# Effects of nutrients on matrix metalloproteinases in human T-lymphotropic virus type 1 positive and negative malignant T-lymphocytes

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**Abstract.** Experimental and clinical studies have revealed the effectiveness of a specific nutrient synergy (SNS) mixture composed of ascorbic acid (AA), lysine, proline, arginine, epigallocatechin gallate (EGCG) and other micronutrients in targeting crucial physiological mechanisms involved in cancer progression and metastasis. HTLV-1 causes adult T-cell leukemia (ATL). The spread and metastases of ATL as well as other tumors has been associated with matrix metalloproteinases, especially the gelatinases MMP-2 and MMP-9. The objective of this study was to investigate whether SNS, AA and EGCG affects the gelatinolytic activity of MMP-2 and its transcriptional and translational levels in HTLV-1-positive and -negative malignant T-cells. The results indicated that SNS and EGCG caused a dose-dependent decline in the activity, transcription and translation of MMP-2 after treatment with SNS and EGCG, while AA was only able to inhibit the activity at maximum doses tested and to some extent, the protein expression levels of MMP-2, without affecting their transcriptional levels. The highest activity was noted in the case of SNS which is likely to be due to a synergistic effect of the different constituents in the formulation. These results point towards the potential integration of SNS in the anti-invasive treatment of ATL and related diseases.

## Introduction

The human T-cell lymphotropic virus type I (HTLV1) is a retrovirus estimated to have infected 5-10 million people worldwide, resulting adult T-cell leukemia (ATL) in ≤5% of the cases (1,2). Aggressive ATL can be associated with the frequent involvement of the gastrointestinal tract as well as meningeal or cerebral infiltration by neoplastic lymphocytes. The extravasation of ATL cells from the blood stream to these secondary organs is mediated by the expression of matrix metalloproteinase (MMP) -2 and -9 that will, subsequently, degrade the subendothelial basement membrane, hence aiding metastasis (3). In fact, these extracellular proteases have been reported to promote the proliferation, angiogenesis and metastatic potential of tumor cells. As such, a number of promising strategies have been devised to repress the expression or enzymatic activity of MMPs; however, their implementation in clinical trials revealed meager performance (4). Therefore, it is imperative to test alternative approaches that can effectively target these metalloproteinases in cancer in general and ATL specifically.

Experimental and clinical studies have revealed the effectiveness of a specific nutrient synergy mixture composed of ascorbic acid (AA), lysine, proline, arginine, epigallocatechin-gallate (EGCG) and other micronutrient, also known as SNS, in targeting crucial physiological mechanisms involved in cancer progression and metastasis (5-7). This natural assortment of nutrients, has exhibited synergistic anticancer properties in a large number of cancer cell lines, in part, by inhibiting MMP-2 and MMP-9 secretion (8-13). With respect to ATL, we have previously documented that SNS induces an antiproliferative and pro-apoptotic effect in HTLV1 infected malignant T-cells (14,15) and inhibits the transcriptional expression and activity

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of MMP-9 in these cells (Harakeh *at al*, unpublished data). However, to our knowledge, there has not been any study on the effect of SNS on MMP-2 expression and activity in ATL.

AA, a major constituent of SNS, has been integrated into the formulation based primarily on its own established cytotoxic and anti-metastatic actions against a number of cancer cell lines (16), including HTLV1 infected malignant T-cells (17) and inhibited MMP-9 expression and activity (unpublished data). Indeed, high dose ascorbate has been indicated to impede cancer growth via the prevention of cancer cell invasion (18) which is supported by the fact that AA is required for collagen synthesis that increases the stability of the extracellular matrix (ECM) (19). In addition to its anticancer effects, AA has been reported to harbor an effective activity against both RNA and DNA viruses (20). EGCG, which is the one of the most abundant catechins that are responsible for the antioxidant properties of green tea, is another major constituent of SNS. Previous study has indicated that it possesses pro-apoptotic and anti-proliferative effects on ATL cancer cells (21), and also acts to inhibit the invasiveness of cells by negating the activity of MMP-9 (22).

In light of the above, and since metastasis is the chief cause of death of patients suffering from malignant tumors (23) and the existing standard treatment against aggressive ATL continues to be inadequate (24), the aim of this study was to investigate the respective differential effects of the nutrient mixture SNS and two of its main components AA and EGCG on the activity of MMP-2 as well as its expression at the transcriptional and translational levels in both HTLV-I-infected and non-infected malignant T-cells, so as to determine the potency of each of these nutrients on the invasive potential of ATL cells.

**Materials and methods**

*Cell lines*. Two HTLV-1-positive (HuT-102 and C91-PL) and -negative (CEM and Jurkat) ATL cell lines were used. The cells were maintained in RPMI-1640 media with 25 mM of HEPES supplemented with 10% fetal bovine serum with 100 $\mu$g/ml of streptomycin and 100 U/ml of penicillin in 37°C and 5% $CO_2$. Cells were split every two days at a cell:media ratio of 1:4.

*Compounds*
*SNS*. The specific nutrient synergic mixture was obtained from Dr. Rath Research Institute and was dissolved in RPMI-1640 media in stock solutions of 33.3 mg/ml. The solution of 1 mg/ml of SNY contains 900 $\mu$M of ascorbate, 1.1 mM of lysine, 1.1 mM of proline, 500 $\mu$M of arginine, 250 $\mu$M of N-acetylcysteine, 150 $\mu$M of EGCG, 85 $\mu$M of selenium, 7 $\mu$M of copper and 4 $\mu$M of manganese and 4 $\mu$M calcium.

*EGCG*. EGCG was obtained from Sigma (St. Louis, MO, USA) in powder form. EGCG (50 mg) was dissolved in 5 ml of RPMI-1640 medium and pH of solution was maintained at 7.0.

*Ascorbic acid*. Ascorbic acid was obtained from Sigma, in powder form and was dissolved in RPMI-1640 medium as to prepare a 10 mg/ml stock solution. The pH was adjusted to 7.0.

All stock solutions were filter sterilized using a 0.22-$\mu$m filter, aliquoted into Eppendorf tubes and stored at -20°C until the day of the experiment. For the experiments, aliquots were thawed on the day of the experiment and used for one experiment only.

*Zymography for MMP-2 activity*. Cells were plated at density of $1 \times 10^5$ cells/ml of RPMI-1640 media with 10% FBS in 25 cm² flasks. They were treated with various concentrations of the test compound for three days and then starved and treated with various amounts of the test compound for 24 h. The cells were then centrifuged and the supernatant collected and concentrated 10-fold. Appropriate amounts of the supernatant were loaded on 10% acrylamide gels with 10% gelatin and run at 90 V and zymography was conducted as described previously (22).

*ELISA for MMP-2 secretion*. MMP-2 released from cells were determined by ELISA using MMP-2 detection kits (Roche, Mannheim, Germany). Supernatant from cells grown under different conditions was diluted with appropriate amounts of assay buffer supplied with the kit and experiments were performed according to the manufacturer's instructions.

*Western blotting for detection of the MMP-2 translational level*. Proteins were extracted from cells treated with various concentrations of the test compound and kept at -70°C. The proteins were quantified and then appropriate amounts of proteins were run on 10% acrylamide gel at 90 V and then blotted onto a polyvinyl difluoride (PVDF) membrane electrically at 30 V overnight. The membrane was probed with primary antibodies for MMP-2 (Santa Cruz Biotechnology). A secondary antibody linked to horseradish peroxidase specific to the primary was used and then the reaction was initiated using a chemiluminescence system. Bands were visualized on an X-ray film developed using Xomat. Equal loading was ensured using an antibody specific for GAPDH (Santa Cruz Biotechnology).

*RT-PCR for MMP-2 transcriptional level detection*. After treatment with different test compounds, cells were collected and stored at -70°C. Total RNA was extracted from the cells using NucleoSpin RNA II kit (Macherey, Nagel). Then, 2 $\mu$g of mRNA were reverse transcribed into first strand cDNA using RT-PCR kit; Reddy Mix Version (Abgene, Promega). PCR was conducted in 50 $\mu$l volume using oligonucleotide primers for MMP-2 (S: 5'-GTGCTGAAGGACACACTAAAGAAGA-3'; AS: 5'-TTGCCATCCTTCTCAAAGTTGTAGG-3') and ribosomal protein (S: 5'-GTTCACCAAGGAGGACCTCA-3'; AS: 5'-CAC-ATTAGGCAGAGGTGTCT-3') as described previously (22).

**Results**

*Effects of the test compounds on MMP-2 activity*. In order to check the effect of EGCG, AA and SNS treatment on cellular invasion potential, zymography was conducted by measuring the gelatinolytic activity of MMP-2. Starting with AA, it had an inhibitory effect on this activity only at the maximum concentrations tested, 150 $\mu$M for the Hut-102 and CEM cell
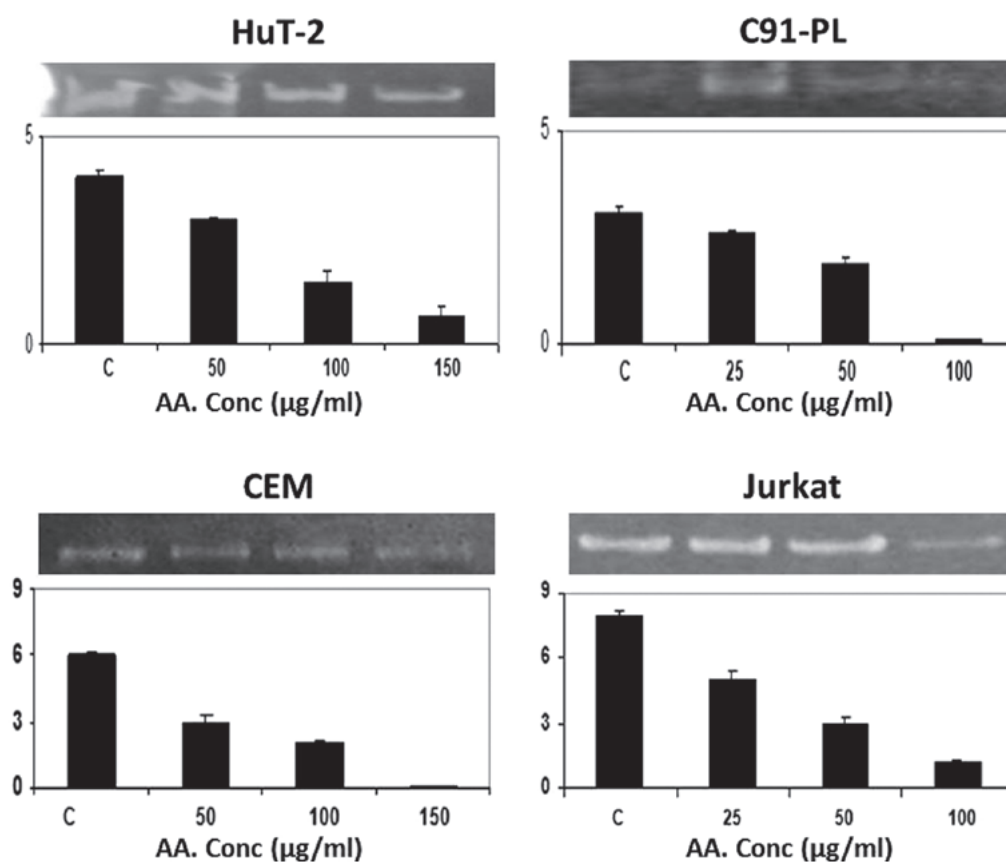
Figure 1. Effect of AA on MMP-2 activity and secretion. Activity was detected by zymography (gels) and secretion by ELISA (histograms) using HTLV-1-positive (HuT-102 and C91-PL) and -negative cells (CEM, Jurkat).
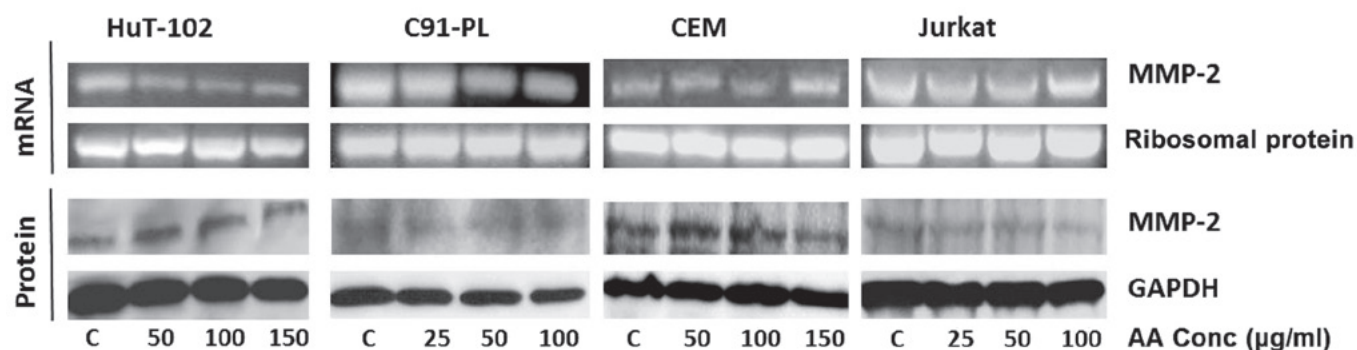


Figure 2. Effect of AA on MMP-2 transcriptional and translational levels. Transcription of MMP-2 was studied by measuring mRNA level by RT-PCR (upper gels) and translational level by western blotting (lower gels) on HTLV-1-positive cells (HuT-102 and C91-PL) and -negative cells (CEM, Jurkat). Ribosomal protein (for RT-PCR) and GAPDH (for western blotting) were used to ensure equal loading.

lines and 100 $\mu$M for the C91-PL and Jurkat cells (Fig. 1). On the other hand, EGCG induced a dose-dependent reduction in the activity of MMP-2 in all cell lines, which culminated in its total inhibition at 225 $\mu$M for Hut-102; while total inhibition occurred at maximum concentrations for the C91-PL (75 $\mu$M), CEM (100 $\mu$M) and Jurkat (250 $\mu$M) cell lines (Fig. 3). Finally, with respect to the effect of SNS, it induced total inhibition of MMP-2 activity in the CEM cells at 300 $\mu$M, while promoting a dose-dependent decrease in this activity in the remaining three cell lines which culminated in total inhibition only in the

Hut-102 cells at the maximum concentration used (400 $\mu$M) (Fig. 5).

*Effects of the test compounds on MMP-2 secretion.* To further confirm the effect of the test compounds on MMP-2 secretion quantitatively, ELISA was performed on the supernatant of cells grown on serum-free media. As illustrated, the inhibitory effects of SNS, EGCG and AA on the secretion of MMP-2 seem to be, in general, more pronounced in the non-infected malignant T-cells (CEM and Jurkat) than the infected
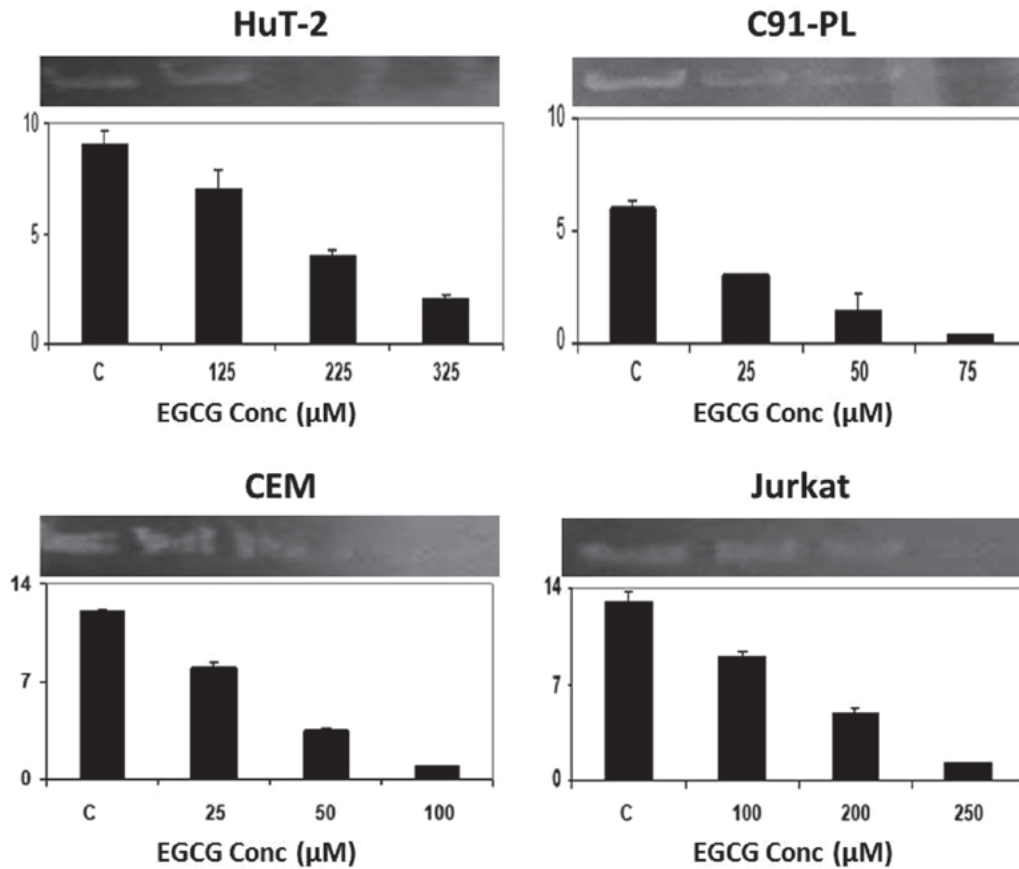
Figure 3. Effect of EGCG on MMP-2 activity and secretion. Activity was detected by zymography (gels) and secretion by ELISA (histograms) using HTLV-1-positive (HuT-102 and C91-PL) and -negative cells (CEM, Jurkat).
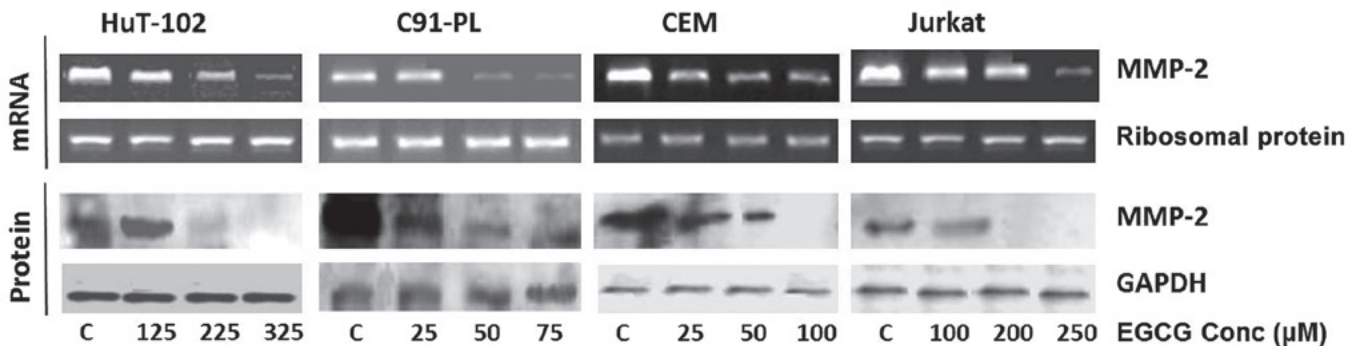


Figure 4. Effect of EGCG on MMP-2 transcriptional and translational levels. Transcription of MMP-2 was studied by measuring mRNA level by RT-PCR (upper gels) and translational level by western blotting (lower gels) on HTLV-1-positive cells (HuT-102 and C91-PL) and -negative cells (CEM, Jurkat). Ribosomal protein (for RT-PCR) and GAPDH (for western blotting) were used to ensure equal loading.

malignant T-cells (HuT-102 and C91-PL) (Figs. 1, 3 and 5, histograms). The highest fold decrease induced by AA was in the CEM cells (Fig. 1) while that for EGCG (Fig. 3) and SNS (Fig. 5) was in the Jurkat cells. Nonetheless, both HuT-102 and C91-PL cells exhibited a ~4-fold decrease in the level of secreted MMP-2 after a 96-h treatment with EGCG (Fig. 3) and SNS (Fig. 5), respectively. Moreover, AA was the most potent compound in the latter cell line (Fig. 1).

*Effect of test compounds on the transcriptional level of MMP-2.* For evaluating the effect of each of EGCG, AA, and SNS on the transcriptional level of MMP-2, RT-PCR was conducted on the mRNA isolated from treated cells (Figs. 2, 4 and 6). As can be seen, AA had no effect on MMP-2 mRNA levels in any of the tested cell lines (Fig. 2), while EGCG reduced the mRNA levels of MMP-2 in all four cell lines in a dose-dependent manner culminating in almost total inhibition at maximum concentrations in the HTLV1 infected cells (325 $\mu$M for the Hut-102 cells and 75 $\mu$M for the C91-PL cells) (Fig. 4). As for SNS, it caused a reduction in the activity at the lowest concentration used (200 $\mu$M) in the CEM and Hut-102 cell lines that was not altered by the increase in tested
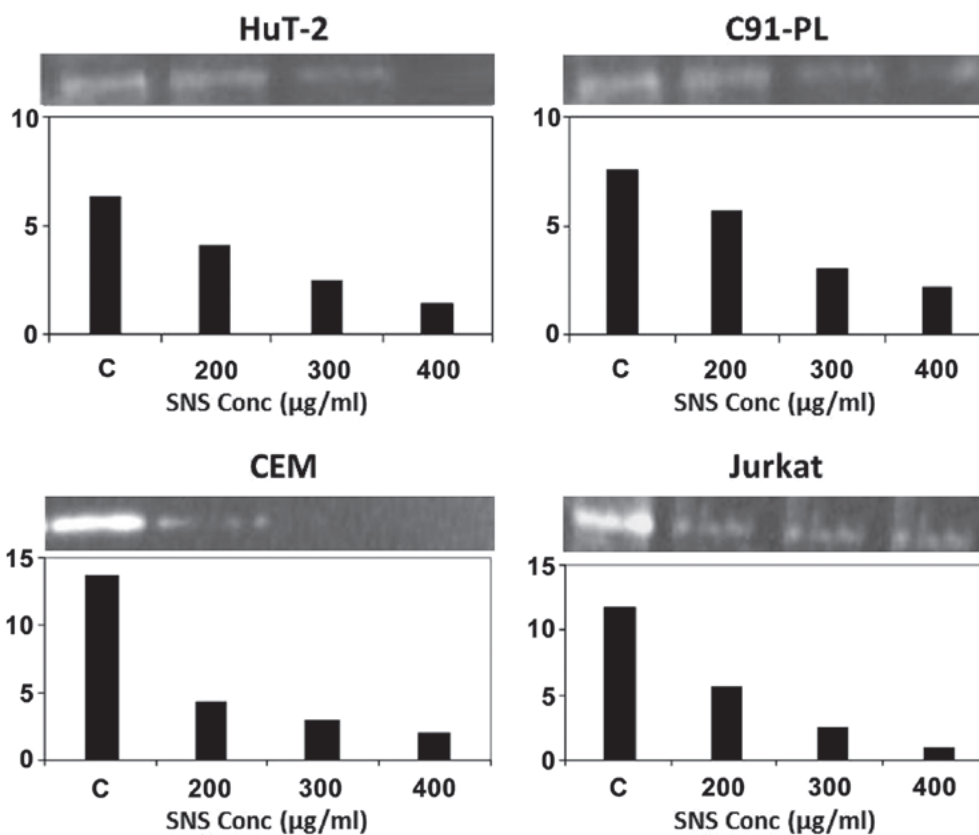
Figure 5. Effect of SNS on MMP-2 activity and secretion. Activity was detected by zymography (gels) and secretion by ELISA (histograms) using HTLV-1-positive (HuT-102 and C91-PL) and -negative cells (CEM, Jurkat).
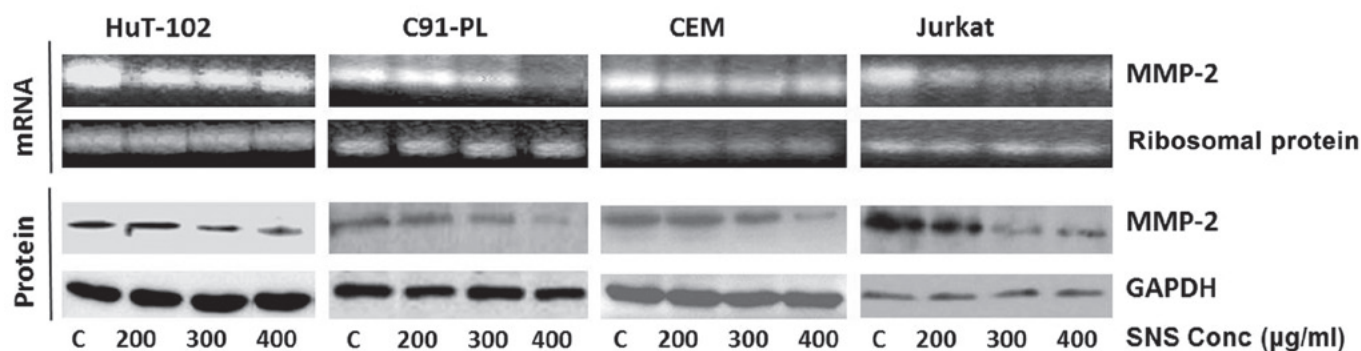


Figure 6. Effect of SNS on MMP-2 transcriptional and translational levels. Transcription of MMP-2 was studied by measuring mRNA level by RT-PCR (upper gels) and translational level by western blotting (lower gels) on HTLV-1-positive cells (HuT-102 and C91-PL) and -negative cells (CEM, Jurkat). Ribosomal protein (for RT-PCR) and GAPDH (for western blotting) were used to ensure equal loading.

concentration, while inducing a dose-dependent decrease that ended with almost total inhibition in MMP-2 mRNA levels in the C91-PL and Jurkat cells at the maximum concentration (400 $\mu$M) (Fig. 6). Equal loading was ensured using ribosomal protein.

*Effect of test compounds on translational levels of MMP-2 and MMP-9.* In order to investigate the effect of the test compounds. The translational levels of MMP-2 were measured by western blotting (Figs. 2, 4 and 6). AA did not show any significant effect on MMP-2 protein level of the

HTLV1-positive cells (HuT-102 and C91-PL), however, it acted at maximum concentrations to reduce MMP-2 levels in the HTLV1-negative cells (150 $\mu$M for CEM and 100 $\mu$M for Jurkat) (Fig. 2). On the other hand, the MMP-2 protein levels were totally inhibited by EGCG starting from 225 and 200 $\mu$M in the Hut-102 and Jurkat cells respectively, while decreasing dose-dependently inhibition in the other two cell lines that concluded with total loss of MMP-2 protein at maximum concentrations (75 $\mu$M for the C91-PL and 250 $\mu$M for the CEM) (Fig. 4). Finally, SNS reduced the protein levels of MMP-2 in all four cell lines in a dose-dependent manner

culminating in almost total inhibition at maximum concentration (400 $\mu$M) in the C91-PL and CEM cell lines (Fig. 6).

## Discussion

The majority of cancer-related deaths come as a result of the development of secondary tumors at distant sites which occurs upon the dissemination of the metastatic tumor cells (25). This process relies on the crossing of the endothelial basement membrane which is promoted by the overexpression of MMPs, especially MMP-2 and MMP-9 (4). In patients suffering from ATL cell infiltration, a significant increase in plasma MMP-9 was observed (26). Moreover, MMP-2 expression has been shown to be correlated with multi-organ extramedullary infiltration in adult acute lymphoblastic leukemia (ALL) (27). These MMPs have been dubbed as potential prognostic and diagnostic biomarkers in various cancer types and stages and have therefore been targeted by a wide variety of inhibitors, only to be met with failure in clinical trials (4). We have previously reported that each of AA, EGCG and SNS induce apoptosis and cell cycle arrest *in vitro* in both HTLV-1 infected and non-infected malignant T-lymphocyte cell lines (14,15,17,21) and dose-dependently inhibit MMP-9 expression and activity in HTLV-1-positive cells (22) (Harakeh *et al*, unpublished data). In the current study, we further investigated the potential of these natural compounds to inhibit MMP-2 activity as well as its mRNA and protein expression levels in four malignant T-lymphocytic cell lines, of which two were infected with HTLV-1.

According to our results, it seems that while each of AA, EGCG and SNS significantly and dose-dependently inhibited the level of secreted MMP-2, their inhibitory effects on MMP-2 activity, transcriptional and translational levels as they pertain to the different malignant T-cell lines used, were quite different.

AA is unique among other vitamins in that it is implicated in ECM formation and thus it increases ECM strength and can block cancer spread (28). In addition to its effects on HIV replication (29-33), and its anticancer effects (17), AA has shown inhibitory effects on matrix metalloproteinases (34,35). In our study, ascorbic acid was only effective against the MMP-2 gelatinolytic activity at the highest dose applied in each of the four malignant cell lines and this effect was independent of transcription and, at least in the case of the HTLV-1-negative cell lines, might be related to the AA inhibitory effect on translation. This is in accordance with previous research which showed that a derivative of AA, phospho-ascorbyl palmitate, had an antimetastatic effect on fibrosarcoma and melanoma cell lines by inhibiting the production and enzymatic activity of matrix metalloproteinases (MMP-2 and MMP-9) (34). It was also shown by Nagao *et al* that it takes repeated supplementation of L-ascorbic acid to inhibit tumor invasion by inhibiting the production of MMPs and cell motility (35), which would explain the high dose of AA required to induce an effect in our tested cell lines. While the mechanism behind MMP-2 expression is mostly unknown (36), the functional activity of MMPs is known to be detained by tissue inhibitors of metalloproteinases (TIMPs) and to be impacted by reactive oxygen species (ROS), where excess production of ROS, in association with the myeloperoxidase

enzyme, would eventually inactivate MMPs (37). Ascorbate has been shown to promote $H_2O_2$-mediated cell death (38,39) and a combination therapy of AA and vitamin K significantly decreased both the activity and protein expression of MMP-2 and MMP-9 while increasing the protein expression of TIMP-1 and TIMP-2 (40). As such, the high dose of AA possibly decreased the enzymatic activity of MMP-2 through the production of large amounts of ROS or via an inductive effect on TIMPs.

EGCG seemed to strongly inhibit the MMP-2 activity as well as its mRNA and protein expression levels that culminated with their total inhibition at various concentrations in the four cell lines. Moreover, it is quite apparent that EGCG was more potent, on every level, than AA which only resulted in significant inhibition at the highest tested concentrations. The inhibitory effect of EGCG on the activity of MMP-2 was previously documented to occur in multiple cancers (41-45). One study found green tea polyphenols to be more effective than other MMP inhibitors in counteracting the activity of MMP-2 and MMP-9 in glioblastomas and pituitary tumors (46). MMP-2 is involved in various physiological processes via its degrading action on both extracellular and non-extracellular matrix components which endows it with a potential to cause tissue damage. The MMP-2 activity is tightly regulated at multiple levels including transcription, compartmentalization, pro-enzyme activation, and inhibition of the active enzyme by extracellular inhibitors (47). Unlike most MMPs, proMMP-2 is activated at the cell surface via a distinctive multistep mechanism that involves MT-MMPs, which act as physiological activators of MMP-2; however like other MMPs, its activity is tightly modulated by TIMPs (48). EGCG was shown to obstruct the activity of MMP-2 and its activation from the proMMP-2 zymogen form in various human brain tumors (46). The inhibitory effect of this green tea extract on the activity of MMP-2 can be via its direct binding to this protease or through its indirect effect on MT1-MMP and TIMP (49,50). The production of MMP-2 in cancer cells has been shown to be regulated by both p38, JNK and PI3K (51). Treatment with EGCG decreased MMP-2 mRNA expression through the abrogation of the signaling in the highly invasive CL1-5 lung cancer cells (52), DU145 human prostate carcinoma cells (53), pancreatic carcinoma (54) and human bladder cancer cells (55).

Finally, with respect to SNS, it showed a variable profile since it dose-dependently inhibited MMP-2 gelatinolytic activity and protein expression levels in all four cell lines, its inhibitory effect on the mRNA in the Hut-102 and CEM cell lines was slight and unaltered by increasing the dose of SNS while being dose-dependent in the C91-PL and Jurkat cells. Therefore, the effect of SNS was independent of infectivity with HTLV-1 and was solely dependent on the cell line in question. Moreover, SNS was more effective than either AA or EGCG on the inhibition of MMP-2. In agreement with our results, SNS has been reported to inhibit the expression of MMP-2 and MMP-9 in a number of cancer cell lines (8-13). The inhibition of MMP transcription, translation and activity by SNS may be due to the synergistic effect of EGCG and AA as well as some of its other constituents [magnesium, copper, N-acetylcysteine (NAC) and selenium]. In fact, the supplementation of cultured rat cardiac fibroblasts with a range of

extracellular magnesium concentrations resulted in a dose-dependent decrease in MMP-2 production (56) while copper deficiency in acute lung injury was associated with increased pulmonary MMP-2 and MMP-9 activity (57). Moreover, the treatment of intestinal myofibroblasts isolated from patients suffering from Crohn's disease with NAC decreased MMP-2 secretion and restored its activity to physiological value (58). NAC was also shown to decrease the expression and activity of MMP-2 in hepatic fibrosis of bile duct ligated rats while normalizing the expression of TIMP-2 (59). Similarly, mono-methyl selenium inhibited MMP-2 expression in vascular endothelial cells (60) and selenium downregulated the gene expression of MMP-2 in human malignant brain tumor cells *in vitro* (61). Note that the same specific nutrient synergy exhibited anti-angiogenic, anti-metastatic, and anti-invasion roles both *in vitro* and *in vivo* and was proven to be non-toxic even at very high doses (7).

The present results show for the first time the variability in the effects of AA, EGCG and SNS on MMP-2 activity as well as its mRNA and protein expression levels in HTLV-1-infected and non-infected malignant T-cells. It seems that while AA was able to modulate the activity to a certain extent, on the protein expression levels of MMP-2, it was outdone by both EGCG and SNS which quite potently inhibited MMP-2 at every level. Therefore, these nutrients should be considered as a supplementary, economical and safe approach in the treatment of ATL.

## References

1. Cook LB, Melamed A, Niederer H, Valganon M, Laydon D, Foroni L, Taylor GP, Matsuoka M and Bangham CR: The role of HTLV-1 clonality, proviral structure and genomic integration site in adult T cell leukemia/lymphoma. Blood 123: 3925-3931, 2014.
2. Araujo TH, Barreto FK, Luiz Carlos Júnior A and Miranda AC: Inferences about the global scenario of human T-cell lymphotropic virus type 1 infection using data mining of viral sequences. Mem Inst Oswaldo Cruz 0: 21-24, 2014.
3. Bazarbachi A, Abou Merhi R, Gessain A, Talhouk R, El-Khoury H, Nasr R, Gout O, Sulahian R, Homaidan F, de Thé H, Hermine O and El-Sabban ME: Human T-cell lymphotropic virus type I-infected cells extravasate through the endothelial barrier by a local angiogenesis-like mechanism. Cancer Res 64: 2039-2046, 2004.
4. Gialeli C, Theocharis AD and Karamanos NK: Roles of matrix metalloproteinases in cancer progression and their pharmacological targeting. FEBS J 278: 16-27, 2011.
5. Roomi MW, Kalinovsky T, Roomi NM, Cha J, Rath M and Niedzwiecki A: *In vitro* and *in vivo* effects of a nutrient mixture on breast cancer progression. Int J Oncol 44: 1933-1944, 2014.
6. Roomi MW, Kalinovsky T, Roomi NW, Niedzwiecki A and Rath M: Suppression of metastasis of intratesticular inoculation of B16FO melanoma cells by a novel nutrient mixture in male athymic nude mice. Exp Ther Med 4: 775-780, 2012.
7. Niedzwiecki A, Roomi MW, Kalinovsky T and Rath M: Micronutrient synergy - a new tool in effective control of metastasis and other key mechanisms of cancer. Cancer Metastasis Rev 29: 529-542, 2010.
8. Roomi MW, Kalinovsky T, Niedzwiecki A and Rath M: Modulation of uPA, MMPs and their inhibitors by a novel nutrient mixture in human glioblastoma cell lines. Int J Oncol 45: 887-894, 2014.
9. Roomi MW, Kalinovsky T, Rath M and Niedzwiecki A: Effect of a nutrient mixture on matrix metalloproteinase-9 dimers in various human cancer cell lines. Int J Oncol 44: 986-992, 2014.
10. Roomi MW, Kalinovsky T, Niedzwiecki A and Rath M: Modulation of u-PA, MMPs and their inhibitors by a novel nutrient mixture in pediatric human sarcoma cell lines. Int J Oncol 43: 1027-1035, 2013.
11. Roomi MW, Kalinovsky T, Niedzwiecki A and Rath M: Modulation of u-PA, MMPs and their inhibitors by a novel nutrient mixture in adult human sarcoma cell lines. Int J Oncol 43: 39-49, 2013.
12. Roomi MW, Kalinovsky T, Niedzwiecki A and Rath M: Modulation of u-PA, MMPs and their inhibitors by a novel nutrient mixture in human lung cancer and mesothelioma cell lines. Int J Oncol 42: 1883-1889, 2013.
13. Roomi MW, Monterrey JC, Kalinovsky T, Rath M and Niedzwiecki A: Inhibition of invasion and MMPs by a nutrient mixture in human cancer cell lines: a correlation study. Exp Oncol 32: 243-248. 2010.
14. Harakeh S, Abdel-Massih RM, Gil PR, Sperling RA, Meinhardt A, Niedwiecki A, Rath M, Parak WJ and Baydoun E: The effect of PEG-coated gold nanoparticles on the anti-proliferative potential of Specific Nutrient Synergy. Nanotoxicology 4: 177-185, 2010.
15. Harakeh S, Diab-Assaf M, Niedzwiecki A, Khalife J, Abu-El-Ardat K and Rath M: Apoptosis induction by Epican Forte in HTLV-1 positive and negative malignant T-cells. Leuk Res 30: 869-881, 2006.
16. Cha J, Roomi MW, Ivanov V, Kalinovsky T, Niedzwiecki A and Rath M: Ascorbate supplementation inhibits growth and metastasis of B16FO melanoma and 4T1 breast cancer cells in vitamin C-deficient mice. Int J Oncol 42: 55-64, 2013.
17. Harakeh S, Diab-Assaf M, Khalife JC, Abu-El-Ardat KA, Baydoun E, Niedzwiecki A, El-Sabban ME and Rath M: Ascorbic acid induces apoptosis in adult T-cell leukemia. Anticancer Res 27: 289-298, 2007.
18. Cameron E, Pauling L and Leibovitz B: Ascorbic acid and cancer: a review. Cancer Res 39: 663-681, 1979.
19. Li Y and Schellhorn HE: New developments and novel therapeutic perspectives for vitamin C. J Nutr 137: 2171-2184, 2007.
20. Jariwalla RJ and Harakeh S: Antiviral and immunomodulatory activities of ascorbic acid. Subcell Biochem 25: 213-231, 1996.
21. Harakeh S, Abu-El-Ardat K, Diab-Assaf M, Niedzwiecki A, El-Sabban M and Rath M: Epigallocatechin-3-gallate induces apoptosis and cell cycle arrest in HTLV-1-positive and -negative leukemia cells. Med Oncol 25: 30-39, 2008.
22. Harakeh S, Diab-Assaf M, Azar R, Hassan HM, Tayeb S, Abou-El-Ardat K, Damanhouri GA, Qadri I, Abuzenadah A, Chaudhary A, Kumosani T, Niedzwiecki A, Rath M, Yacoub H, Azhar E and Barbour E: Epigallocatechin-3-gallate inhibits tax-dependent activation of nuclear factor kappa B and of matrix metalloproteinase 9 in human T-cell lymphotropic virus-1 positive leukemia cells. Asian Pac J Cancer Prev 15: 1219-1225, 2014.
23. Wu KC, Yang ST, Hsia TC, Yang JS, Chiou SM, Lu CC, Wu RS and Chung JG: Suppression of cell invasion and migration by propofol are involved in down-regulating matrix metalloproteinase-2 and p38 MAPK signaling in A549 human lung adenocarcinoma epithelial cells. Anticancer Res 32: 4833-4842, 2012.
24. Uozumi K: Treatment of adult T-cell leukemia. J Clin Exp Hematop 50: 9-25, 2010.
25. Kessenbrock K, Plaks V and Werb Z: Matrix metalloproteinases: regulators of the tumor microenvironment. Cell 141: 52-67, 2010.
26. Nakachi S, Nakazato T, Ishikawa C, Kimura R, Mann DA, Senba M, Masuzaki H and Mori N: Human T-cell leukemia virus type 1 Tax transactivates the matrix metalloproteinase 7 gene via JunD/AP-1 signaling. Biochim Biophys Acta 1813: 731-741, 2010.
27. Devy J, Ouchani F, Oudot C, Helesbeux JJ, Vanquelef E, Salesse S, Rabenoelina F, Al-Khara S, Letinois I, Duval O, Martiny L and Charpentier E: The anti-invasive activity of synthetic alkaloid ethoxyfagaronine on L1210 leukemia cells is mediated by down-regulation of plasminogen activators and MT1-MMP expression and activity. Invest New Drugs 29: 730-741, 2011.
28. Rath M and Pauling L: Plasmin-induced proteolysis and the role of apoprotein(a), lysine and synthetic analogs. Orthomol Med 7: 17-23, 1992.
29. Harakeh S, Jariwalla RJ and Pauling L: Suppression of human immunodeficiency virus replication by ascorbate in chronically and acutely infected cells. Proc Natl Acad Sci USA 87: 7245-7249, 1990.
30. Harakeh S and Jariwalla RJ: Comparative study of the anti-HIV activities of ascorbate and thiol-containing reducing agents in chronically HIV-infected cells. Am J Clin Nutr 54: S1231-S1235, 1991.
31. Harakeh S, Niedzwiecki A and Jariwalla RJ: Mechanistic aspects of ascorbate inhibition of human immunodeficiency virus. Chem Biol Interact 91: 207-215, 1994.

32. Harakeh S and Jariwalla RJ: Ascorbate effect on cytokine stimulation of HIV production. Nutrition 11: 684-687, 1995.
33. Harakeh S and Jariwalla RJ: NF-kappa B-independent suppression of HIV expression by ascorbic acid. AIDS Res Hum Retroviruses 13: 235-239, 1997.
34. Liu JW, Nagao N, Kageyama K and Miwa N: Antimetastatic and anti-invasive ability of phospho-ascorbyl palmitate through intracellular ascorbate enrichment and the resultant antioxidant action. Oncol Res 11: 479-487, 1999.
35. Nagao N, Nakayama T, Etoh T, Saiki I and Miwa N: Tumor invasion is inhibited by phosphorylated ascorbate via enrichment of intracellular vitamin C and decreasing of oxidative stress. Cancer Res Clin Oncol 126: 511-518, 2000.
36. Lovaas JD, Zhu L, Chiao CY, Byles V, Faller DV and Dai Y: SIRT1 enhances matrix metalloproteinase-2 expression and tumor cell invasion in prostate cancer cells. Prostate 73: 522-530, 2013.
37. Fu X, Kassim SY, Parks WC and Heinecke JW: Hypochlorous acid generated by myeloperoxidase modifies adjacent tryptophan and glycine residues in the catalytic domain of matrix metalloproteinase-7 (matrilysin): an oxidative mechanism for restraining proteolytic activity during inflammation. J Biol Chem 278: 28403-28409, 2003.
38. Du J, Martin SM, Levine M, Wagner BA, Buettner GR, Wang SH, Taghiyev AF, Du C, Knudson CM and Cullen JJ: Mechanisms of ascorbate-induced cytotoxicity in pancreatic cancer. Clin Cancer Res 16: 509-520, 2010.
39. Frömberg A, Gutsch D, Schulze D, Vollbracht C, Weiss G, Czubayko F and Aigner A: Ascorbate exerts antiproliferative effects through cell cycle inhibition and sensitizes tumor cells towards cytostatic drugs. Cancer Chemother Pharmacol 67: 1157-1166, 2011.
40. Taper HS, Jamison JM, Gilloteaux J, Summers JL and Calderon PB: Inhibition of the development of metastases by dietary vitamin C:K3 combination. Life Sci 75: 955-967, 2004.
41. Maeda-Yamamoto M, Suzuki N, Sawai Y, Miyase T, Sano M, Hashimoto-Ohta A and Isemura M: Association of suppression of extracellular signal-regulated kinase phosphorylation by epigallocatechin gallate with the reduction of matrix metalloproteinase activities in human fibrosarcoma HT1080 cells. J Agric Food Chem 51: 1858-1863, 2003.
42. Lu L, Liu HM and Tang WX: Effect of epigallocatechin-3-gallate on the invasiveness of hepatocarcinoma cells in vitro. Zhonghua Gan Zang Bing Za Zhi 15: 825-827, 2007.
43. Sen T, Moulik S, Dutta A, Choudhury PR, Banerji A, Das S, Roy M and Chatterjee A: Multifunctional effect of epigallocatechin-3-gallate (EGCG) in downregulation of gelatinase-A (MMP-2) in human breast cancer cell line MCF-7. Life Sci 84: 194-204, 2009.
44. Chen PN, Chu SC, Kuo WH, Chou MY, Lin JK and Hsieh YS: Epigallocatechin-3 gallate inhibits invasion, epithelial-mesenchymal transition, and tumor growth in oral cancer cells. J Agric Food Chem 59: 836-844, 2011.
45. Li H, Li Z, Xu YM, Wu Y, Yu KK, Zhang C, Ji YH, Ding G and Chen FX: Epigallocatechin-3-gallate induces apoptosis, inhibits proliferation and decreases invasion of glioma cell. Neurosci Bull 30: 67-73, 2014.
46. Demeule M, Brossard M, Pagé M, Gingras D and Béliveau R: Matrix metalloproteinase inhibition by green tea catechins. Biochim Biophys Acta 1478: 51-60, 2000.
47. Koo BH, Kim YH, Han JH and Kim DS: Dimerization of matrix metalloproteinase-2 (MMP-2): functional implication in MMP-2 activation. J Biol Chem 287: 22643-22653, 2012.
48. Mannello F and Medda V: Nuclear localization of matrix metalloproteinases. Prog Histochem Cytochem 47: 27-58, 2012.
49. Annabi B, Lachambre MP, Bousquet-Gagnon N, Pagé M, Gingras D and Béliveau R: Green tea polyphenol (-)-epigallocatechin 3-gallate inhibits MMP-2 secretion and MT1-MMP-driven migration in glioblastoma cells. Biochim Biophys Acta 1542: 209-220, 2002.
50. Farabegoli F, Papi A and Orlandi M: (-)-Epigallocatechin-3-gallate down-regulates EGFR, MMP-2, MMP-9 and EMMPRIN and inhibits the invasion of MCF-7 tamoxifen-resistant cells. Biosci Rep 31: 99-108, 2011.
51. Peng CC, Hsieh CL, Wang HE, Chung JY, Chen KC and Peng RY: Ferulic acid is nephrodamaging while gallic acid is renal protective in long term treatment of chronic kidney disease. Clin Nutr 31: 405-414, 2012.
52. Deng YT and Lin JK: EGCG inhibits the invasion of highly invasive CL1-5 lung cancer cells through suppressing MMP-2 expression via JNK signaling and induces G2/M arrest. J Agric Food Chem 59: 13318-13327, 2011.
53. Vayalil PK and Katiyar SK: Treatment of epigallocatechin-3-gallate inhibits matrix metalloproteinases-2 and -9 via inhibition of activation of mitogen-activated protein kinases, c-jun and NF-kappaB in human prostate carcinoma DU-145 cells. Prostate 59: 33-42, 2004.
54. Shankar S, Marsh L and Srivastava RK: EGCG inhibits growth of human pancreatic tumors orthotopically implanted in Balb C nude mice through modulation of FKHRL1/FOXO3a and neuropilin. Mol Cell Biochem 372: 83-94, 2013.
55. Qin J, Wang Y, Bai Y, Yang K, Mao Q, Lin Y, Kong D, Zheng X and Xie L: Epigallocatechin-3-gallate inhibits bladder cancer cell invasion via suppression of NF-κB-mediated matrix metalloproteinase-9 expression. Mol Med Rep 6: 1040-1044, 2012.
56. Yue H, Uzui H, Lee JD, Shimizu H and Ueda T: Effects of magnesium on matrix metalloproteinase-2 production in cultured rat cardiac fibroblasts. Basic Res Cardiol 99: 257-263, 2004.
57. Lentsch AB, Kato A, Saari JT and Schuschke DA: Augmented metalloproteinase activity and acute lung injury in copper-deficient rats. Am J Physiol Lung Cell Mol Physiol 281: L387-L393, 2001.
58. Romagnoli C, Marcucci T, Picariello L, Tonelli F, Vincenzini MT and Iantomasi T: Role of N-acetylcysteine and GSH redox system on total and active MMP-2 in intestinal myofibroblasts of Crohn's disease patients. Int J Colorectal Dis 28: 915-924, 2013.
59. Rezaei A, Ardestani SK, Forouzandeh M, Tavangar SM, Khorramizadeh MR, Payabvash S, Nezami BG, Jahanshiri Z, Tavakoli Z, Shariftabrizi A and Dehpour AR: The effects of N-acetylcysteine on the expression of matrix metalloproteinase-2 and tissue inhibitor of matrix metalloproteinase-2 in hepatic fibrosis in bile duct ligated rats. Hepatol Res 38: 1252-1263, 2008.
60. Jiang C, Ganther H and Lu J: Monomethyl selenium - specific inhibition of MMP-2 and VEGF expression: implications for angiogenic switch regulation. Mol Carcinog 29: 236-250, 2000.
61. Rooprai HK, Kyriazis I, Nuttall RK, Edwards DR, Zicha D, Aubyn D, Davies D, Gullan R and Pilkington GJ: Inhibition of invasion and induction of apoptosis by selenium in human malignant brain tumour cells *in vitro*. Int J Oncol 30: 1263-1271, 2007.