Diallyl sulfide induces cell cycle arrest and apoptosis in HeLa human cervical cancer cells through the p53, caspase- and mitochondria-dependent pathways

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Received December 29, 2010; Accepted February 21, 2011

DOI: 10.3892/ijo.2011.973

Abstract. Diallyl sulfide (DAS), one of the main active constituents of garlic, causes growth inhibition of cancer cells in vitro and promotes immune responses in vivo in experimental settings. However, its effects on the induction of cell cycle and apoptosis in human cervical cancer cells are still unclear. The aims of this study were to explore the anti-cancer effects of DAS in HeLa human cervical cancer cells and to investigate the underlying mechanisms in vitro. Cytotoxicity and apoptosis in HeLa human cervical cancer cells were examined by the morphological changes, viability assay, 4',6-Diamidino-2-phenylindole dihydrochloride (DAPI) staining, comet assay, Western blotting and confocal microscopy examination. The results showed that DAS treatment for 24-72 h resulted in a marked decrease in cell viability time- and dose-dependently. Flow cytometric analysis showed that a 48-h treatment of 75 µM DAS induced G0/G1 cell cycle arrest and sub-G1 phase (apoptosis) in HeLa cells. Typical apoptotic nucleus alterations were observed by fluorescence microscopy in HeLa cells after exposure to DAS using DAPI staining. Cells treated with different concentrations of DAS also showed changes typical of apoptosis such as morphological changes, DNA damage and fragmentation, dysfunction of mitochondria, cytochrome c release and increased expression of pro-caspase-3 and -9. DAS also promoted the release of AIF and Endo G from mitochondria in HeLa cells. In conclusion, DAS induced G0/G1 cell cycle arrest and apoptosis in HeLa cells through caspase- and mitochondria and p53 pathways providing further understanding of the molecular mechanisms of DAS action in cervical cancer. This study, therefore, revealed that DAS significantly inhibits the growth and induces apoptosis of human cervical cancer HeLa cells in vitro.

Introduction

Cervical cancer is one of major causes of death among women in most developed countries. In Taiwan, cervical cancer is the sixth leading cause of cancer mortality, about 6.0 persons per 100 thousand die annually from cervical cancer based on the reports from the Department of Health, Executive Yuan, ROC (Taiwan) in year 2008. Apoptosis is a programmed cell death accompanied by chromatin condensation, membrane blebbing, cell shrinkage, apoptotic body and DNA fragmentation (ladder) (1,2). It is known that several factors lead to the induction of apoptosis such as the initiation by oxidative stress, then activation of caspases that are involved in the induction of apoptosis (cell death) (3). Therefore, a good strategy for killing cancer cells is through the induction of apoptosis of cancer cells.

Substantial evidence has demonstrated that some components from natural plants can suppress tumor development and decrease the incidence and severity of cancer in human (4). Garlic (Allium sativum L.), is widely used as foodstuff and medicine throughout the recorded history (5). Based on epidemiologic, clinical, and laboratory studies we have indicated that Allium vegetables and/or their constituents contain biological activities that stimulate immune function
Diallyl sulfide (DAS), one of the component of garlic, has been reported to act as a potential chemopreventive function for many human cancer such as colon, lung, and skin (24). In our earlier studies, DAS inhibited the N-acetyltransferase activity in bacteria (25,26), human colon cancer cells (27) and bladder cancer cells (28), and inhibits murine WEHI-3 leukemia cells in BALB/c mice in vitro and in vivo (29). However, the mechanistic role of DAS-mediated apoptosis in human cervical cancer cells, especially the role of ER stress, caspases, and mitochondria in the induction of apoptosis remains limited. In this study, we present evidence that DAS generated ROS, induced cell cycle arrest and apoptosis in HeLa cells through caspase-3 and mitochondria-dependent pathways.

Materials and methods

Chemicals and reagents. RPMI-1640 medium, fetal calf serum (FCS), trypan-blue, penicillin G and streptomycin were obtained from Invitrogen Corp. (Carlsbad, CA). Dimethylsulfoxide (DMSO), ribonuclease (RNase), and propidium iodide (PI) were purchased from Sigma-Aldrich (St. Louis, MO). All antibodies were obtained from Santa Cruz Biotechnology (Santa Cruz, CA) or from BD Pharmingen (San Diego, CA). The secondary antibody of peroxidase-conjugated was purchased from Pierce (Rockford, IL). Western blotting detection kit was obtained from Amersham Life Science (Buckinghamshire, UK).

Cell culture. Human cervical cancer HeLa cells were obtained from the Food Industry Research and Development Institute (Hsinchu, Taiwan). Cells were maintained in RPMI-1640 medium supplemented with 10% fetal calf serum, 2 mM glutamine, and antibiotics (100 U/ml penicillin and 100 µg/ml streptomycin) at 37°C in a humidified atmosphere of 5% CO2.

Morphological changes examined by a phase-contrast microscopic study. HeLa cells (2x105 cells/well) were maintained in 12-well culture plates and treated with 75 µM of DAS for 0, 0.5, 1 or 2 h before being harvested, washed twice with PBS, and re-suspended in 500 µl of calcium probe Indo 1/AM or 500 µl of the mitochondrial membrane potential indicator 3, 3'-dihexyloxacarbocyanine iodide (DiOCl3), respectively. The samples were incubated at 37°C for 30 min to detect changes in ROS, Ca2+ levels and mitochondrial membrane potential by flow cytometry as previously described (32-34).

Cell viability, cell cycle and apoptosis by PI staining were examined by flow cytometric assay. After cells were treated with or without DAS for various time-periods, cells were harvested by centrifugation for determining the percentage of viability by staining with PI (5 µg/ml) and were analyzed by flow cytometry (Becton-Dickinson, San Jose, CA, USA) as previously described (30,31). For cell cycle distribution and apoptosis determinations, the adherent cells were washed with PBS, and 300 µl trypsin was added for 5 min at room temperature to detect the cells and harvested the cells by centrifugation. Cells were fixed gently in 70% ethanol at 4°C overnight and then re-suspended in PBS containing 40 µg/ml PI and 0.1 mg/ml RNase and 0.1% Triton X-100 in a dark room for 30 min at 37°C. Cells were analyzed with a flow cytometer (32,33). The results were analyzed by Mod Fit LT 3.0 software.

DAPI staining and Comet assay for DNA damage. For DNA condensation studies, exponentially growing HeLa cells were cultured at a density of 2x105 cells/well onto 12-well culture plates and treated with various concentrations of DAS for 24 h. The cells were then washed with PBS, permeabilized in 0.1% Triton X-100 for 10 min at room temperature, stained with 4‘,6-diamidino-2-phenylindole dihydrochloride (DAPI, 2 µg/ml, Sigma) for 15 min at 37°C, and observed and photographed by fluorescence microscopy. The alkaline comet assay was performed basically as described previously with minor modifications (31,32). Several slides were prepared for each treatment and control. Fifty randomly selected cells were blindly examined for each triplicate slide with the same scorer at magnification of x400. Then cells with comet tail were photographed and by using fluorescence microscopy as described previously (32,33). Comet tail length (TL), measured from the estimated centre of the cell, was evaluated for each cell as DNA damage parameter.

Flow cytometric assay for the production of Ca2+ and the level of mitochondrial membrane potential. To examine the Ca2+ and mitochondrial membrane potential in DAS induced apoptosis, HeLa cells were maintained in 12-well culture plates and treated with 75 µM of DAS for 0, 0.5, 1 or 2 h before being harvested, washed twice with PBS, and re-suspended in 500 µl of calcium probe Indo 1/AM or 500 µl of the mitochondrial membrane potential indicator 3,3'-dihexyloxacarbocyanine iodide (DiOCl3), respectively. The samples were incubated at 37°C for 30 min to detect changes in ROS, Ca2+ levels and mitochondrial membrane potential by flow cytometry as described previously (32-34).

Western blot analysis. HeLa cells (5x106) were treated with 75 µM DAS for 0, 6, 12, 24, 48 and 72 h. Cells were harvested and the total cellular proteins were extracted by incubating the cells in the lysis buffer [50 mM Tris-HCl (pH 7.5), 100 mM NaCl, 0.5% (v/v) Triton X-100, 1 mM EDTA, 2.5 mM sodium orthovanadate, 10 µl/ml protease inhibitor cocktail, 1 mM PMSF]. The total protein concentrations in the cell lysates from each treatment were determined by Bio-Rad assay according to the manufacturer's protocols. All samples were loaded with equal amounts of protein into the SDS-PAGE in 10% tricine gels. At the end of electrophoresis, the proteins in the gels were transferred to a nitrocellulose membrane which was blocked with 5% non-fat milk in TBST buffer for 1 h then incubated with primary antibodies (anti-β-actin, -CDK6, -CDK2, -cyclin D, -cyclin E, -p53, -Fas, -FasL, -caspase-8, -Bax, -cytochrome c, -Apaf-1, -Bid, -caspase-9, -caspase-3, -AIF and -Endo G) at 1:1000 dilution in 5% non-fat milk overnight at 4°C, then washed twice, followed by secondary antibodies (rabbit anti-IgG) conjugated with horseradish peroxidase at 1:1000 dilution for 1 h at room temperature. After extensive washing with TBST, protein bands were...
visualized by the enhanced chemiluminescence reagent (SuperSignal West Pico Chemiluminescent Substrate; Pierce, Rockford, IL, USA). The expression ratio of experimental and control was calculated according to the reference band of β-actin (32,34).

Confocal laser scanning microscopy. The preparations of samples for examining the translocation of Endo G were performed as described (31,35). HeLa cells (5x10⁴ cells/well) were maintained on 4-well chamber slides and were treated with 75 µM DAS for 24 h. All samples (cells from each treatment) were fixed in 4% formaldehyde in PBS for 15 min then were permeabilized with 0.3% Triton X-100 in PBS for 1 h with blocking of non-specific binding sites using 2% BSA as described previously (31,36). The primary antibody (anti-Endo G) (1:100 dilution) (green fluorescence) was added to the fixed cells for primary staining overnight then followed by the exposure of secondary antibody (FITC-conjugated goat anti-mouse IgG at 1:100 dilution) and then stained with PI (red fluorescence). Then cells were examined and photographed by using a Leica TCS SP2 Confocal Spectral microscope.

Microarray assay. The total RNA was extracted from HeLa cells treated with or without 75 µM DAS for 24 h by using Qiagen RNeasy Mini Kit. The total RNA was used for cDNA synthesis and labeling, then microarray hybridization. Fluorolabeled cDNA hybridized their complements on the chip, and the resulting localized concentrations of fluorescent molecules were detected and quantitated (Asia BioInnovations Corp.). Resulting data were analysed by using Expression Console software (Affymetrix) with default RMA parameters. Genes regulated by DAS were determined with a 2-fold change (37).

Statistical analysis. Significance of the mean values between intergroup was obtained using Student’s t-test. Data are expressed as the mean ± SD. p≤0.05 was considered significant.

Results

DAS inhibited the growth of HeLa cells. To assess the antitumor potential of DAS in human cervical cancer cells, HeLa cells were treated with 0, 25, 50, 75, and 100 µM of DAS, and cell viability was evaluated by flow cytometric assay. When cells were treated with DAS, it significantly decreased the percentage of viable HeLa cells in a dose-dependent manner (Fig. 1A). After cells were treated with DAS for 24 h they were examined for cell morphology by phase-contrast microscopy. The results revealed that some cells became round, blunt and
smaller in size, furthermore, cells became detached and suspended in the medium, especially with 50-100 µM DAS. The control group cells maintained their regular morphology and grew fully in patches and conflously (Fig. 1B).

**DAS induces DNA damage in HeLa cells.** To assess whether or not DAS could induce apoptosis and DNA damage in HeLa cells, DNA damage was assessed by DAPI staining and Comet assay, respectively. The present study found that DAS induced dose-dependent apoptosis in HeLa cells as determined by the DAPI nuclear staining assay (Fig. 2A). DNA strand cleavage induced by DAS was also observed in HeLa cells (Fig. 2B) which suggested that DAS treatment could induce cytotoxicity in HeLa cells.

**Induction of cell cycle arrest by DAS.** In order to determine whether DAS had any effect on progression through the cell cycle, HeLa cells were treated with 75 µM of DAS for 0, 6, 12, 24, 48 and 72 h. As depicted in Fig. 3A, DAS significantly increased in the G0/G1 cell population, accompanied by a decrease in G2/M and S cell populations and the effects were time-dependent. To assess whether DAS induced G0/G1 phase arrest through the inhibition of check-point protein, cells were harvested after exposure to 75 µM of DAS then assayed by Western blotting (Fig. 3B). DAS treatment for 24 h resulted in an up-regulation of p53 and CDK6 in HeLa cells. In addition, DAS down-regulated cyclin D and E protein levels which is a hallmark for G0/G1 accumulation.

**DAS decreases the levels of mitochondrial membrane potential and increases the levels of Ca²⁺ in HeLa cells.** To assess whether DAS induced cell death through the dysfunction, cells were harvested after exposure to DAS then assayed by flow cytometry (Fig. 4). DAS treatment in HeLa cells at 75 µM led to decrease the levels of mitochondrial membrane potential (Fig. 4A) at 1 and 2 h treatment. Fig. 4B also shows that DAS promoted the levels of Ca²⁺ in HeLa cells and these effects were time-dependent.

**DAS affects apoptosis-associated protein levels in HeLa cells.** To examine the role of apoptotic associate proteins in HeLa cells after exposure to DAS Western blotting was used (Fig. 5). Results indicated that DAS promoted the levels of Fas, FasL and caspase-8 (Fig. 5A), Bax, cytochrome c, Apaf-1, Bid, caspase-9 and -3 (Fig. 5B) which may be through the induction of apoptosis. Fas and FasL were promoted which indicated that DAS may be via the connection with Fas then activation of caspase-8 and -3 leading to apoptosis. These

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Figure 2. DAS-induced apoptosis and DNA damage in HeLa cells. Cells were treated with various concentrations of DAS for 24 h and apoptosis was determined by DAPI staining (A), DNA damage was measure by Comet assay (B) and DNA fragmentation was examined by DNA gel electrophoresis, and photographed by fluorescence microscopy (×200) as described in Materials and methods.
results suggest that DAS induces HeLa cell apoptosis, at least partly, through up-regulation of pro-apoptotic Bax, resulting in dysfunction of mitochondria and activation of caspase-3 and -9.

DAS affects Endo G at protein level and translocation in HeLa cells. To investigate the mechanism underlying apoptosis induced by DAS, we tested the effect of this compound on Endo G and AIF levels released from mitochondria. Fig. 4A shows that DAS decreased the levels of mitochondrial membrane potential. DAS induced apoptosis may also be through the mitochondrial-dependent pathway (Fig. 5B) and DAS promoted the levels of AIF and Endo G (Fig. 6A) showing Endo G release from mitochondria by Confocal laser scanning microscopy analysis (Fig. 6B).

DNA microarray analysis for DAS-induced cell cycle arrest and apoptosis in HeLa cells. DNA microarray analysis was performed to examine the gene expression profile in the DAS-treated HeLa cells. HeLa cells were treated with DAS for 12 h. The microarray analysis showed that 28 genes (17 genes, up-regulated; 11 genes, down-regulated) were expressed
Figure 6. DAS promotes the release of AIF and Endo G from mitochondria in HeLa cells. The cells were exposed to 75 µM of DAS for 24 h, then either were harvested for Western blotting (A) or were stained and examined and photographed by confocal microscopy (B) and were photographed as described in Materials and methods. Scale bar, 40 µm.

Figure 7. The top scorers by the number of pathways from GeneGo analysis. Thick cyan lines indicate the fragments of canonical pathways.
at least by 2-fold compared with the untreated control cells. We observed that SNORA62, LOC441233, ZNF69, AKR1C2, FOXD1, LOC284861, POM121L1P, LIPK, SUMO1P3, POM121L2, CST1, SAA1, KIR2DL3, SSX9, SLFN12L and UGT2B28 mRNA were up-regulated and SPRR2D, NCRNA00116, B3GALT5, CD209, STARD9, PDCD1LG2, VN1R4, PSG2, RNU13P2, LOC201229 and ROCK1 mRNA were down-regulated in the DAS-treated cells (Table I). The top scorers by the number of pathways network from GeneGo analysis program is shown in Fig. 7. Thick cyan lines indicate the fragments of canonical pathways. These genes may also be involved in cell cycle arrest and apoptosis, inducing the effect of DAS on HeLa cells.

### Discussion

It is well documented that apoptosis plays an important role in organisms such as for the developmental processes, maintenance of homeostasis, and elimination of the damage cells. Clinical anti-cancer drugs are used for causing cell death by induction of apoptosis in cancer cells (38,39). DAS has been showed to promote immune responses in leukemic mice in vivo (29). However, DAS induces cell apoptosis in cervical cancer is still unclear. Therefore, the purpose of the present study was to clarify the molecular mechanism of DAS underlying human cervical cancer cells (HeLa). We first demonstrated that HeLa cells treated with DAS showed a

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dose- and time-dependent decrease of viable cell number and it also induced morphological changes. DAS also induced apoptosis in HeLa cells based on the observations of nuclear fragmentation (DAPI staining), chromosome condensation, sub-G1 phase of cell cycle and cell shrinkage.

It is known that apoptosis can be through Fas and FasL pathway to activate the caspase-8 and -3 or through caspase-8 and mitochondria signaling pathways. Our results from Western blotting showed that DAS promoted the levels of Fas and FasL, caspase-8 and -3 (Fig. 5). Furthermore, we also showed that DAS decreased the levels of mitochondrial membrane potential and promoted Ca$^{2+}$ levels in HeLa cells (Fig. 4). Some drugs induced apoptosis via mitochondrion in cancer cells (40). It was reported that the characteristic of mitochondrial death pathway are: i) the changes in the permeability of the outer mitochondrial membrane and ii) the collapse of membrane potential (41,42). Furthermore, mitochondrial membrane permeability has been indicated as controlled by Bax and Bcl-2, both belong to the Bcl-2 family through regulation of the formation of apoptotic protein-conducting pores in the outer mitochondrial membrane (43,44) and at the mitochondrial levels (45).

Our results also showed that DAS promoted the protein levels of cytochrome c, caspase-9 and -3 and Apaf-1 (Fig. 5B). These observations indicated that DAS promoted the release of cytochrome c from mitochondria into the cytosol. This is in agreement with other reports showing that the cytosolic cytochrome c binds to Apaf-1, leading to the activation of caspase-9, -3 and poly(ADP-ribose) polymerase (46,47). Our result clearly demonstrated that DAS induced apoptosis in HeLa cells also through caspase-dependent pathways. It was reported that caspases are integral parts of the apoptotic pathway in response to various stimuli (48). Furthermore, it has been determined that a variety of chemotherapeutic agents induce apoptosis through the activation of caspases (38). Our results showed that DAS promoted the levels of AIF and Endo G in HeLa cells (Fig. 6). It was reported that apoptosis can be induced through caspases-independent pathways, directly through AIF or Endo G release from mitochondria leading to apoptosis (49).

In conclusion, in Fig. 8, we have outlined the molecular mechanism and the overall possible signaling pathways for DAS-induced cell cycle arrest and apoptosis in HeLa cells. According to the present findings, DAS is activated through Fas and FasL, then caspase-8 and -3, or increased Bax and Bid, which leads to disruption of mitochondrial membrane potential, and then activates mitochondria-mediated downstream molecular events including cytochrome c release and sequential activation of caspase-9 and -3 or through the release of AIF and Endo G causing apoptosis in HeLa cells.

Acknowledgements

This work was supported by the grant CMU99-TC-15 from China Medical University and the grant NSC96-2815-C-039-044-B from National Science Council, Taiwan.

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