of the tumors in three mice and caused a complete remission in one animal (Figure 6B). To investigate if a higher As$_2$O$_3$ concentration would result in a higher percentage of remissions, we treated a second group of mice with 200 $\mu$M As$_2$O$_3$. This higher concentration turned out to be much more effective and caused four complete remissions within 22–40 days, one complete remission after 90 days and delayed tumor growth in another animal (Figure 6C), demonstrating a dose-dependent effect of As$_2$O$_3$ on in vivo tumor growth. At both concentrations, we could often observe the formation of an ulcer-like lesion in the skin adjacent to the tumor which got smaller and finally disappeared as the tumor volume decreased. There was no lasting visible scar formation in the mouse skin after treatment (Figure 7B and C). No lasting side effects of As$_2$O$_3$ on the surrounding skin or other tissues and organs could be observed.

Tumors that showed partial remission of both series of experiments were excised and underwent histological investigation (Figure 7D). The greatest cell destruction was observed in the center of the lesions where tissue was

![Figure 4. Prolonged arsenic trioxide treatment reduces the binding of the NFkB transcription factor to its recognition sequence in (A) Hut78 and (B) MyLa 2059 cells. The DNA binding of the Oct-1 transcription factor remains unchanged. Lane 1: untreated cells, lane 2: cell treated for 2 days, lane 3: cell treated for 5 days, lane 4: cell treated for 4 days with 1 $\mu$M arsenic trioxide.](https://academic.oup.com/annonc/article-abstract/19/8/1488/230515)

![Figure 5. Transcription factor enzyme-linked immunosorbent assays of NFkB and signal transducer and activator of transcription proteins of As$_2$O$_3$-treated and -untreated (A) Hut78 and (B) MyLa 2059 cells. The As$_2$O$_3$ concentration is indicated by the x-axis and the relative amount of specific DNA-binding protein (extinction at OD595) is indicated by the y-axis.](https://academic.oup.com/annonc/article-abstract/19/8/1488/230515)
fragmented to acellular debris. This area was surrounded by dead cells with fragmented nuclei followed by cells in several stages of apoptosis. Living cells could be detected in the periphery of the tumors. Unfortunately, the unspecific reactions of the antibodies with the cellular debris of the As$_2$O$_3$-treated tumor lesions prevented the analysis of these lesions for the expression of apoptosis-regulating genes by specific antibodies. The tissue surrounding the tumor showed no damage caused by As$_2$O$_3$ and no significant scarring could be detected.

discussion

Here, we demonstrate that the treatment of MF skin tumors with As$_2$O$_3$ may be feasible. Recent data of Michel et al. [23] have shown that intravenous concentrations of 1–2 μM As$_2$O$_3$ are sufficient to kill malignant SS T cells in the blood but had no effect on skin lesions, suggesting that the resulting nanomolar As$_2$O$_3$ concentrations in the skin were too low. Our findings that up to 200 μM were needed to achieve a complete remission confirm this assumption. Fortunately, such high concentrations were well tolerated by the surrounding tissues when the As$_2$O$_3$ was injected into the tumor or its close vicinity. There were no signs of significant scarring in the mouse skin although we often observed a temporary formation of an ulcer-like lesion in the skin surrounding the tumor.

Michel et al. [23] observed that As$_2$O$_3$-triggered apoptosis induced the translocation of cytochrome c from the mitochondria to the cytoplasm. Here, we demonstrate that As$_2$O$_3$ down-regulates the antiapoptotic genes bcl-2, bcl-xL, and mcl-1 which counteract the release of cytochrome c from mitochondria. The down-regulation of these genes is therefore a good explanation for the observed translocation of cytochrome c from the mitochondria. This mechanism would be comparable to the one observed in anoxia-induced apoptosis [26].

Figure 6. Growth of MyLa 2059 cells derived tumors on immune-deficient athymic nude mice; $3 \times 10^6$ MyLa 2059T cells were injected s.c. into nude mice and treatment was initiated once the tumors had reached a volume of 100 mm$^3$. Mice received daily intralesional injections of (A) PBS, (B) 50 μM or (C) 200 μM As$_2$O$_3$. Day 0 represents the time point when the tumors had reached a volume of ~100 μl and when the treatment was started. Mice were euthanized once the tumors reached a volume of 1 ml (1000 mm$^3$), according to the directions of the Swiss Animal Protection Law.

Figure 7. Tumor regression during (A–C) arsenic trioxide treatment and (D) biopsy of a treated tumor. (A) Untreated tumor, (B) regression and formation of a central necrotic area in an As$_2$O$_3$-treated tumor, (C) site after complete tumor regression, (D) biopsy of a treated tumor. Dead tumor tissue can be seen on the left with fragmented nuclei and on the right living tumor tissue showing first signs of apoptosis (chromatin condensation).
The proapoptotic bax gene was also somewhat down-regulated by As$_2$O$_3$, but the concentration of the bad protein remained nearly unaffected. Thus, in a sum the equilibrium between antiapoptotic and proapoptotic proteins that is crucial for the survival of the cell [27, 28] was clearly tipped to the side of the proapoptotic proteins. The data of the annexin V/7-AAD assay confirm that As$_2$O$_3$ induces cell death mainly by apoptosis.

As$_2$O$_3$ also down-regulates the constitutive DNA-binding activities of the transcription factors of the NFkB and STAT gene families. Especially the STATs may be important for the regulation of the bcl-2, bcl-xl, and mcl-1 genes, since a STAT5-binding site has been identified in the regulatory gene of the bcl-2 gene [29]. Thus, the down-regulation of STAT5 and other STATs should result in a reduced expression of the antiapoptotic genes.

The relationship between NFkB and these antiapoptotic genes in MF and SS is less clear, since the NFkB-regulated antiapoptotic cIAP genes are not expressed in these cells (J.-Z. Qin, C.-L. Zhang and U. Döebeling, unpublished data), although they possess constitutive NFkB activities. The literature on the effect of NFkB on bcl-2 and related proteins is contradictory. An NFkB-regulated gene that could be important for cell survival of CTCL cells is FLIP which is an important mediator of antiapoptotic signals and has been shown to play a role in the pathogenesis of anaplastic large-cell lymphoma by protecting cells from apoptosis [30].

Taken together, our results show that the death of MF and SS cells by As$_2$O$_3$ is caused by reduced expression levels of antiapoptotic proteins, which are paralleled by the down-regulation of STAT and NFkB transcription factors. The in vivo tumor regression upon local As$_2$O$_3$ treatment demonstrates that As$_2$O$_3$ could be a novel and effective approach in the treatment of CTCL tumors.

acknowledgements

The authors would like to thank C. Dudli for the processing of the histological samples and M. Johnson and M. Bär for the preparation of the photographs.

references