Introduction

Pharmacological studies of ginseng have identified the ginsenosides as the plant’s principal active components [1]. Over 40 ginsenosides have been identified; each ginsenoside shows different biological activities based on structural differences. The ginsenosides Rb1 (G-Rb1), one of the most extensively studied of the ginsenosides, and they have been shown to have a variety of biological activities, including anti-inflammatory and anti-allergic activities [2]. However, the anti-arthritis and anti-apoptotic effects of G-Rb1 have not been reported.

Osteoarthritis (OA) is a degenerative joint disease that is principally characterized by the erosion of articular cartilage, meniscus damage, low-grade synovitis, bone remodeling, sclerosis of the subchondral bone and osteophyte formation in some cases [3]. OA occurs as the result of a variety of factors, such as aging, mechanical stress and obesity, and alters the physiological and biomechanical environment of the knee [4,5]. It has been relatively well demonstrated that cartilage matrix degradation and chondrocyte apoptosis induced by certain proteases (including matrix metalloproteinases, collagenases, and aggrecanases) and apoptotic factors (such as cytochome c, Bax and caspases) are the two primary pathogenic events occurring in OA [4,5].

Hydrogen peroxide (H2O2) is formed from a superoxide anion through superoxide dismutase. H2O2 has
a variety of biological effects on various cell types. 

H2O2, which produces reactive oxygen species (ROS), is closely associated with the induction of chondrocyte apoptosis in vivo [6] and in vitro [7]. The prevention of chondrocyte apoptosis can therefore be considered to contribute to the control of the progression of OA. H2O2 alters mitochondrial membrane permeability, which allows for the release of cytochrome c into the cytoplasm [8]. Additionally, caspase-3 is one of the key mediators in apoptotic signaling pathways, and the activation of caspase-3 ultimately results in cellular apoptosis [8].

G-Rb1 has garnered a great deal of research interest, and it has been shown to exert protection effects with anti-inflammatory agents [9,10]. The results of previous studies have also demonstrated that G-Rb1 may function as a scavenger of toxic species, such as H2O2 [6,11]. The principal objective of the present study, therefore, was to determine whether G-Rb1 treatment results in the inhibition of both the mitochondrial permeability transition (MPT) and caspase-3 in H2O2-treated chondrocytes.

MATERIALS AND METHODS

Harvesting chondrocytes and establishing cell cultures

A modified method for harvesting chondrocytes was conducted as described previously [5]. In brief, chondrocytes were isolated from the articular cartilage of three week-old male Sprague-Dawley rats. The cartilage was removed from animals that were subsequently euthanized via an overdose of anesthesia. The cartilage was cut into thin slices, washed with sterile phosphate-buffered saline (PBS) and soaked for 15 min in 5% penicillin–streptomycin–neomycin (Sigma, St. Louis, MO, USA). The cartilage slices were washed in PBS to remove residual antibiotic solution and then digested with 0.02% collagenase type II (Sigma) in Dulbecco’s modified Eagle’s medium (DMEM; HyClone, Logan, UT, USA) for 3 h in a water bath at 37°C. The digested cartilage was collected and centrifuged. The pellet was resuspended in DMEM and filtered through a 70-μM nylon mesh. The resulting chondrocytes were cultured in DMEM supplemented with 10% fetal bovine serum and 1% penicillin–streptomycin–neomycin in a 5% CO2 incubator at 37°C. All of the experiments were conducted when the cells reached confluence within the first passage with G-Rb1 purchased from the Ambo Institute (Daejeon, Korea)

Cell viability assay

Cell survival was determined using a 3-(4,5-dimeth-

ylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay kit from Sigma. The chondrocytes were replated in 48-well plates at a density of 1.0×104 cells per well, incubated for 24 h, and treated with various concentrations (25 to 400 μM) of G-Rb1 (Ambo Institute) for 24 h. We then determined whether 1 h of pretreatment with G-Rb1 (50 and 100 μM) affected the cell viability of chondrocytes treated with 500 μM H2O2 for 24 h. After the incubation period, 10 μL of the kit solution was added to each well and incubated for 3 h at 37°C in 5% CO2. After this treatment, the chondrocytes were incubated with MTT for 2 h at 37°C. The resulting formazan crystals were subsequently dissolved in MTT solubilization solution. The absorbance was determined at 540 nm using a microplate reader.

Mitochondrial permeability transition analysis

Chondrocytes were replated at 2×104 cells in 4-well chamber slides (Nunc, New York, NY, USA). After an overnight incubation under standard tissue culture conditions, the chondrocytes were exposed to 500 μM H2O2 with or without G-Rb1 (100 μM) and C3 (caspase-3 inhibitor). After 2 h, the cells were labeled with Mitotracker Red CMXRos (Invitrogen, Eugene, OR, USA) for 15 min. The cells were washed with PBS, and fluorescence microscopy was conducted using the appropriate filters.

Western blotting

Total proteins from chondrocyte lysates were subjected to sodium dodecyl sulfate polyacrylamide gel electrophoresis using 12% to 15% gels and electrophoretically transferred to polyvinylidene difluoride membranes (Bio-Rad Laboratories, Hercules, CA, USA). The membranes were blocked in 5% skim milk in PBS and then incubated with primary antibodies against Bcl-xL (Cell Signaling, Danvers, MA, USA), Bax (Santa Cruz Biotechnology, Santa Cruz, CA, USA) and β-actin (Cell Signaling) diluted 1:500 in 1% skim milk in PBS overnight at 4°C. The blots were then incubated with peroxidase-conjugated goat anti-rabbit IgG (1:5,000; Millipore, Bedford, MA, USA) for 1 h. The immunoreactions were visualized with SuperSignal West Dura Extended Duration Substrate (Thermo Scientific, San Jose, CA, USA) and analyzed using a chemilumager analyzer system (Alpha Innotech, San Leandro, CA, USA).

Caspase-3 activity analysis

Caspase-3 activation was assessed using Caspase-Glo3/7 Assays (Promega, Madison, WI, USA) as an index of apoptosis. The chondrocytes were replated at
onto 48-well plates. After 24 h of incubation, the chondrocytes were exposed to 500 μM H2O2 with or without G-Rb1 (100 μM) and C3 (caspase-3 inhibitor). After this treatment, 60 μL of supernatant was transferred from each well to a new 96-well plate. Equal volumes of Caspase-Glo 3/7 reagents were added, and the plate was incubated for 1 h at room temperature before the luminescence was measured.

**Cell apoptosis analysis with immunocytochemistry**

The chondrocytes were replated at 5×10^4 in 4-well chamber slides (Nunc). After 24 h of incubation, the chondrocytes were exposed to 500 μM H2O2 with or without G-Rb1 (100 μM) and C3 (caspase-3 inhibitor). After 12 h, the cells were labeled with Hoechst (Invitrogen) and propidium iodine for 15 min. The cells were washed with PBS and then analyzed with fluorescence microscopy using the appropriate filters.

**Statistical analysis**

The data are expressed as the means±SD. The data were analyzed via Student’s t-test and a repeated measures ANOVA followed by a Bonferroni test. A p-value of less than 0.05 was considered significant.

**RESULTS**

**Cell viability**

MTT assays were conducted to determine the effects of G-Rb1 on cell viability in relation to the mitochondrial activity of H2O2-treated chondrocytes. The chondrocytes exposed to G-Rb1 at various concentrations (0 to 400 μM) showed no significant toxicity for 24 h as previously reported [12]. The percentage of cell viability was approximately 60% after 24 h of treatment with 500 μM H2O2. As shown in Fig. 1, 1 h of pretreatment with G-Rb1 (100 μM) prior to 24 h of incubation with H2O2 (500 μM) produced higher cell viability (approximately 93%, p<0.05) than H2O2 alone. Therefore, all of the subsequent experiments were conducted in chondrocytes that were pretreated for 1 h with 50 or 100 μM G-Rb1. Fig. 1. Cell viability of ginsenosides Rb1 (G-Rb1) in native chondrocytes and hydrogen peroxide (H2O2)-treated chondrocytes. Culture medium pretreated for 1 h with G-Rb1 (50 to 400 μM) and incubated with 500 μM H2O2 for 24 h. After incubation, cell viability was assessed by the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide analysis and expressed as a percentage of viable untreated control cells grown in a defined medium. Data are expressed as the means ± SD of four to six independent experiments. Statistical analysis: *p<0.05 vs. positive control (H2O2 alone treatment).

1.0×10^4 onto 48-well plates. After 24 h of incubation, the chondrocytes were exposed to 500 μM H2O2 with or without G-Rb1 (100 μM) and C3 (caspase-3 inhibitor). After this treatment, 60 μL of supernatant was transferred from each well to a new 96-well plate. Equal volumes of Caspase-Glo 3/7 reagents were added, and the plate was incubated for 1 h at room temperature before the luminescence was measured.

**Statistical analysis**

The data are expressed as the means±SD. The data were analyzed via Student’s t-test and a repeated measures ANOVA followed by a Bonferroni test. A p-value of less than 0.05 was considered significant.

**RESULTS**

**Cell viability**

MTT assays were conducted to determine the effects of G-Rb1 on cell viability in relation to the mitochondrial activity of H2O2-treated chondrocytes. The chondrocytes exposed to G-Rb1 at various concentrations (0 to 400 μM) showed no significant toxicity for 24 h as previously reported [12]. The percentage of cell viability was approximately 60% after 24 h of treatment with 500 μM H2O2. As shown in Fig. 1, 1 h of pretreatment with G-Rb1 (100 μM) prior to 24 h of incubation with H2O2 (500 μM) produced higher cell viability (approximately 93%, p<0.05) than H2O2 alone. Therefore, all of the subsequent experiments were conducted in chondrocytes that were pretreated for 1 h with 50 or 100 μM G-Rb1. Fig. 1. Cell viability of ginsenosides Rb1 (G-Rb1) in native chondrocytes and hydrogen peroxide (H2O2)-treated chondrocytes. Culture medium pretreated for 1 h with G-Rb1 (50 to 400 μM) and incubated with 500 μM H2O2 for 24 h. After incubation, cell viability was assessed by the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide analysis and expressed as a percentage of viable untreated control cells grown in a defined medium. Data are expressed as the means ± SD of four to six independent experiments. Statistical analysis: *p<0.05 vs. positive control (H2O2 alone treatment).

**Cell apoptosis analysis with immunocytochemistry**

The chondrocytes were replated at 5×10^4 in 4-well chamber slides (Nunc). After 24 h of incubation, the chondrocytes were exposed to 500 μM H2O2 with or without G-Rb1 (100 μM) and C3 (caspase-3 inhibitor). After 12 h, the cells were labeled with Hoechst (Invitrogen) and propidium iodine for 15 min. The cells were washed with PBS and then analyzed with fluorescence microscopy using the appropriate filters.

**Statistical analysis**

The data are expressed as the means±SD. The data were analyzed via Student’s t-test and a repeated measures ANOVA followed by a Bonferroni test. A p-value of less than 0.05 was considered significant.

**RESULTS**

**Cell viability**

MTT assays were conducted to determine the effects of G-Rb1 on cell viability in relation to the mitochondrial activity of H2O2-treated chondrocytes. The chondrocytes exposed to G-Rb1 at various concentrations (0 to 400 μM) showed no significant toxicity for 24 h as previously reported [12]. The percentage of cell viability was approximately 60% after 24 h of treatment with 500 μM H2O2. As shown in Fig. 1, 1 h of pretreatment with G-Rb1 (100 μM) prior to 24 h of incubation with H2O2 (500 μM) produced higher cell viability (approximately 93%, p<0.05) than H2O2 alone. Therefore, all of the subsequent experiments were conducted in chondrocytes that were pretreated for 1 h with 50 or 100 μM G-Rb1.

**Statistical analysis**

The data are expressed as the means±SD. The data were analyzed via Student’s t-test and a repeated measures ANOVA followed by a Bonferroni test. A p-value of less than 0.05 was considered significant.

**RESULTS**

**Cell viability**

MTT assays were conducted to determine the effects of G-Rb1 on cell viability in relation to the mitochondrial activity of H2O2-treated chondrocytes. The chondrocytes exposed to G-Rb1 at various concentrations (0 to 400 μM) showed no significant toxicity for 24 h as previously reported [12]. The percentage of cell viability was approximately 60% after 24 h of treatment with 500 μM H2O2. As shown in Fig. 1, 1 h of pretreatment with G-Rb1 (100 μM) prior to 24 h of incubation with H2O2 (500 μM) produced higher cell viability (approximately 93%, p<0.05) than H2O2 alone. Therefore, all of the subsequent experiments were conducted in chondrocytes that were pretreated for 1 h with 50 or 100 μM G-Rb1.

**Statistical analysis**

The data are expressed as the means±SD. The data were analyzed via Student’s t-test and a repeated measures ANOVA followed by a Bonferroni test. A p-value of less than 0.05 was considered significant.

**RESULTS**

**Cell viability**

MTT assays were conducted to determine the effects of G-Rb1 on cell viability in relation to the mitochondrial activity of H2O2-treated chondrocytes. The chondrocytes exposed to G-Rb1 at various concentrations (0 to 400 μM) showed no significant toxicity for 24 h as previously reported [12]. The percentage of cell viability was approximately 60% after 24 h of treatment with 500 μM H2O2. As shown in Fig. 1, 1 h of pretreatment with G-Rb1 (100 μM) prior to 24 h of incubation with H2O2 (500 μM) produced higher cell viability (approximately 93%, p<0.05) than H2O2 alone. Therefore, all of the subsequent experiments were conducted in chondrocytes that were pretreated for 1 h with 50 or 100 μM G-Rb1.

**Statistical analysis**

The data are expressed as the means±SD. The data were analyzed via Student’s t-test and a repeated measures ANOVA followed by a Bonferroni test. A p-value of less than 0.05 was considered significant.

**RESULTS**

**Cell viability**

MTT assays were conducted to determine the effects of G-Rb1 on cell viability in relation to the mitochondrial activity of H2O2-treated chondrocytes. The chondrocytes exposed to G-Rb1 at various concentrations (0 to 400 μM) showed no significant toxicity for 24 h as previously reported [12]. The percentage of cell viability was approximately 60% after 24 h of treatment with 500 μM H2O2. As shown in Fig. 1, 1 h of pretreatment with G-Rb1 (100 μM) prior to 24 h of incubation with H2O2 (500 μM) produced higher cell viability (approximately 93%, p<0.05) than H2O2 alone. Therefore, all of the subsequent experiments were conducted in chondrocytes that were pretreated for 1 h with 50 or 100 μM G-Rb1.

**Statistical analysis**

The data are expressed as the means±SD. The data were analyzed via Student’s t-test and a repeated measures ANOVA followed by a Bonferroni test. A p-value of less than 0.05 was considered significant.
followed by 24 h of treatment with 500 μM H₂O₂.

**Mitochondrial permeability transition analysis**

MPT leads to apoptosis in various cells after oxidative stress. To determine whether MPT was a requirement for H₂O₂-induced chondrocyte apoptosis, we conducted MPT analyses. Chondrocytes pretreated with G-Rb₁ (100 μM) and C3 (50 μM) prior to treatment with H₂O₂ (500 μM) were stained with Mitotracker Red CMXRos. The results showed that MPT was inhibited, and the mitochondrial membrane potential was maintained (Fig. 2).

**Western blot analysis of Bcl-xL and Bax expression**

To assess the correlation of apoptotic proteins with MPT, Bcl-xL and Bax expression levels were detected. The expression of the pro-apoptotic protein Bax was higher in the H₂O₂-treated cells than the control cells ($p<0.05$), whereas the expression of the anti-apoptotic protein Bcl-xL was significantly lower in the H₂O₂-treated cells. However, after co-treatment with G-Rb₁ and C3, Bax expression was significantly lower and Bcl-xL expression was higher compared with H₂O₂ treatment alone ($p<0.05$) (Fig. 3).

**Caspase-3 activity**

To assess the effect of H₂O₂ and G-Rb₁ on caspase-3 activity, caspase-Glo assays were conducted. Caspase-3 activity was significantly induced by H₂O₂ and was significantly suppressed by G-Rb₁ and C3. Data were expressed as the mean±SD of four independent experiments. Statistical analysis: **$p<0.01$ vs. positive control (H₂O₂ alone treatment). CON, negative control.**
activity was increased by the addition of H$_2$O$_2$. However, G-Rb$_1$ significantly suppressed the H$_2$O$_2$-induced activation of caspase-3 in a dose-dependent manner, similar to C3 (Fig. 4).

**DISCUSSION**

Ginsenosides are unique saponins that exist only in ginseng, and they have a variety of pharmacological effects, such as anticancer activities [10]. The results of the present study demonstrated that Rb$_1$, one of the principal active ingredients in ginseng, can protect chondrocytes against H$_2$O$_2$-induced apoptotic insults. Thus, we demonstrated that in vitro treatment with G-Rb$_1$ exerted protective effects against H$_2$O$_2$-induced cytotoxicity in rat articular chondrocytes (Fig. 1).

ROS are generated during metabolic processes and perform several biological functions. However, excessive oxidative stress causes cellular damage to DNA, lipids, and proteins [13,14]. H$_2$O$_2$ results in direct injury to the cartilage matrix by inhibiting proteoglycan synthesis in the chondrocytes. We analyzed the effects of G-Rb$_1$ on mitochondrial stability and caspase activation. MPT caused by ROS is dependent on non-selective inner membrane permeabilization that may precede actual apoptotic cell death [14,15]. Our results demonstrated that G-Rb$_1$ had strong MPT inhibition effects similar to C3, the caspase-3 inhibitor, in H$_2$O$_2$-treated chondrocytes (Fig. 2). Additionally, the expression of the anti-apoptotic protein Bcl-xL was increased in H$_2$O$_2$-treated chondrocytes after G-Rb$_1$ treatment (Fig. 3). Bcl-xL is a potent cell death inhibitor, and its expression prevents cell death. Conversely, the reduced level of the apoptotic protein Bax induced by G-Rb$_1$ treatment is consistent with the inhibition of MPT. The ratio between the two subsets helps to determine, in part, the susceptibility of cells to a death signal. These proteins regulate the apoptotic process principally via the mitochondrial pathway, which is activated via the activation of major apoptotic executioner caspases resulting from the release of cytochrome c from the mitochondria [8]. Therefore, the apoptotic cells observed in H$_2$O$_2$-treated chondrocytes (Fig. 5) most likely depend on variations in the balance between Bax and Bcl-xL. Some recent reports have demonstrated the ability of caspase inhibitors to attenuate chondrocyte apoptosis while maintaining cell functionality [11]. Although apoptosis can occur independently of caspase involvement in some cell types [16,17], all of the existing data indicate that caspase activation is a prerequisite for chondrocyte apoptosis. In particular, caspase-3 is a critical mediator of apoptosis in many cell types, including chondrocytes. Caspase-3 activity in cultured chondrocytes was increased after H$_2$O$_2$ exposure (Fig. 4). These findings clearly demonstrate that caspase-3 activation is a necessary step in the cascade of cellular events that leads

**Immunocytochemistry**

In the chondrocytes treated with H$_2$O$_2$, prominent positively stained cells were observed. In contrast, few positively stained cells were observed in the chondrocytes pretreated with G-Rb$_1$ (100 μM) and C$_3$ (50 μM) prior to treatment with H$_2$O$_2$ (500 μM). G-Rb$_1$ was shown to reduce the H$_2$O$_2$-induced apoptosis of chondrocytes (Fig. 5). The untreated controls showed a similar appearance to cells treated with H$_2$O$_2$ plus G-Rb$_1$ and C3.

![Fig. 5. Anti-apoptotic effect of ginsenosides Rb$_1$ (G-Rb$_1$) in hydrogen peroxide (H$_2$O$_2$)-treated chondrocytes. Chondrocytes were treated with media alone (negative control), H$_2$O$_2$ (500 μM, positive control) and H$_2$O$_2$ (500 μM) after pretreatment with G-Rb$_1$ (100 μM) and C$_3$ (50 μM, caspase-3 inhibitor). The chondrocytes were labeled with the potential sensitive dye Hoechst and propidium iodide staining solution. Immunocytochemistry confirmed via fluorescence microscopy (×10). CON, negative control; PI, propidium iodine.]
to chondrocyte apoptosis after exposure to H$_2$O$_2$. Our results showed that H$_2$O$_2$-elicited caspase-3 activity was significantly suppressed by G-Rb$_1$, (Fig. 4). This result is consistent with our observation that MPT inhibition and Bcl-xL are increased by G-Rb$_1$ treatment.

In our assays, the cytoprotective effects of G-Rb$_1$ were evaluated on H$_2$O$_2$-stimulated chondrocytes. By detecting mitochondrial stabilization and the inhibition of caspase-3 activity, we showed the protective function of G-Rb$_1$ in articular chondrocyte death induced by H$_2$O$_2$. This result is consistent with recent studies indicating that Bcl-2 family members interfere with the activation of caspases [18], regulate the mitochondrial membrane potential, and inhibit the accumulation of cytochrome c in the cytosol [19]. Bcl-xL has been reported to maintain cell viability after the activation of caspases [20]. In conclusion, the results of this study demonstrated the protective effect of G-Rb$_1$ with anti-apoptotic effects in chondrocytes and suggested that G-Rb$_1$ might prove useful as a novel preventive agent against H$_2$O$_2$-induced cytotoxicity.

REFERENCES

20. Boise LH, Thompson CB. Bel-x(L) can inhibit apoptosis in cells that have undergone Fas-induced protease activation. Proc Natl Acad Sci U S A 1997;94:3759-3764.