

The novel selenium heteropoly compound (NH₄)₄H₄[Se₂Mo₂V₄O₂₄]·7H₂O induces apoptosis of K562 cells

JUNYING YANG, XIANGUANG YANG, JINYU FAN, QINGQING ZHAO and CUNSHUAN XU

College of Life Sciences and Key Laboratory for Cell Differentiation Regulation,
Henan Normal University, Xinxiang, Henan 453007, P.R. China

Received May 5, 2011; Accepted August 22, 2011

DOI: 10.3892/mmr.2011.580

Abstract. The purpose of this study was to investigate the antitumor effects and mechanism of the selenium heteropoly compound (NH₄)₄H₄[Se₂Mo₂V₄O₂₄]·7H₂O (SeMoV) in K562 cells. The results showed that 0.313-10 mg/l SeMoV significantly inhibited the proliferation of K562 cells *in vitro* in a time- and concentration-dependent manner as determined by a microculture tetrazolium assay; the IC₅₀ values were 7.69 and 4.06 mg/l following 48 and 72 h of treatment with SeMoV, respectively. Analysis of the cell cycle indicated that the proportion of cells in the G0/G1 phase was decreased at 48 h whereas the proportion of cells in the S phase was increased following treatment for 24 and 48 h. A significant sub-G1 peak was observed at 5 mg/l for 24 h. Morphological observation revealed typical apoptotic features. SeMoV significantly caused the accumulation of Ca²⁺, Mg²⁺ and ROS, and a reduction in the pH value and the mitochondrial membrane potential (MMP) in the K562 cells compared with the control (p<0.01), as shown by confocal laser scanning microscopy. Experiments also showed that the expression of Bcl-2 was significantly inhibited by 20 mg/l SeMoV, while Bax expression increased. Meanwhile, the amount of cytochrome C and IκB in K562 cells was increased, while NF-κB expression was significantly decreased, following treatment with SeMoV for 24 h. The experiment implied that SeMoV had antitumor activity and its mechanism was attributed partially to apoptosis, which was induced by the elevation of the intracellular Ca²⁺, Mg²⁺ and ROS concentration, a reduction in the pH value and MMP, and the NF-κB/IκB signaling pathway.

Introduction

Selenium is an essential dietary component and has been used as an anticarcinogenic or preventive chemical against

tumors (1,2). It has been known for a number of years that populations with a low selenium intake and low plasma selenium levels have an increased incidence of cancer (3-9). Therefore, investigators have focused their attention on searching for potent selenium compounds, which possess higher antitumor efficacy and lower tissue toxicity.

Heteropoly complexes represent a class of polyanionic compounds with a variety of significant biological activities including antiviral or antitumor effects (10,11) and lower tissue toxicity. Heteropoly complexes have attracted attention in view of their potential application as antiviral and antitumoral agents (12). Recently, certain evidence showed that heteropoly complexes were promising anti-fungal compounds (13,14) and candidates for Alzheimer's disease treatments (15). However, little has been reported for selenium heteropoly complexes. In order to obtain a selenium heteropoly complex that has higher antitumor efficacy and lower tissue toxicity, a series of compounds were synthesized (16) with Selenium, vanadium, molybdenum, butyl, amido and hydroxyl.

Earlier studies performed *in vitro* have suggested that induction of apoptosis and/or inhibition of cell growth accounts for the cancer prevention by selenium compounds (17-19). Evasion of apoptosis is one of the hallmarks of human cancer. Apoptosis evasion is responsible for tumor promotion and progression, as well as for treatment resistance (20). Investigators have reported that genetic mutations culminating in the disturbance of apoptosis or derangement of apoptosis-signaling pathways appear to be an essential factor of carcinogenesis (20,21), and induction of apoptosis in cancer cells is one of the most significant methods for cancer treatment (21). A number of anticancer agents have been reported to induce apoptosis of cancer cells, and apoptosis induced by a change in intracellular ion concentrations such as Ca²⁺, Mg²⁺ and H⁺ is one of the mechanisms of cytotoxicity (22-24). Therefore, the aim of this study was to test whether (NH₄)₄H₄[Se₂Mo₂V₄O₂₄]·7H₂O (SeMoV) (16), a novel selenium compound, has antitumor activity in K562 cells and to explore its mechanism of action.

Materials and methods

Drugs and chemicals. (NH₄)₄H₄[Se₂Mo₂V₄O₂₄]·7H₂O brown crystal was kindly provided by the Laboratory of Chemistry, Lanzhou University (Lanzhou, China). MTT and SDS were purchased from Sigma (St. Louis, MO, USA). Fluo-3/AM,

Correspondence to: Dr Junying Yang, College of Life Sciences and Key Laboratory for Cell Differentiation Regulation, Henan Normal University, 46 Jianshe Road, Xinxiang, Henan 453007, P.R. China
E-mail: junyingyang@yahoo.com.cn

Key words: SeMoV, antitumor, apoptosis, Cytochrome C, NF-κB/IκB

Mag-Fluo-4/AM, carboxy SNARF-1/AM, 2',7'-dichlorofluorescein diacetate and MitoTracker Green FM were purchased from Molecular Probes Co. (Eugene, OR, USA). Monoclonal antibodies to Bcl-2 and Bax and the Bio-Rad protein assay kit were purchased from Molecular Probes Co. Mouse anti-human cytochrome C, I κ B α antibody, anti-rabbit IgG antibody and anti-goat IgG antibody were purchased from Sigma. Anti-mouse IgG antibody was purchased from Amersham. RPMI-1640 medium was obtained from Gibco BRL (Grand Island, NY, USA). Bovine serum was purchased from Hangzhou Sijiqing Biotechnology Co. (Hangzhou, China). Other chemicals were of analytical purity.

Cell cultures and the MTT assay *in vitro*. The K562 cell line was purchased from the Cell Bank of Shanghai Institute of Cell Biology (Chinese Academy of Sciences, Shanghai, China). Cells were grown in complete RPMI-1640 medium containing 10% heat-inactivated bovine serum, 2 mmol L-glutamine, 100 U/ml penicillin and 100 μ g/ml streptomycin at 37°C in a humidified atmosphere of 5% CO₂, and were routinely passaged every other day.

Cytotoxicity was measured by MTT assay (25). Briefly, exponentially growing cells were resuspended in complete RPMI-1640 medium to a concentration of 1×10^8 cells/l. A total amount of 100 μ l aliquots of cells containing 0.313–10 mg/l SeMoV were seeded in quadruplicate into a 96-well flat bottom microculture plate (Costar, Corning, Lowell, MA, USA) for the designated amount of time. At the end of the incubation period, MTT was added for the last 4 h, and then SDS was added and mixed thoroughly at 37°C. Optical density was read on a microplate reader (Elx800, BioTek Instruments, Inc., USA) at 570 nm after agitating the plates for 5 min.

Flow cytometry. The percentage of K562 cells in each phase of the cell cycle was analyzed by flow cytometry. Following treatment with 0.625–5 mg/l SeMoV for the designated time, cells were fixed in ice-cold 70% ethanol at 4°C for at least 24 h, and then stained with propidium iodide (PI) solution (containing PI 50 mg/l and RNase 50 mg/l, respectively) at room temperature in the dark for 30 min. The samples were read on a Coulter Epics XL flow cytometer (Beckman-Coulter Inc., Fullerton, CA, USA). The percentage of cells in the sub-G1, G0/G1, S and G2/M phase were calculated by Multicycle software (Phoenix Flow System, San Diego, CA, USA).

Morphological features of apoptosis

Inverted microscopy. K562 cells (1×10^5 cells/ml) were grown in complete medium containing 0.313–10 mg/l SeMoV for 24 h, then stained with right-Giemsa and observed under inverted microscopy.

Electron microscopy. K562 cells treated with 5 mg/l SeMoV for 24 h were prefixed in cacodylate-buffered glutaraldehyde (2%), post-fixed in 1% osmium tetroxide, dehydrated in a graded series of alcohol and embedded in Epon (PolyBed 812). Sections were stained with uranyl acetate and lead citrate and examined with an EM-1230 electron microscope (Japan).

Confocal laser scanning microscopy assay. Following treatment as described above, K562 cells were washed twice in ice-cold phosphate-buffered saline (PBS), then loaded

with Fluo-3/AM (5 μ mol/l), Mag-fluo-4 (5 mmol/l), carboxy SNARF-1/AM (10 μ mol/l), 2', 7'-dichlorofluorescein diacetate and MitoTracker Green FM (1.25 μ mol/l), respectively, for 45 min at 37°C, then washed twice in PBS. The fluorescence intensity changes of intracellular Ca²⁺, Mg²⁺, ROS, pH value and mitochondrial membrane potential (MMP) were measured by confocal laser scanning microscopy.

Immunohistochemistry assay. Following treatment with 20 mg/l SeMoV for 24 h, cells were washed in cold PBS three times, smeared, air dried and fixed, then processed according to the manufacturer's instructions and examined with a microscope.

Western blot assay. Cells were treated for 24 h with SeMoV and resuspended in lysis buffer. The protein concentration was determined by the Bradford assay (Pierce, Rockford, IL, USA). A total amount of 20 μ g protein extract/lane was loaded onto SDS-PAGE (20 MA) and separated under denaturing conditions. Protein samples were then transferred onto nitrocellulose membranes (180 MA, 90 min) and the individual target protein was immunoreacted with the appropriate dilution of its primary antibodies (cytochrome C, NF- κ B, I κ B) at 4°C overnight. The protein was then incubated with an appropriate dilution of horseradish peroxidase-conjugated anti-rabbit IgG antibody (1:2,000 dilution), anti-mouse IgG antibody (1:670 dilution) or anti-goat IgG antibody (1:1,000 dilution) as a secondary antibody. Enhanced chemiluminescence (ECL, Amersham) was used to reveal antibody binding.

Statistical analysis. The two-tailed Student's t-test was employed to assess the significance of the data. The data were presented as the mean \pm SD. $P < 0.05$ was considered to be statistically significant.

Results

Anti-proliferation activity of SeMoV *in vitro*. As shown in Table I, 0.313–10 mg/l SeMoV significantly inhibited the proliferation of K562 cells *in vitro*. Following a 24 h treatment, inhibition rates (IRs) were 13.18, 16.24, 17.91, 18.64, 20.36 and 40.66%, respectively. Following treatment with SeMoV for 48 and 72 h, proliferation of K562 cells was significantly inhibited in a time- and dose-dependent manner, with IRs of 13.29, 22.92, 26.79, 27.76, 37.35 and 63.85%, respectively, after a 48 h treatment, and 17.62, 17.71, 24.42, 28.09, 50.29 and 78.15%, respectively, after a 72 h treatment.

Effect of SeMoV on apoptosis and cell cycle progression of K562 cells. The cell cycle distribution was analyzed by flow cytometry in K562 cells treated with various concentrations of SeMoV for 24 and 48 h, as shown in Fig. 1. The proportion of cells in the S phase was increased with the 24 and 48 h treatment, while the proportion of cells in the G0/G1 phase was decreased with the 48 h treatment. A significant sub-G1 peak was noted at 5 mg/l for 24 h. This indicates that SeMoV may induce changes in the cell cycle distribution and apoptosis.

Morphological features of apoptosis. Typical apoptotic characteristics were present in the K562 cells treated with

Table I. Antitumor effect of SeMoV in K562 cells *in vitro* following 24, 48 and 72 h treatment.

Groups	Concentration (mg/l)	24 h (OD ₅₇₀)	48 h (OD ₅₇₀)	IC ₅₀ (mg/l)	72 h (OD ₅₇₀)	IC ₅₀ (mg/l)
Control	0	0.692±0.010	0.956±0.116	7.69 (2.34-25.26)	1.316±0.115	4.06 (1.95-8.47)
SeMoV	0.313	0.601±0.014 ^b	0.824±0.042	7.69 (2.34-25.26)	1.081±0.039 ^a	4.06 (1.95-8.47)
SeMoV	0.625	0.579±0.016 ^b	0.730±0.079 ^a	7.69 (2.34-25.26)	1.073±0.108	4.06 (1.95-8.47)
SeMoV	1.25	0.563±0.019 ^b	0.693±0.049 ^a	7.69 (2.34-25.26)	0.992±0.073 ^a	4.06 (1.95-8.47)
SeMoV	2.5	0.568±0.027 ^b	0.682±0.035 ^a	7.69 (2.34-25.26)	0.942±0.006 ^b	4.06 (1.95-8.47)
SeMoV	5	0.551±0.033 ^b	0.593±0.006 ^b	7.69 (2.34-25.26)	0.652±0.027 ^b	4.06 (1.95-8.47)
SeMoV	10	0.411±0.025 ^b	0.345±0.031 ^b	7.69 (2.34-25.26)	0.288±0.035 ^b	4.06 (1.95-8.47)

OD, optical density. An MTT assay was used to measure the cytotoxic effect of SeMoV in the K562 cells. Results were expressed as the mean ± SD of three experiments. ^ap<0.05, ^bp<0.01 vs. the control. The potency of the drug was determined by the IC₅₀ (50% growth-inhibition concentration) value.

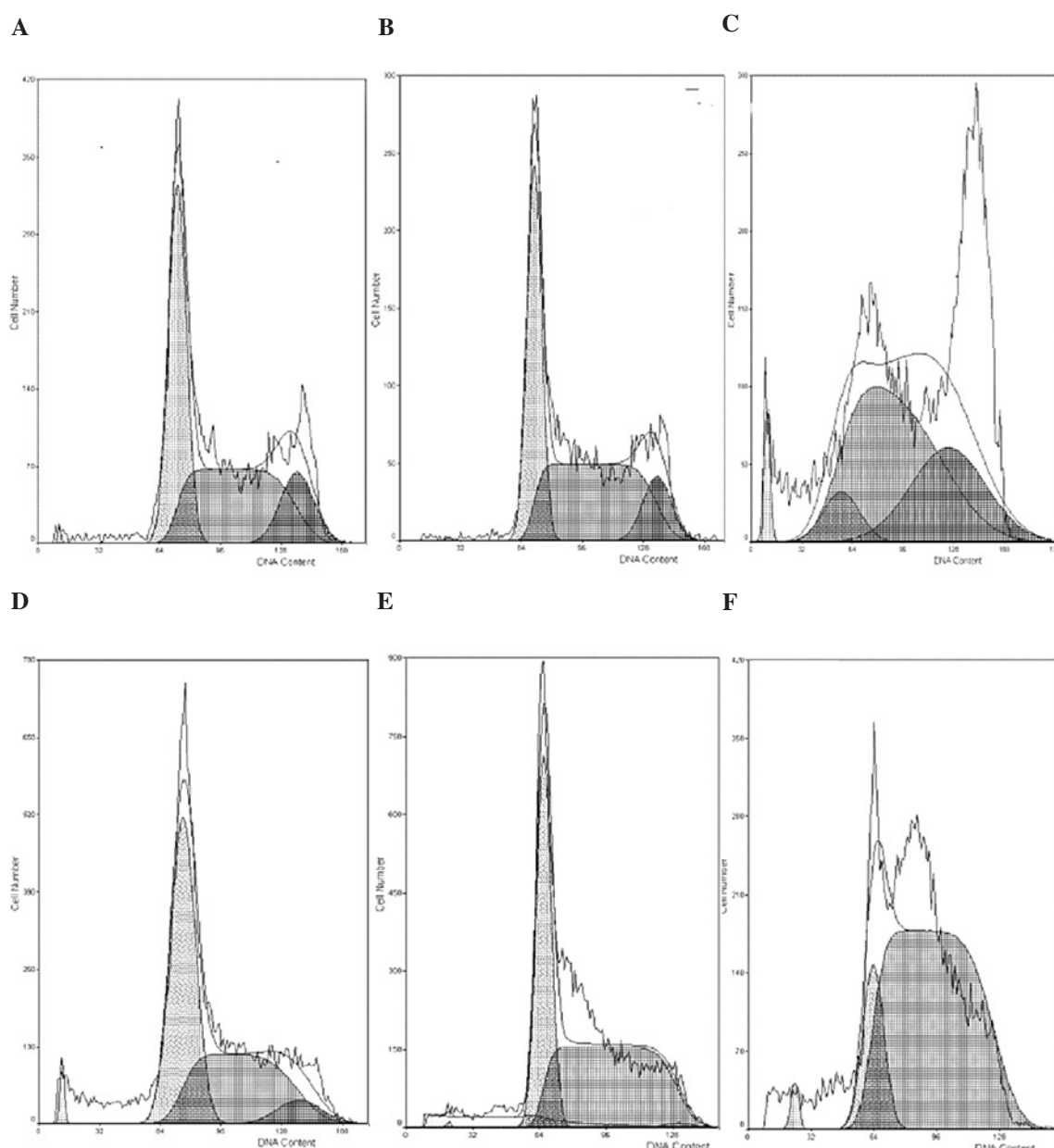


Figure 1. Apoptosis of the K562 cells treated for 24 and 48 h as determined by flow cytometry. (A and D) Control cells. (B and E) Cells treated with SeMoV 0.625 mg/l. (C and F) Cells treated with 5 mg/l. (A-C) Cells treated with SeMoV for 24 h. (D-F) Cells treated for 48 h. (A) The proportion of cells in the G0/G1, G2/M, S and sub-G1 phase is 37, 11.2, 51.8 and 0.4%, respectively; (B) 37.5, 12.2, 50.3 and 0.2%, respectively; (C) 8.2, 31.3, 60.5 and 3.6%, respectively; (D) 50.8, 7.0, 42.2 and 1.8%, respectively; (E) 39.2, 1.0, 59.8 and 0.2%, respectively; (F) 15.3, 0.48.7 and 1.6%, respectively.

0.313–10 mg/l SeMoV for 24 h. Nuclear condensation, chromosome fragmentation and apoptotic bodies were observed using an inverted microscope (data not shown). The electron microscopic observation also revealed typical apoptotic features, including shrinkage of cellular and nuclear membranes, condensed heterochromatin around the nuclear periphery and cytoplasmic vacuolation in the K562 cells treated with 5 mg/l SeMoV for 24 h (Fig. 2).

Effect of SeMoV on the intracellular Ca^{2+} , Mg^{2+} and ROS concentration, pH value and MMP. The changes in intracellular ion homeostasis may induce mitochondrial apoptosis and lower its membrane potential. The experiment showed that the fluorescence intensity of intracellular Ca^{2+} , Mg^{2+} and ROS was greatly increased following treatment with SeMoV as compared with the control group. However, the fluorescence intensity of intracellular pH value and MMP was markedly lowered as shown in Fig. 3.

Effect of SeMoV on the expression of Bcl-2 and Bax. The sensitivity of cells to apoptotic stimuli depends on the balance of pro- and anti-apoptotic proteins. The expression of Bcl-2 and Bax were used as symbolic genes of apoptosis. The study showed that the expression of Bcl-2 was significantly inhibited, while the expression of Bax was increased by 20 mg/l SeMoV (data not shown).

Effect of SeMoV on the content of cytochrome C, NF- κ B and I κ B. Release of cytochrome C induced by perturbations of MMP may be one of the most conspicuous manifestations of apoptosis, and NF- κ B is also closely related to apoptosis. Fig. 4 shows that the content of Cytochrome C and I κ B in the K562 cells was increased and NF- κ B expression was decreased markedly following treatment with various concentrations of SeMoV for 24 h.

Discussion

Our results clearly demonstrated that SeMoV significantly inhibited the proliferation of K562 cells *in vitro* in a concentration-dependent manner. Cell cycle analysis showed that SeMoV decreased the proportion of cells in the G0/G1 phase, and increased S phase cells following treatment for

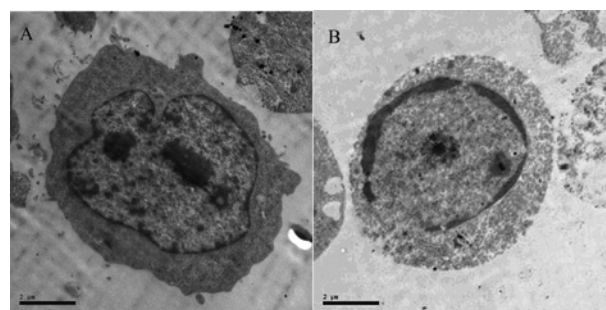


Figure 2. Morphological observation by electron microscopy of K562 cells treated with SeMoV 5 mg/l for 24 h. (A) Control cells (x8000). (B) Treatment cells (x8000).

24 and 48 h. A significant sub-G1 peak was also observed at high concentrations of SeMoV for 24 h, which was similar to the report that a number of selenium compounds are capable of arresting cells in either phase (26). SeMoV also induced typical apoptotic features.

It is known that apoptosis is not only a genetically controlled mechanism essential for development and the elimination of unwanted or damaged cells such as tumor cells (9) but is also a commonly accepted cellular event that may account for the cancer preventive effects of selenium compounds (27). In addition, mitochondrial disruption plays a major role during apoptosis induction, resulting in membrane permeability transition and the release of mitochondrial apoptogenic factors such as mitochondrial cytochrome C, which is released into the cytosol leading to activation of caspase 9 and the caspase cascade in response to apoptotic signals (28). Evaluation of the mitochondrial function during induction of apoptosis is recorded through decreased MMP, which when monitored by fluorescent probe has generally been adopted as an indicator of cell apoptosis (28,29). The Bcl-2 proteins are a family of proteins also involved in the response to apoptosis. A number of the pro-apoptotic and anti-apoptotic members, including Bax and Bcl-2, regulate apoptosis through the mitochondria either by their interaction, or their direct actions on the mitochondrial membrane.

Our results showed that SeMoV markedly induced the collapse of intracellular MMP and increased cytochrome C. The results were consistent with a report (30) that selenite

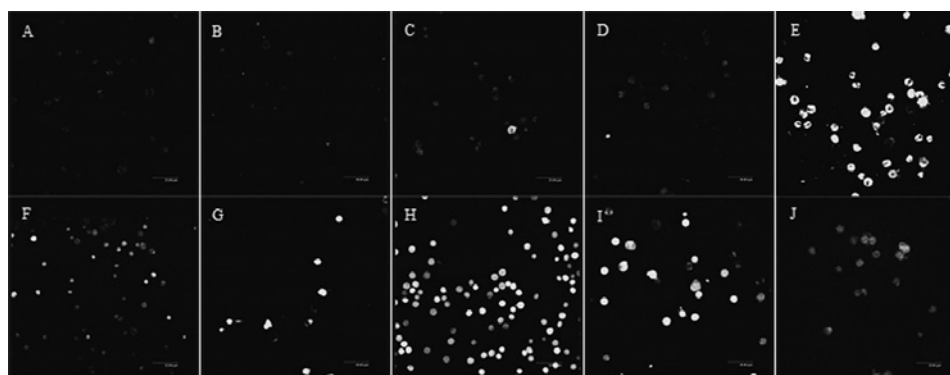


Figure 3. Fluorescent intensity of intracellular Ca^{2+} , Mg^{2+} , ROS, H^+ and MMP in K562 cells by confocal laser scanning microscopy following 24 h of treatment with SeMoV. (A–E) Control. (F–J) Treatment with SeMoV 2.5 mg/l. Fluorescent intensity of (A and F) intracellular Ca^{2+} , (B and G) Mg^{2+} , (C and H) ROS, (D and I) H^+ and (E and J) MMP, respectively. Scale bar, 20 μm .

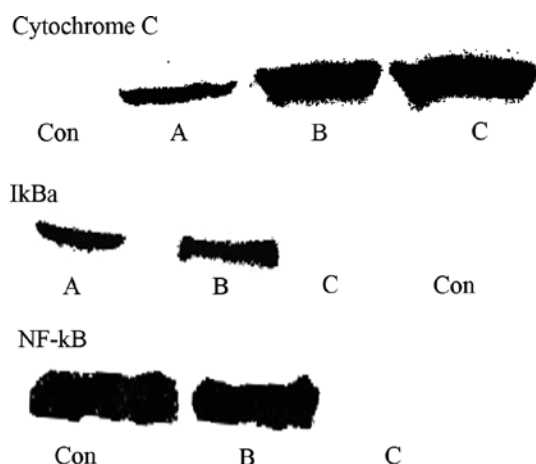


Figure 4. A Western blot assay was used to test the content of cytochrome C, IκBα and NF-κB in K562 cells after treatment with SeMoV at a concentration of (A) 1.25 (B) 5 and (C) 20 mg/l.

induces mitochondrial permeability transition and provokes the release of cytochrome C. The experiments also showed that the expression of Bcl-2 was significantly inhibited by 20 mg/l SeMoV, and that Bax expression increased. These results imply that the mechanism of SeMoV may relate to apoptosis induced by decreased MMP and the release of cytochrome C.

An excellent approach to apoptosis research has focused on changes in intracellular ion concentrations. It is presumed that perturbations of intracellular ion homeostasis could be the other conspicuous manifestation of apoptosis. The multitude of proteins activated in the apoptotic cascade invariably depends on the existence of certain intracellular ions. Munaron *et al* reported (31) that cell proliferation and differentiation is linked to the stimulation of the intracellular Ca^{2+} signal, and perturbations of intracellular Ca^{2+} appear to be a common mechanism of apoptosis. Particular emphasis has been placed on the influence of Ca^{2+} and Mg^{2+} ions (32). Ca^{2+} is one of the most significant intracellular messengers in modulating cell growth and differentiation, and plays an essential role in the induction of apoptosis. However, the role of Ca^{2+} as an intracellular messenger is incomplete without the coexistence of internal Mg^{2+} ions (33). Consistent with the above implication, the experiment showed that SeMoV markedly increased intracellular Ca^{2+} and Mg^{2+} concentrations. The present study suggests that Mg^{2+} may be adjunct to Ca^{2+} ions responsible for apoptosis induction, and the results were consistent with other research (34,35).

Changes in intracellular ion homeostasis, such as Ca^{2+} and Mg^{2+} accumulation, may induce mitochondrial apoptosis and lower its membrane potential. Ca^{2+} and Mg^{2+} play a crucial role in governing the morphological and biochemical changes attributed to apoptotic cell death (33). Therefore, the perturbations of intracellular ion homeostasis, pH value and MMP may be a conspicuous manifestation of apoptosis.

Another crucial factor, ROS, has been implicated as a main mediator of apoptosis in a number of different cellular systems (36). ROS may induce cell death by themselves or act as intracellular messengers during the cell death induced by various other types of stimuli (37). An excess of selenium was found to create an over-oxidized environment in cells and cause

cell dysfunction and apoptosis (36,37). Our experiment showed that intracellular ROS was significantly increased by treatment with SeMoV, and suggests that apoptosis induced by SeMoV is closely correlated to the increase in intracellular ROS level through the affects of the intracellular redox status.

In general, these results are similar to another selenium heteropoly compound, $\text{Na}_5\text{SeV}_5\text{O}_{18}\cdot 3\text{H}_2\text{O}$, reported previously (38) in the same experimental system. Although there are different elements between selenium heteropoly $(\text{NH}_4)_4\text{H}_4[\text{Se}_2\text{Mo}_2\text{V}_4\text{O}_{24}]\cdot 7\text{H}_2\text{O}$ and $\text{Na}_5\text{SeV}_5\text{O}_{18}\cdot 3\text{H}_2\text{O}$, both of them contain the element selenium, as well as the same anti-tumor activity and mechanism. Thus, the element selenium may be a functional component of the compound.

In order to study further the apoptotic mechanism of SeMoV, we assessed the intracellular content of NF-κB and IκB. NF-κB is a nuclear transcription factor that regulates expression of a large number of genes that are critical for the regulation of apoptosis, viral replication, tumorigenesis, inflammation and various autoimmune diseases (39). The activation of NF-κB is thought to be part of a stress response as it is activated by a variety of stimuli that include growth factors, cytokines, agents and stress. Disturbance of the activation of NF-κB is related to a number of diseases, including chronic inflammatory arthritis and cancer (39), so investigators pay attention to the regulation of the activation of NF-κB. In its inactive form, NF-κB is sequestered in the cytoplasm, bound by members of the IκB family of inhibitor proteins. The various stimuli (TNF, IL-1) that activate NF-κB cause phosphorylation of IκB, which is followed by its ubiquitination and subsequent degradation. Degradation of IκB results in the exposure of the nuclear localization signals (NLS) on NF-κB subunits and the subsequent translocation of the molecule to the nucleus and the initiation of transcription (39). Our experiments showed that SeMoV markedly increased the intracellular content of IκB and clearly decreased NF-κB in a concentration-dependent manner.

Acknowledgements

This study was supported by the Foundation and Advancing Program of Henan Province (no. 0823004505201), the Education department (2008A180013), and the Program of the Key Problems in Science and Technology of Henan Province (no. 082102310105).

References

1. Brozmanová J, Mániková D, Vlčková V and Chovanec M: Selenium: a double-edged sword for defense and offence in cancer. *Arch Toxicol* 84: 919-938, 2010.
2. Rojas E, Herrera LA, Poirier LA and Ostrosky-Wegman P: Are metals dietary carcinogens? *Mutat Res* 443: 157-181, 1999.
3. Huang YL, Sheu JY and Lin TH: Association between oxidative stress and changes of trace elements in patients with breast cancer. *Clin Biochem* 32: 131-136, 1999.
4. Burney PG, Comstock GW and Morris JS: Pancreatic cancer. *Clin Nutr* 49: 895-900, 1997.
5. Glatte E, Thomassen Y, Thoresen SO, Haldorsen T, Lund-Larsen PG, Theodorsen L, and Aaseth J: Prediagnostic serum selenium in a case-control study of thyroid cancer. *Int J Epidemiol* 18: 45-49, 1989.
6. Jaskiewicz K, Marasas WF, Rossouw JE, Van Niekerk FE and Heine Tech EW: Selenium and other mineral elements in populations at risk for esophageal cancer. *Cancer* 62: 2635-2639, 1988.

7. Westin T, Ahlbom E, Johansson E, Sandström B, Karlberg I and Edström S: Circulating levels of selenium and zinc in relation to nutritional status in patients with head and neck cancer. *Arch Otolaryngology Head Neck Surg* 115: 1079-1082, 1989.
8. Nguyen N, Sharma A, Nguyen N, *et al*: Melanoma chemoprevention in skin reconstructs and mouse xenografts using isoselenocyanate-4. *Cancer Prev Res (Phila)* 4: 248-258, 2011.
9. Sinha R and El-Bayoumy K: Apoptosis is a critical cellular event in cancer chemoprevention and chemotherapy by selenium compounds. *Curr Cancer Drug Targets* 4: 13-28, 2004.
10. Liu J, Mei WJ, Xu AW, Tan CP, Shi S and Ji LN: Synthesis, characterization and antiviral activity against influenza virus of a series of novel manganese-substituted rare earth borotungstates heteropolyoxometalates. *Antiviral Res* 62: 65-71, 2004.
11. Liu YN, Shi S, Mei WJ, *et al*: In vitro and in vivo investigations on the antiviral activity of a series of mixed-valence rare earth borotungstate heteropoly blues. *Eur J Med Chem* 43: 1963-1970, 2008.
12. Inouye Y, Tokutake Y, Yoshida T, *et al*: In vitro antiviral activity of polyoxomolybdates. Mechanism of inhibitory effect of PM-104 (NH₄)₁₂H₂(Eu₄(MoO₄)(H₂O)₁₆(Mo₇O₂₄)₄)-13H₂O on human immunodeficiency virus type 1. *Antiviral Res* 20: 317-331, 1993.
13. Wang X, Li J, He J and Liu J: Synthesis, properties and biological activity of organotitanium substituted heteropolytungstates. *Met Based Drugs* 8:179-182, 2001.
14. Sivaprasad G, Perumal PT, Prabavathy VR and Mathivanan N: Synthesis and anti-microbial activity of pyrazolylbisindoles-promising anti-fungal compounds. *Bioorg Med Chem Lett* 16: 6302-6305, 2006.
15. Borkin D, Morzhina E, Datta S, Rudnitskaya A, Sood A, Török M and Török B: Heteropoly acid-catalyzed microwave-assisted three-component aza-Diels-Alder cyclizations: diastereoselective synthesis of potential drug candidates for Alzheimer's disease. *Org Biomol Chem* 9: 1394-1401, 2011.
16. Zhang YP, Wang W and Wu JG: Synthesis and Characterization of Two Unprecedented Heteropolymetalates [Se₂Mo₂V₄O₂₄]⁸⁻ and [Se₂Mo₃V₃O₂₄]⁷⁻. *Chem J Res and appl (in Chinese)* 4: 403-405, 2006.
17. Ip C, Dong Y and Ganther HE: New concepts in selenium chemoprevention. *Cancer Metastasis Rev* 21: 281-289, 2002.
18. Gasparian AV, Yao YJ, Lü J, Yemelyanov AY, Lyakh LA, Slaga TJ and Budunova IV: Selenium compounds inhibit I κ B Kinase (IKK) and Nuclear Factor- κ B (NF- κ B) in prostate cancer cells. *Mol Cancer Ther* 1: 1079-1087, 2002.
19. Sinha R, Bansal MP, Ganther H and Medina D: Significance of selenium-labeled proteins for selenium's chemopreventive functions. *Carcinogenesis* 14: 1895-1900, 1993.
20. Fulda S: Tumor resistance to apoptosis. *Int J Cancer* 124: 511-515, 2009.
21. Lowe SW and Lin AW: Apoptosis in cancer. *Carcinogenesis* 21: 485-495, 2000.
22. Wang XW: Role of p53 and apoptosis in carcinogenesis. *Anticancer Res* 19: 4759-4771, 1999.
23. Kornblau SM: The role of apoptosis in the pathogenesis, prognosis, and therapy of hematologic malignancies. *Leukemia* 12: S41-46, 1998.
24. McConkey DJ and Orrenius S: The role of calcium in the regulation of apoptosis. *Biochem Biophys Res Commun* 239:357-366, 1997.
25. Mosmann T: Rapid colorimetric assay for cellular growth and survival: application to proliferation and cytotoxicity assays. *J Immunol Methods* 65: 55-63, 1983.
26. Kamesaki H: Mechanisms involved in chemotherapy-induced apoptosis and their implications in cancer chemotherapy. *Int J Hematol* 68: 29-43, 1998.
27. Simon SM, Roy D and Schindler M: Intracellular pH and the control of multidrug resistance. *Proc Natl Acad Sci USA* 91: 1128-1132, 1994.
28. Nicholls DG and Ward MW: Mitochondrial membrane potential and neuronal glutamate excitotoxicity: mortality and millivolts. *Trends Neurosci* 23: 166-174, 2000.
29. Bolduc JS, Denizeau F and Jumarie C: Cadmium-induced mitochondrial membrane-potential dissipation does not necessarily require cytosolic oxidative stress: studies using rhodamine-123 fluorescence unquenching. *Toxicol Sci* 77: 299-306, 2004.
30. Shilo S, Aronis A, Komarnitsky R and Tirosh O: Selenite sensitizes mitochondrial permeability transition pore opening in vitro and in vivo: a possible mechanism for chemo-protection. *Biochem J* 370: 283-290, 2003.
31. Munaron L, Antoniotti S, Fiorio Pla A, Lovisolo D: Blocking Ca²⁺ entry: a way to control cell proliferation. *Curr Med Chem* 11: 1533-1543, 2004.
32. Fernanded RS and Cotter TG: Activation of a calcium magnesium independent endonuclease in human leukemic cell apoptosis. *Anticancer Res* 13: 1253-1259, 1993.
33. Cain K, Inayat-Hussain SH, Kokileva L and Cohen GM: DNA cleavage in rat liver nuclei activated by Mg²⁺ or Ca²⁺ + Mg²⁺ is inhibited by a variety of structurally unrelated inhibitors. *Biochem Cell Biol* 72: 631-638, 1994.
34. Wang HT, Yang XL, Zhang ZH, Lu JL, Xu HB: Reactive oxygen species from mitochondria mediate SW480 cells apoptosis induced by Na₂SeO₃. *Biol Trace Elem Res* 85: 241-254, 2002.
35. Zhong W and Oberley TD: Redox-mediated effects of selenium on apoptosis and cell cycle in the LNCaP human prostate cancer cell line. *Cancer Res* 61(19): 7071-8, 2001.
36. Jacobson MD: Reactive oxygen species and programmed cell death. *Trends Biochem Sci* 21: 83-86, 1996.
37. Jung U, Zheng X, Yoon SO and Chung AS: Se-Methylselenocysteine induces apoptosis mediated by reactive oxygen species in HL-60 cells. *Free Radic Biol Med* 31: 479-489, 2001.
38. Yang JY and Wang ZR: The antitumoreffects of Na₅SeV₅O₁₈·3H₂O in K562 Cell. *Arch Pharm Res* 29: 859-865, 2006.
39. Culver C, Sundqvist A, Mudie S, Melvin A, Xirodimas D and Rocha S: Mechanism of hypoxia-induced NF-kappaB. *Mol Cell Biol* 30:4901-4921, 2010.