

Goniothalamine induces mitochondria-mediated apoptosis associated with endoplasmic reticulum stress-induced activation of JNK in HeLa cells

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Abstract. Goniothalamine, a natural occurring styryl-lactone isolated from *Goniothalamus macrophyllus* (Blume) Hook. f. & Thomson var. *macrophyllus*, can trigger cancer cell death in various types of cancer cell. The present study focused on elucidation of the mitochondria-mediated apoptosis associated with endoplasmic reticulum (ER) stress-induced activation of c-Jun NH₂-terminal kinase (JNK) by goniothalamine in HeLa cervical cancer cells. Cell viability was determined using an MTT assay, and DNA condensation and loss of mitochondrial membrane potential were determined using Hoechst 33342 and JC-1 staining, respectively. Flow cytometry was used for cell cycle and phosphatidyl-serine exposure analyses. Apoptotic-associated ER stress signaling pathways were determined using immunoblotting, reverse transcription-polymerase chain reaction (RT-PCR) and RT-quantitative PCR analyses. The results suggested that goniothalamine suppressed cell proliferation in a time- and dose-dependent manner. The induction of apoptosis was confirmed by increased DNA condensation, loss of mitochondrial membrane potential and cell surface phosphatidyl-serine presentation. The cell cycle analysis demonstrated that the goniothalamine-treated HeLa cells were in G2/M arrest. Determination of the caspase cascade and apoptotic proteins indicated the induction of apoptosis through the intrinsic pathway. In addition, the levels of phosphorylated JNK and the transcription factor, C/EBP homologous protein (CHOP), an ER stress-associated apoptotic molecule, were increased

in the goniothalamine-treated cells. These data indicated that goniothalamine exerted a cytotoxic effect against HeLa cells via the induction of mitochondria-mediated apoptosis, associated with ER stress-induced activation of JNK.

Introduction

The use of natural compounds for treatment is one of the strategies used for cancer therapy and prevention. Styryl-lactone compounds are one type of bioactive compound showing cytotoxic activity towards several cancer cell lines (1,2). These secondary metabolites are found ubiquitously in the *Goniothalamus* plant genus, indigenous to South East Asia. Goniothalamine is a major styryl-lactone compound extracted from *Goniothalamus macrophyllus* (Blume) Hook.f. & Thomson (3). The cytotoxicity of styryl-lactones towards cancer cells is specific, as these compounds have been reported to have no significant effects on normal cell lines, including liver, kidney and fibroblast cell lines (4). Previous studies have shown that goniothalamine induces apoptosis predominantly through the intrinsic pathway. However, the detailed mechanism remains to be fully elucidated (5-11).

Endoplasmic reticulum (ER) stress is stress in the ER caused by the accumulation of unfolded/misfolded proteins. It triggers a response to restore homeostasis in the ER, termed the unfolded protein response (UPR). In mild ER stress, the UPR triggers and promotes ER-associated protein degradation to remove misfolded proteins and then restores normal ER function. In prolonged or severe ER stress, the UPR triggers the cell to commit suicide, usually in the form of apoptosis, also termed ER stress-induced apoptosis. It stimulates the apoptotic-associated signaling of ER stress sensor transmembrane proteins, including protein kinase RNA-like ER kinase (PERK), activating transcription factor 6 (ATF6) and inositol-requiring enzyme 1 α (IRE1 α), and increases the expression of C/EBP homologous protein (CHOP), a critical molecule of ER stress-induced apoptosis (12,13).

Apoptosis is a crucial mechanism of anticancer drug-induced cell death. The majority of chemotherapeutic agents inhibit tumors by triggering cancer cell apoptosis. Apoptosis can be

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activated either by cell surface death receptor- or mitochondria-mediated apoptosis signaling pathways (14,15). However, ER stress is primarily associated with mitochondria-mediated apoptosis. In a number of studies on ER stress, several signaling mechanisms of crosstalk between ER stress and mitochondria-mediated apoptosis have been suggested. These include IRE1 α $\rightarrow$ tumor necrosis factor receptor-associated factor 2 $\rightarrow$ apoptosis signal-regulating kinase 1 $\rightarrow$ c-Jun NH₂-terminal kinase (JNK) and PERK $\rightarrow$ eukaryotic initiation factor 2 α $\rightarrow$ ATF4 $\rightarrow$ CHOP, and result in the induction of mitochondria-mediated apoptosis (12,13,16). The activation of IRE1 α also activates the endonuclease domain, which splices mRNA of X-box binding protein 1 (XBP1) and results in expression of the spliced form of the UPR gene (12,13). In addition, the activation of IRE1 α leads to the phosphorylation of JNK, which is one of three major mitogen-activated protein kinase (MAPK) pathways that have generally been associated with pro-apoptotic action in several cell types (16-18). Thus, this information indicates that JNK activation is sustained in severe ER stress-induced apoptotic cell death.

Cervical cancer is the fourth most common type of cancer among women and the seventh most common worldwide (19,20). Annual incidence rates of >450,000 and >240,000 cases have been estimated in low- and middle-income countries, respectively, with the mortality rates in these countries estimated to reach >88% and predicted to increase to at least 91.5% by 2030 (21). This emphasizes the requirement for identifying effective and non-cytotoxic chemical agents for chemoprevention and treatment. The HeLa cell line is most widely used as a cervical cancer model for investigating human cellular and molecular biology (22). The present study investigated the induction of mitochondria-mediated apoptosis associated with the ER stress-induced activation of JNK caused by goniothalamine treatment in HeLa cells. As the first investigation of the effects of goniothalamine on ER stress-induced activation of JNK-associated apoptosis on cancer cells, the results may be useful for enabling further investigations of the drug action of styryl-lactone compounds and indicate the potential application of goniothalamine as an anticancer agent for the treatment of cervical cancer.

Materials and methods

Chemicals and antibodies. Goniothalamine was obtained from Professor Wilawan Mahabusarakam of the Faculty of Science, Prince of Songkla University (Songkhla, Thailand) in purified powder form, the structure of which is shown in Fig. 1A. The stems of *Goniothalamus macrophyllus* were collected from Songkhla province in the southern region of Thailand in September 2007. Identification was performed by Mr. Ponlawat Pattarakulpisutti of the Department of Biology, Faculty of Science, Prince of Songkla University. The specimen (Uraivan 01) was deposited in the Herbarium of the Department of Biology, Faculty of Science, Prince of Songkla University. Antibodies (Abs) for immunoblotting analysis, including mouse monoclonal Abs against CHOP, and rabbit monoclonal Abs against glucose-regulated protein 78 (GRP78), poly ADP ribose polymerase (PARP), caspase-3, caspase-9, p38, phosphorylated (phospho)-p38 at Thr180/Tyr182, stress-activated protein kinase (SAPK)/JNK,

phospho-SAPK/JNK at Thr183/Tyr185, p44/42 MAPK [extracellular signal-regulated kinase (Erk1/2)], phospho-p44/42 MAPK (Erk1/2) at Thr202/Tyr204, p53, B cell lymphoma 2 (Bcl2), phospho-Bcl2 at Ser70, Bcl2-associated X protein (Bax), Bcl2-associated death promoter (Bad) and β -actin, and anti-mouse immunoglobulin G and anti-rabbit immunoglobulin G horseradish peroxidase-conjugated secondary antibodies were obtained from Cell Signaling Technology, Inc. (Danvers, MA, USA).

Cell culture. The HeLa human cervical cancer cell line was obtained from the American Type Culture Collection (Manassas, VA). The cells were maintained in Dulbecco's modified Eagle's medium (DMEM; Gibco Life Technologies; Thermo Fisher Scientific, Inc., Waltham, MA, USA) supplemented with 10% fetal bovine serum (GE Healthcare Life Sciences, Little Chalfont, UK), 100 U/ml penicillin and 100 μ g/ml streptomycin (GE Healthcare Life Sciences) at 37°C in a humidified 5% CO₂ atmosphere, and were used for assays during the exponential phase of growth.

Cell viability assessment using an MTT assay. The cells were plated at a density of 5x10³ cells/well in 96-well plates and allowed to grow for 24 h. The cells were then treated with goniothalamine at serial concentrations of 100, 50, 25, 12.5, 6.25, 3.125 and 1.562 μ M, and the control group was treated with 0.5% DMSO. The cytotoxicity of goniothalamine was determined by cell proliferation analysis using an MTT assay, as described by Denizot and Lang (23). Briefly, the cells were incubated at 37°C with the indicated concentration of goniothalamine for 24 h to determine the half maximal inhibitory concentration (IC₅₀) value, or at different time points (3, 6, 9 and 12 h), to investigate the effect of time and dose on cell viability. Following the indicated treatment, 0.5 mg/ml of MTT solution (Sigma-Aldrich; Merck Millipore, Darmstadt, Germany) dissolved in culture medium was added and the cells were incubated for 2 h at 37°C with 5% CO₂. The MTT solution was then aspirated and 100 μ l of DMSO was added to each well to dissolve the formazan crystals, a product of cell respiration reacting with MTT tetrazolium compound to indicate viable cells. The absorbance at 540 nm was quantified using an Epoch™ microplate spectrophotometer and analyzed using Gen5™ data analysis software (BioTek Instruments, Inc., Winooski, VT, USA).

Hoechst 33342 staining analysis for chromatin condensation. The fluorescent dye, Hoechst 33342, was used to detect chromatin condensation, which is a characteristic of apoptotic cells. The protocol was modified from Oberhammer *et al* (24). The HeLa cells were plated at a density of 2x10⁵ cells/well in 6-well plates and treated with 15 μ M of goniothalamine for 0, 3, 6, 9 and 12 h at 37°C with 5% CO₂. The treated cells were then washed with PBS and fixed with 4% paraformaldehyde for 15 min at room temperature. The fixed cells were washed with PBS and stained with 5 μ g/ml of Hoechst 33342 solution (Invitrogen™; Thermo Fisher Scientific, Inc.) for 15 min. The cells were washed with PBS and the plates were observed using a fluorescence microscope (IX73; Olympus Corporation, Tokyo, Japan) using U-MWU2 mirror units for ultraviolet excitation.

Cell cycle determination. The HeLa cells were plated at a density of 2×10^5 cells/well in 6-well plates. The cells were incubated with $15 \mu\text{M}$ of goniothalamin for various durations of 0, 3, 6, 9 and 12 h at 37°C with 5% CO_2 . The protocol used for the flow cytometric analysis of cell cycle distributions using propidium iodide was modified from Krishan (25). Following treatment, the whole cells were collected and fixed with ethanol (70% final concentration). The fixed cells were washed with PBS and stained with $50 \mu\text{g/ml}$ propidium iodide solution (Invitrogen™; Thermo Fisher Scientific, Inc.). The stained cells were incubated at 4°C in the dark, and were then sorted and analyzed for DNA content using the CyAn™ ADP Beckman Coulter International S.A. Flow cytometer and Kaluza® flow analysis software (Beckman Coulter, Inc., Brea, CA, USA), respectively.

Cell surface phosphatidyl-serine determination. The HeLa cells were plated at a density of 2×10^5 cells/well in 6-well plates. The cells were incubated with $15 \mu\text{M}$ goniothalamin for 0, 3, 6, 9 and 12 h at 37°C , 5% CO_2 . DMSO-treated HeLa cells at a 0.5% final concentration were used as a control. The whole cells were collected and stained according to the manufacturer's protocol of the fluorescein isothiocyanate (FITC) Annexin V/Dead Cell apoptosis kit for flow cytometry (Invitrogen™; Thermo Fisher Scientific, Inc.). Following staining, the stained cells were sorted and analyzed for outer membrane phosphatidylserine content using the CyAn™ ADP Beckman Coulter International S.A. flow cytometer and Kaluza® flow analysis software (Beckman Coulter, Inc.), respectively.

Analysis of the loss of mitochondrial membrane potential. The loss of mitochondrial membrane potential was detected using JC-1 dye. The protocol for the observation of mitochondrial membrane potential under a fluorescence microscope using JC-1 dye was modified from Perelman *et al* (26). The HeLa cells were treated with $15 \mu\text{M}$ goniothalamin for 3 and 6 h, and DMSO-treated HeLa cells at a final concentration of 0.5% were used as a control. The treated cells were stained with $10 \mu\text{g/ml}$ JC-1 (Invitrogen™; Thermo Fisher Scientific, Inc.) and washed with PBS to remove excess dye. Subsequently, the stained cells were qualitatively analyzed by observation under a fluorescence microscope (IX73; Olympus Corporation) with U-MWB2 mirror units for excitation at 480 nm. The aggregated form is emitted at red light (590 nm), indicating healthy mitochondria, whereas monomer formation is emitted at green light (525 nm), indicating damaged mitochondria or loss of mitochondrial membrane potential.

Analysis of mRNA levels of spliced XBPI using reverse transcription-polymerase chain reaction (RT-PCR) analysis. The HeLa cells were plated at a density of 5×10^4 cells/well in 12-well plates. The cells were incubated with $15 \mu\text{M}$ goniothalamin for 0, 3, 6, 9 and 12 h at 37°C , 5% CO_2 . DMSO-treated HeLa cells at a final concentration of 0.5% were used as a control. The whole cells were collected and their RNA was extracted using QIAzol™ lysis reagent (Qiagen N.V., Venlo, The Netherlands) and cDNA was synthesized by RT using a RevertAid™ First Strand cDNA Synthesis kit (Fermentas™; Thermo Fisher Scientific, Inc.) with $2 \mu\text{g}$ of total RNA from each sample. These steps were performed according to the

manufacturer's protocol. The PCR step was performed using Taq polymerase (Vivantis Technologies Sdn. Bhd., Selangor Darul Ehsan, Malaysia) using a pair of primers corresponding to the spliced site of the XBPI gene; forward 5'-AATGAAGTG AGGCCAGTGGCC-3' and reverse 5'-AATACCGCCAGA ATCCATGGG-3'. In detail, the PCR step was performed in a $20 \mu\text{l}$ reaction volume using $1 \mu\text{l}$ of cDNA with a PCR mixture containing $0.3 \mu\text{M}$ forward primer, $0.3 \mu\text{M}$ reverse primer, 0.25 mM deoxynucleotide triphosphate, 10 mM Tris-HCl, 50 mM KCl, 0.01% Triton X-100, 1.5 mM MgCl_2 and 2 units of Taq polymerase. The PCR thermal cycler conditions used were as follows: 94°C for 2 min, followed by 35 cycles at 94°C for 15 sec, 55°C for 30 sec and 72°C for 30 sec; final extension was not included. The PCR products were analyzed using 8% polyacrylamide gel electrophoresis with ethidium bromide staining. The unspliced- and spliced- forms of the XBPI gene were indicated at 125 and 99 base pairs, respectively.

Analysis of ER stress-mediated mRNA expression using RT-quantitative PCR (RT-qPCR) analysis. The HeLa cells were plated at a density of 5×10^4 cells/well in 12-well plates. The cells were incubated with $15 \mu\text{M}$ goniothalamin for 0, 3, 6, 9 and 12 h at 37°C , 5% CO_2 . DMSO-treated HeLa cells at a final concentration of 0.5% were used as a control. The whole cells were collected and the RNA was extracted using QIAzol™ lysis reagent (Qiagen N.V.). The cDNA was synthesized by RT using the RevertAid™ First Strand cDNA Synthesis kit (Fermentas™; Thermo Fisher Scientific, Inc.) with $2 \mu\text{g}$ of total RNA from each sample, and the synthesized cDNA was diluted 20X prior to use in the qPCR step. The subsequent qPCR step was performed in a $10\text{-}\mu\text{l}$ reaction volume containing $1 \mu\text{l}$ diluted cDNA, SYBR® Select Master Mix (Applied Biosystems; Thermo Fisher Scientific, Inc.), $0.2 \mu\text{M}$ forward primer and $0.2 \mu\text{M}$ reverse primer. The following primers were used for amplification: CHOP, forward 5'-GCG CATGAAGGAGAAAGAAC-3' and reverse 5'-TCACCA TTCGGTCAATCAGA-3'; ER-localized Dna J homologue 4 (ERdj4), forward 5'-AAAATAAGAGCCCGGATGCT-3' and reverse 5'-CGCTTCTTGATCCAGTGTT-3'; growth arrest and DNA damage protein 34 (GADD34), forward 5'-AAA CCAGCAGTTCCCTTCCT-3' and reverse 5'-CTCTTCCTC GGCTTTCTCCT-3'; GRP78, forward 5'-GCTCGACTCGAA TTCCAAAG-3' and reverse 5'-GATCACCAGAGAGCA CACCA-3'; and GAPDH, forward 5'-AGGTCGGAGTCAACG GATTT-3' and reverse 5'-TAGTTGAGGTCAATGAAGGG-3'. The qPCR cycling conditions were optimized for all the primers and performed according to the SYBR® Select Master Mix user guide's protocol as follows: 50°C for 2 min, 95°C for 2 min, and 40 cycles at 95°C for 15 sec and 60°C for 60 sec. The qPCR amplification was analyzed using the CFX96 Touch™ Real-Time PCR detection system with CFX Manager™ software (Bio-Rad Laboratories, Inc., Hercules, CA, USA). The relative quantification ($\Delta\Delta\text{Cq}$) method described by Livak and Schmittgen (27) was used to analyze the results of gene expression using GAPDH as a reference gene. The gene expression calculation was performed according to the CFX Manager™ software manufacturer's protocol.

Analysis of protein expression via immunoblotting. SDS-PAGE and immunoblotting were used to detect the

expression levels of apoptotic intermediate proteins. The procedures for SDS-PAGE and immunoblotting were modified from Taylor *et al.* (28). The HeLa cells were plated at a density of 2×10^5 cells/well in 6-well plates and incubated with 15 μ M goniothalamin for 0, 3, 6, 9 and 12 h at 37°C with 5% CO₂. DMSO-treated HeLa cells at a final concentration of 0.5% were used as a control. The whole cells were then collected for protein extraction in RIPA lysis buffer, containing 50 mM Tris-HCl (pH 7.4), 1% NP-40, 0.5% C₂₄H₃₉NaO₄, 0.1% SDS, 150 mM NaCl, 2 mM EDTA and 50 mM NaF. Protein concentration was determined using Bio-Rad® Protein Assay kit (Bio-Rad Laboratories, Inc.), which is based on the Bradford method (29) using bovine serum albumin as the standard protein. The cell lysates (containing 10 μ g of protein) were separated on 8-15% acrylamide gels by SDS-PAGE and then transferred onto polyvinylidene difluoride membranes (Merck Millipore), following which, they were blocked with 5% skimmed-milk in TBS-Tween buffer for 1 h at room temperature. The membranes were then incubated with mouse monoclonal Abs against CHOP (1:1,000), and rabbit monoclonal Abs against GRP78 (1:1,000), PARP (1:1,000), caspase-3 (1:1,000), caspase-9 (1:1,000), p38 (1:1,000), phospho-p38 at Thr180/Tyr182 (1:1,000), SAPK/JNK (1:1,000), phospho-SAPK/JNK at Thr183/Tyr185 (1:1,000), p44/42 MAPK (Erk1/2; 1:1,000), phospho-p44/42 MAPK (Erk1/2) at Thr202/Tyr204 (1:1,000), p53 (1:1,000), Bcl2 (1:1,000), phospho-Bcl2 at Ser70 (1:1,000), Bax (1:1,000), Bad (1:1,000) and β -actin (1:5,000) overnight at 4°C. Following incubation with anti-mouse immunoglobulin G or anti-rabbit immunoglobulin G horseradish peroxidase-conjugated secondary antibodies (1:10,000) for 1 h at room temperature, the signals were developed using Immobilon™ Western Chemiluminescent HRP substrate (Merck Millipore) and detected using a chemiluminescent imaging system (GeneGnome gel documentation; Synoptics Ltd., Cambridge, UK).

Statistical analysis. To compare the data from different treatment groups, student's *t*-test was used. Microsoft Excel version 2010 software (Microsoft Corporation, Redmond, WA, USA) was used to analyze the data. All data presented were obtained from at least three independent experiments and are presented as the mean $\pm$ standard deviation. $P \leq 0.05$ was considered to indicate a statistically significant difference.

Results

Effect of goniothalamin on HeLa cell viability and toxicity. The cytotoxicity of goniothalamin towards HeLa cells was analyzed and the results are shown in Fig. 1B and C. Goniothalamin induced a cytotoxic effect with an IC₅₀ value of 13.28 ± 2.89 μ M at 24 h. Goniothalamin induced these cytotoxic effects in a time- and dose-dependent manner.

Effect of goniothalamin on chromatin condensation. An important characteristic of apoptotic cells is chromatin condensation. Goniothalamin was shown to induce chromatin condensation and apoptotic body-like formation in the treated HeLa cells (Fig. 2A). The number of cells with chromatin condensation following treatment with 15 μ M goniothalamin increased in a time-dependent manner.

Loss of mitochondrial membrane potential. The loss of mitochondrial membrane potential is one of the apoptotic characteristics of the intrinsic pathway. The present study investigated this event using the fluorescent dye, JC-1, to stain the treated HeLa cells. The results showed that goniothalamin increased the presence of green puncta, indicating the monomer form of JC-1 in cells with loss of mitochondrial membrane potential. Red puncta were observed in the control sample, indicating the aggregated form of JC-1 in cells with a normal mitochondrial membrane potential or healthy cells (Fig. 2B). These results indicated that goniothalamin induced the loss of mitochondrial membrane potential in the HeLa cells and this was likely due to the intrinsic apoptotic pathway.

Effect of goniothalamin on the regulation of cell cycle arrest. The majority of apoptosis-inducing compounds interrupt cell cycle regulation, which may lead to cell cycle arrest and subsequent apoptosis. Therefore, the present study investigated the effect of goniothalamin on the cell cycle of HeLa cells treated with 15 μ M goniothalamin. The results indicated that goniothalamin predominantly affected cell cycle arrest at the G2/M phase in a time-dependent manner (Fig. 3). The increase in G2/M arrest was ~15% following treatment with 15 μ M goniothalamin for 12 h.

Effect of goniothalamin on cell surface phosphatidyl-serine presentation. The translocation of phosphatidyl-serine out of the cell membrane and exposed to annexin V is an important characteristic in differentiating cell apoptosis from necrosis. In the present study, goniothalamin predominantly induced HeLa cell accumulation at the early apoptotic stage (Fig. 4). The results showed that goniothalamin increased the percentage of total apoptotic HeLa cells to $16.59 \pm 2.4\%$ within 12 h, indicating the induction of apoptosis.

Effect of goniothalamin on ER stress. The mRNA and protein expression levels of CHOP following treatment with goniothalamin are shown in Fig. 5A and B, respectively, which showed increased mRNA and protein levels of CHOP, the key mediator of ER stress-induced apoptosis. The increased expression of other ER stress-associated genes, including ERdj4 and GADD34, were also detected, with the exception of GRP78. In addition, the results of the XBP1 splicing analysis (Fig. 5C) showed an increase in the level of spliced XBP1 following goniothalamin treatment. These results indicated that goniothalamin triggered ER stress in the HeLa cells.

Induction of apoptosis is associated with the ER stress-induced activation of JNK, which is triggered by goniothalamin. The protein expression levels of apoptotic-associated mediators are shown in Fig. 6, which corresponded with induction of ER stress. The results, as shown in Fig. 6A, revealed that phosphorylation of SAPK/JNK and p38 increased in a time-dependent manner, which was not observed for ERK. The inhibition of Bcl2 through phosphorylation was also observed. The level of phospho-Bcl2 at Ser70, one of the phosphorylated residues activated by phospho-SAPK/JNK, increased in a time-dependent manner. The activation of p38 and SAPK/JNK was closely associated with the inhibition of Bcl2 via phosphorylation, leading to apoptosis (Fig. 6C). This event led

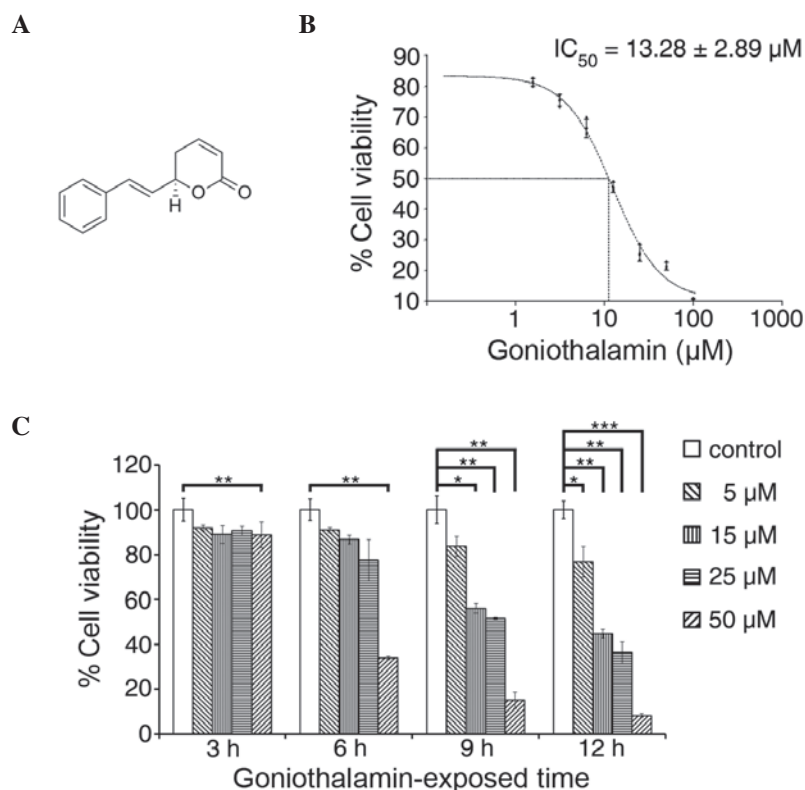


Figure 1. Effect of goniiothalamine on cell viability of HeLa cells. (A) Structure of goniiothalamine. (B) Evaluation of the IC_{50} using an MTT assay. (C) Effects of goniiothalamine on cell viability at various concentrations and exposure durations. Values are expressed as the mean $\pm$ standard deviation from at least three independent experiments. * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$, vs. control for each exposure. IC_{50} , half maximal inhibitory concentration.

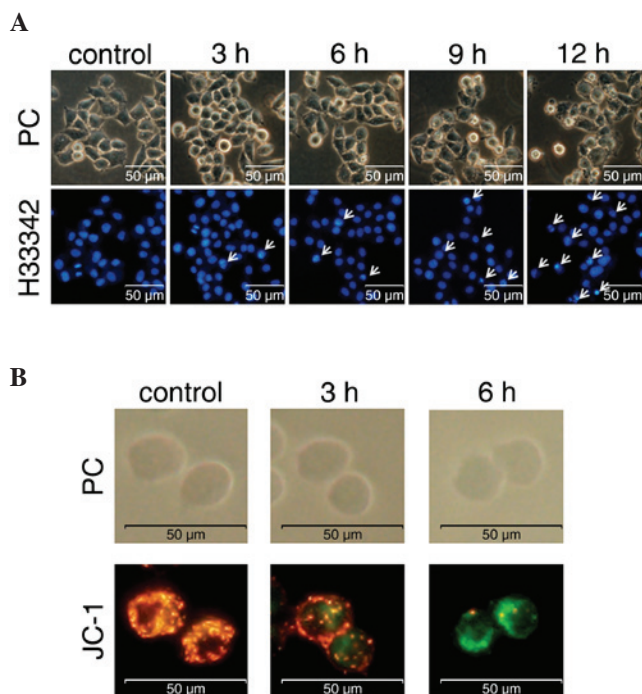


Figure 2. Induction of apoptosis in HeLa cells by goniiothalamine. (A) Chromatin condensation was shown using Hoechst 33342 staining. Cells were treated with 15 μM goniiothalamine for 3, 6, 9 and 12 h. Chromatin condensation is indicated by white arrows. (B) Mitochondrial membrane potential was shown using JC-1 staining. Cells were treated with 15 μM of goniiothalamine for 3 and 6 h. Red puncta altered to green indicating loss of mitochondrial membrane potential, a characteristic of the mitochondrial mediated apoptotic pathway in early apoptosis. PC, phase-contrast; H33342, Hoechst 33342.

to mitochondrial dysfunction and the induction of apoptosis via the intrinsic pathway. Activation of the caspase cascade components (Fig. 6B), including the initiator caspase-9, executioner caspase-3 and PARP, were detected upon treatment with 15 μM goniiothalamine, indicating the induction of apoptosis. These results suggested that goniiothalamine induced mitochondria-mediated apoptosis, which was associated with ER stress-induced activation of the JNK pathway.

Discussion

At present, the use of traditional medicine or natural compounds extracted from plants is of interest as it may reduce the adverse effects of conventional therapies (30). Previous studies have reported that goniiothalamine inhibits proliferation and induces apoptosis in various cancer cell lines, including human cervical cancer (7-11). Although the effect of goniiothalamine on the induction of apoptosis in the HeLa cell line was reported previously by Alabsi *et al* (9,10), the molecular signaling pathway of goniiothalamine-induced apoptosis in HeLa cells remains to be elucidated. The present study is the first, to the best of our knowledge, to indicate that ER stress-induced activation of JNK was associated with goniiothalamine-induced HeLa cervical cancer cell apoptosis. The results showed that goniiothalamine reduced HeLa cell viability with an IC_{50} value of $13.28 \pm 2.89 \mu M$, and this reduced viability occurred in a dose- and time-dependent manner. In addition, the induction of apoptosis by goniiothalamine was assessed by examining chromatin condensation, cell cycle arrest, cell surface phosphatidyl-serine presentation and caspase cascade

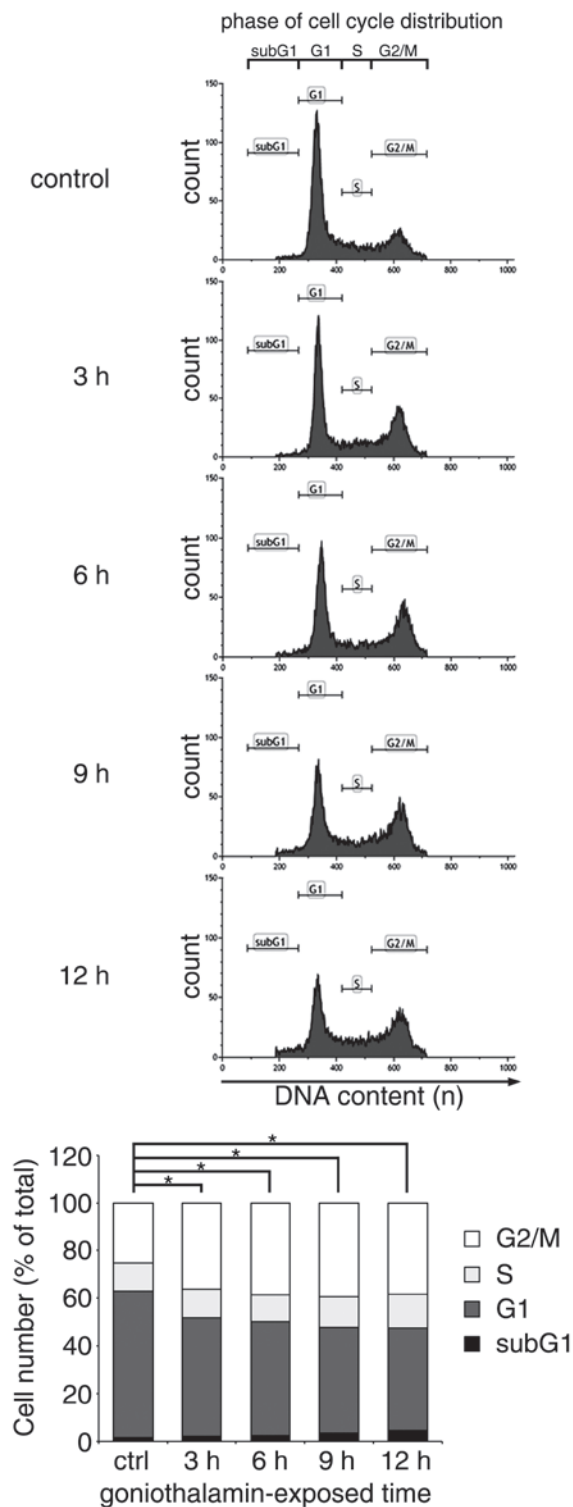


Figure 3. Induction of cell cycle arrest in HeLa cells by goniiothalamine. Distribution of the cell cycle phases in HeLa cells treated with 15 μ M of goniiothalamine for 3, 6, 9 and 12 h, as analyzed using flow cytometry following staining with propidium iodide. The results showed that goniiothalamine triggered cell cycle accumulation predominantly in the G2/M phase. Data are presented as the mean of each cell cycle phase. All data were obtained from at least three independent experiments, and the mean values of G2/M arrest for individual exposure durations were compared with the control. * $P < 0.05$, vs. ctrl (control). n, number of sets of chromosomes in a cell or ploidy.

activation in goniiothalamine-treated HeLa cells. The effect of goniiothalamine on cell cycle distribution was investigated by observing DNA content in the treated cells using propidium

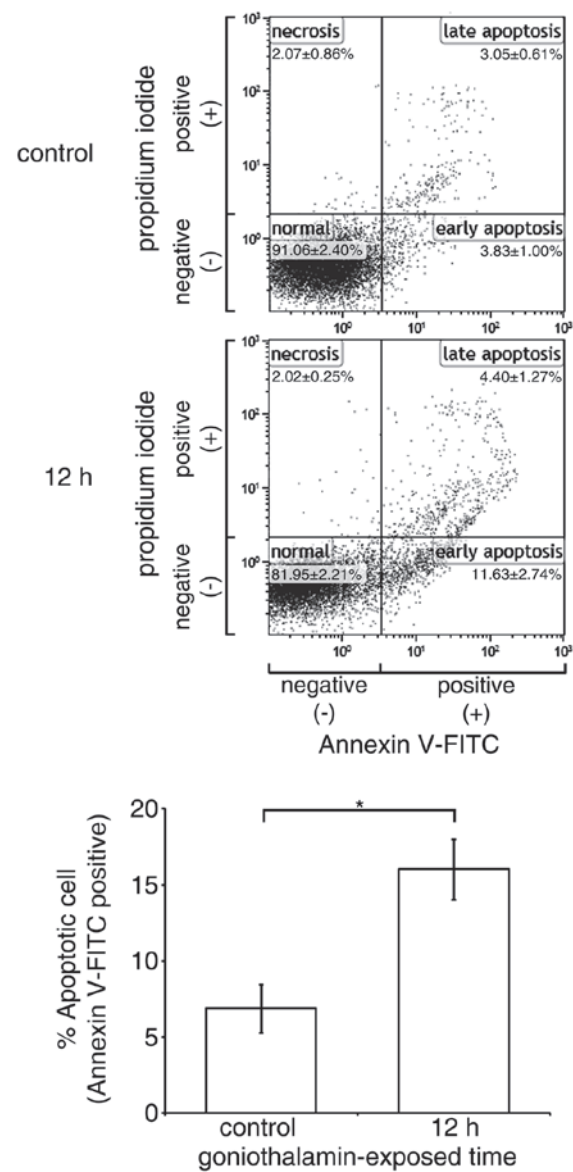


Figure 4. Increases of cell surface phosphatidyl-serine presentation in HeLa cells by goniiothalamine. The Cell surface presentation of phosphatidyl-serine presentation on HeLa cells treated with 15 μ M goniiothalamine for 12 h was detected via Annexin V assessment. The percentage in each quadrant indicates the levels of normal cells (annexin V-FITC-/propidium iodide-), early apoptotic cells (annexin V-FITC+/propidium iodide-), late apoptotic cells (annexin V-FITC+/propidium iodide+), and necrotic cells (annexin V-FITC-/propidium iodide+). These results indicated that goniiothalamine induced phosphatidyl-serine exposure, indicative of apoptosis induction. The results shown are representative data from three independent experiments. Percentages of apoptotic cells are presented as the mean $\pm$ standard deviation from at least three independent experiments. * $P < 0.05$, vs. control. FITC, fluorescein isothiocyanate.

iodide staining. The results showed that goniiothalamine caused accumulation at the G2/M phase of arrest in apoptosis (Fig. 3). This response differed from the cell cycle arrest induced by goniiothalamine in Ca9-22 oral cancer cells and HL-60 promyelocytic leukemia cells, which showed subG1 arrest (11,31). However, cell cycle arrest in MDA-MB-231 breast cancer cells showed accumulation at the G2/M phase of arrest (32). This suggested that differences in cell cycle arrest depend on the type of cancer cell. In addition, the accumulation of cells at the G2/M phase arrest can trigger p53-dependent p38

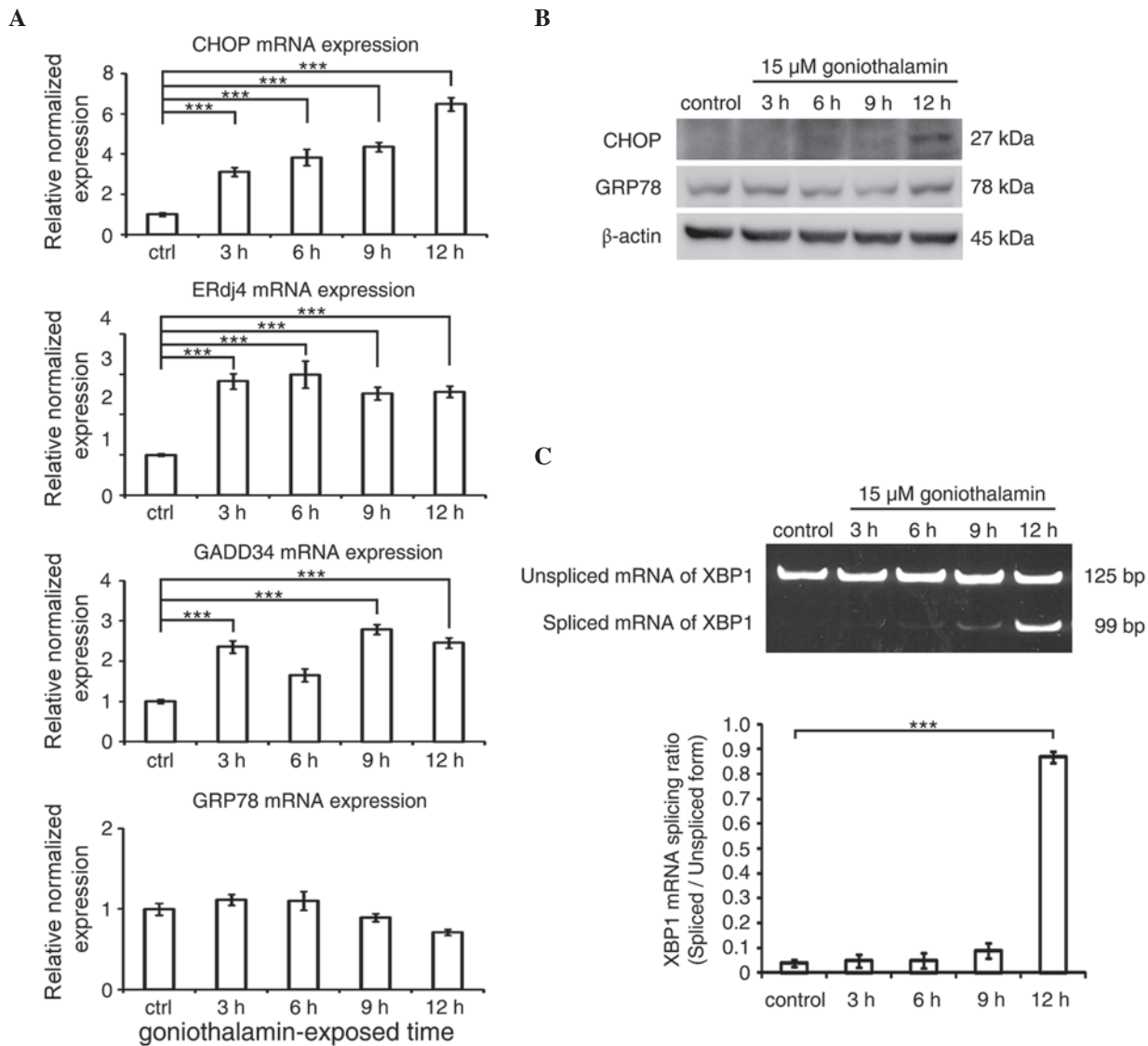


Figure 5. ER stress is triggered in goniothalamin-treated HeLa cells. (A) mRNA expression levels of ER stress-associated genes, including CHOP, ERdj4, GADD34 and GRP78 in HeLa cells treated with 15 μ M of goniothalamin for 3, 6, 9 and 12 h using RT-qPCR analysis. (B) Immunoblotting analysis of ER stress mediators, CHOP and GRP78. Images shown are representative from three independent experiments. (C) Analysis of the splicing of XBP1 mRNA using RT-PCR analysis. Values of fluorescence intensity are presented as the mean $\pm$ standard deviation from at least three independent experiments. *** P <0.001, vs. ctrl (control). ER, endoplasmic reticulum; CHOP, C/EBP homologous protein; ERdj4, ER-localized Dna J homologue 4; GADD34, growth arrest and DNA damage protein 34; GRP78; glucose-regulated protein 78; RT-qPCR, reverse transcription-quantitative polymerase chain reaction; ctrl, control.

MAPK activation (33), and the goniothalamin-induced G2/M phase arrest was associated with p38 MAPK phosphorylation and increased expression of p53 (Fig. 6A and C). In early apoptosis, phosphatidyl-serine is translocated from the inner surface to the outer surface of the cellular membrane due to the loss of membrane asymmetry, which can be detected by Annexin V (34-37). In the present study, it was observed that the numbers of positively-stained Annexin V cells were increased in the goniothalamin-treated HeLa cells, compared with the control (Fig. 4). This effect of goniothalamin on the HeLa cells correlated with previous reports, which showed goniothalamin-induced increases in positively-stained Annexin V cells in cell lines, including human leukemia cells, hepatoblastoma and urinary bladder cancer cells (5,11,38,39). These results also confirmed the ability of goniothalamin to induce apoptosis.

During apoptosis, the loss of mitochondrial membrane potential is a characteristic of early apoptosis, which triggers the mitochondria-mediated pathway. In this process, following mitochondrial membrane collapse, the mitochondrial permeability transition pore (MPTP) is opened by pro-apoptotic signaling proteins, including Bax and Bid, resulting in decreased mitochondrial membrane potential, following which cytochrome *c* is released into the cytoplasm and induces activation of the apoptosome-dependent apoptosis cascade (40). In the present study, the loss of mitochondrial membrane potential was detected by staining cells with specific fluorescent dye, JC-1, which can selectively enter mitochondria through the MPTP and alters in color from red to green as the membrane potential decreases. The results of the present study indicated that goniothalamin induced the loss of mitochondrial membrane potential in HeLa cells

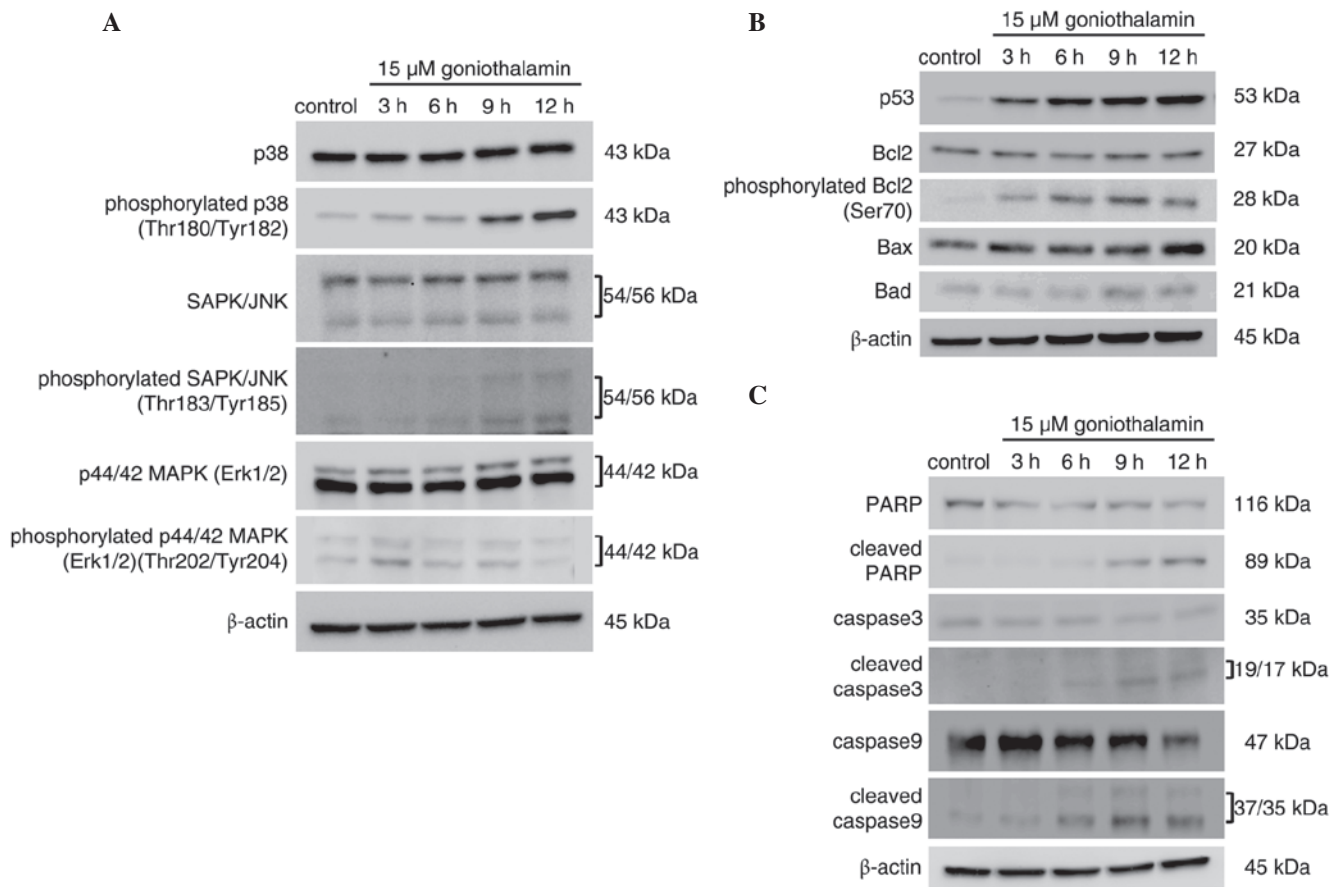


Figure 6. MAPK activation is associated with the induction of apoptosis. HeLa cells were treated with 15 μ M of goniothalamin for 3, 6, 9 and 12 h. Immunoblotting assays of (A) MAPK pathway mediators, (B) apoptosis mediators, and (C) p53, antiapoptotic Bcl2, proapoptotic Bax and Bad molecules and phosphorylated Bcl2 (Ser70). The results indicated that goniothalamin induced apoptosis in HeLa cells, associated with activation of the MAPK pathway. Images shown are representative from three independent experiments. MAPK, mitogen-activated protein kinase; SAPK, stress-activated protein kinase; JNK, c-Jun NH₂-terminal kinase; Erk1/2, extracellular signal-regulated kinase 1/2; PARP, poly ADP ribose polymerase; Bcl2, B cell lymphoma 2; Bax, Bcl2-associated X protein; Bad, Bcl2-associated death promoter.

(Fig. 2B). In addition, activation of the caspase cascade was triggered and resulted in apoptotic cell death. Following the loss of mitochondrial membrane potential in the apoptotic cells, the released cytochrome *c* interacts with Apaf-1 and forms the apoptosome, which activates caspase-9 and then caspase-3, and destroys PARP (41-43). This results in cells undergoing apoptotic cell death. In the present study, the activation of initiator caspase-9 and executioner caspase-3, and the inactivation of PARP were investigated. The results (Fig. 6B) showed increases in the cleaved form of caspase-9, caspase-3 and PARP in the goniothalamin-treated HeLa cells in a time-dependent manner. Thus, goniothalamin may have induced apoptosis through the mitochondria-mediated pathway or intrinsic pathway in the HeLa cells. The activation of initiator caspase-8, which is a mediator of the death receptor-mediated pathway or extrinsic pathway, was observed in the present study; however, the active form of caspase-8 was not detected (data not shown). In a previous report by Petsoponsakul *et al* (11), it was shown that goniothalamin increased the activation of caspase-8 in human leukemic HL-60 cells, but not in human leukemic U937 cells. Thus, whether goniothalamin induced apoptosis through the intrinsic or extrinsic pathway was dependent on the specific cell type.

The present study also investigated the ER stress-associated mitochondrial-mediated apoptosis signaling pathway. Generally, the ER stress response of cells depends on its severity. The ER chaperone, GRP78, usually binds to the transmembrane ER proteins, including PERK, ATF6 and IRE1 α , preventing their activation by dimerization or polymerization. However, when unfolded proteins accumulate in the ER, GRP78 is released from transmembrane ER proteins to target the accumulated unfolded protein, and these transmembrane ER proteins are then activated by dimerization or polymerization to initiate the UPR. In initial or mild ER stress, the UPR is triggered to recover homeostasis in ER and reestablish ER function. Prolonged or severe ER stress triggers ER stress-induced apoptosis (12,13). One ER stress-associated mitochondrial-mediated apoptosis signaling pathway is the cascade of IRE1 α $\rightarrow$ spliced XBP1 $\rightarrow$ JNK $\rightarrow$ loss of mitochondrial membrane activation (16,44). The activated IRE1 α has ribonuclease and kinase activities, and one signaling pathway of IRE1 α activation is to promote the mRNA splicing of XBP1 via its ribonuclease activity. The spliced XBP1 mRNA is translated to spliced XBP1 protein, an active transcription factor, which regulates the transcription of several UPR genes, including ER chaperones and genes encoding the components of ER-associated degradation, including

ERdj4 (45). Another signaling pathway of IRE1 α activation is the activation of JNK via phosphorylation, resulting in the JNK-mediated apoptotic pathway (46,47). The JNK mediator is one of the MAPK signaling molecules, which is critical in the determination of cell fate between proliferation and death. Several studies have reported that the mechanisms underlying the induction of apoptosis in cancer cells by anticancer agents are regulated through the MAPK signaling pathway (17,18,48). Another ER stress-mediated apoptosis signaling pathway is the activation of PERK. Activated PERK signaling leads to the increase translation of specific mRNAs, including ATF4, which is a transcription factor for pro-apoptotic CHOP and GADD34 proteins, resulting in the initiation of apoptosis signaling (49).

To the best of our knowledge, the present study was the first to demonstrate that ER stress- and MAPK signaling-associated apoptosis were activated in goniiothalamine-treated HeLa cells. The results showed that goniiothalamine induced the mRNA splicing of XBP1 (Fig. 5B). The ratio of spliced:unspliced XBP1 increased following goniiothalamine treatment for 12 h. In addition, goniiothalamine treatment upregulated the mRNA expression levels of ER stress-associated genes, including CHOP, ERdj4 and GADD34. However, GRP78 did not respond to goniiothalamine treatment at either the mRNA or protein levels, although other evidence supported that goniiothalamine treatment induced ER stress in the HeLa cells (Fig. 5A and C). These findings suggested that goniiothalamine may induce ER stress in HeLa cells by a different mechanism to that observed in several other ER stress inducers, including tunicamycin, thapsigargin and brefeldin A (50). Furthermore, the present study found the MAPK pathway, was activated, particularly through JNK phosphorylation, as were associated apoptosis-associated events downstream of this activation, including the phosphorylation of Bcl2, triggering the loss of mitochondrial membrane potential. These results corresponded with the IRE1 α activation pathway (51). The results of the present study are the first, to the best of our knowledge, to show that goniiothalamine triggered the ER stress-associated activation of IRE1 α , and activated JNK through phosphorylation associated with the mitochondria-mediated induction of apoptosis.

In conclusion, although goniiothalamine-induced apoptosis in the HeLa cell line has been previously reported, as mentioned above, the present study is the first, to the best of our knowledge, to show that the induction of apoptosis in the HeLa cell line by goniiothalamine was associated with the ER stress-induced activation of JNK. The effect of goniiothalamine on the ER stress-induced activation of JNK may be useful for further investigations of the drug action of styryl-lactone compounds, and suggests a potential candidate for preventive and therapeutic applications in the treatment of cervical cancer.

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