



# Triptolide, histone acetyltransferase inhibitor, suppresses growth and chemosensitizes leukemic cells through inhibition of gene expression regulated by TNF-TNFR1-TRADD-TRAF2-NIK-TAK1-IKK pathway

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## ABSTRACT

Triptolide, a diterpene triepoxide, from the Chinese herb *Tripterygium wilfordii* Hook.f, exerts its anti-inflammatory and immunosuppressive activities by inhibiting the transcription factor nuclear factor- $\kappa$ B (NF- $\kappa$ B) pathway, through a mechanism not yet fully understood. We found that triptolide, in nanomolar concentrations, suppressed both constitutive and inducible NF- $\kappa$ B activation, but did not directly inhibit binding of p65 to the DNA. The diterpene did block TNF-induced ubiquitination, phosphorylation, and degradation of I $\kappa$ B $\alpha$ , the inhibitor of NF- $\kappa$ B and inhibited acetylation of p65 through suppression of binding of p65 to CBP/p300. Triptolide also inhibited the I $\kappa$ B $\alpha$  kinase (IKK) that activates NF- $\kappa$ B and phosphorylation of p65 at serine 276, 536. Furthermore, the NF- $\kappa$ B reporter activity induced by TNF-TNFR1-TRADD-TRAF2-NIK-TAK1-IKK $\beta$  was abolished by the triepoxide. Triptolide also abrogated TNF-induced expression of cell survival proteins (XIAP, Bcl-x<sub>L</sub>, Bcl-2, survivin, cIAP-1 and cIAP-2), cell proliferative proteins (cyclin D1, c-myc and cyclooxygenase-2), and metastasis proteins (ICAM-1 and MMP-9). This led to enhancement of apoptosis induced by TNF, taxol, and thalidomide by the diterpene and to suppression of tumor invasion. Overall, our results demonstrate that triptolide can block the inflammatory pathway activated by TNF-TNFR1-TRADD-TRAF2-NIK-TAK1-IKK, sensitizes cells to apoptosis, and inhibits invasion of tumor cells.

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## 1. Introduction

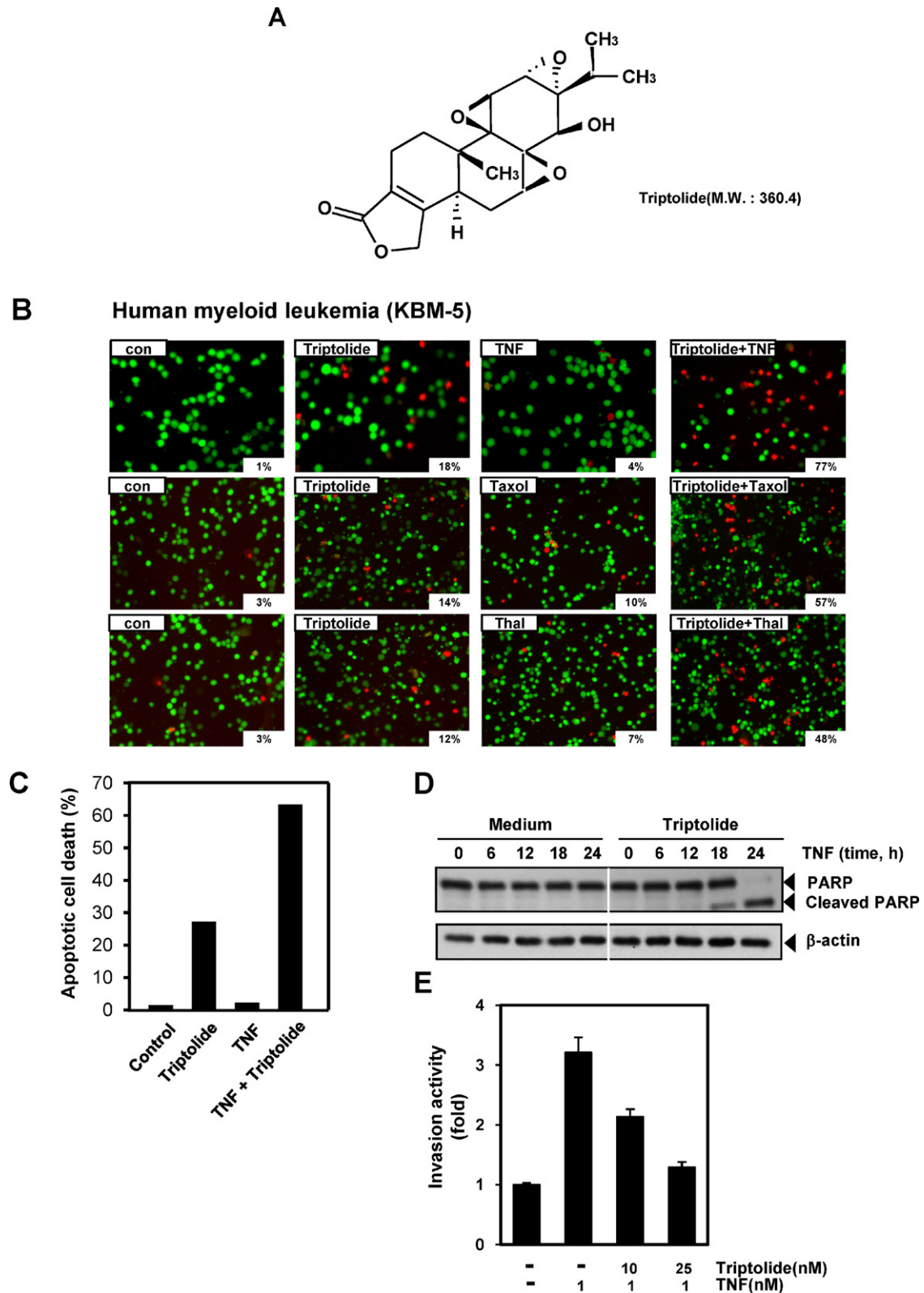
Traditional medicines that have been used for thousands of years are still being used by a majority of the people of the world even today. Their persistence can be attributed, at least in part, to the problems with modern drugs used in allopathic medicine: these drugs are, with some exceptions, highly toxic, expensive, and mono-targeted for specific disease [1,2]. Mono-targeted or “smart” drugs and single chemical entities are unlikely to succeed against diseases as complex as cancer, especially given that around 25,431 human genes, out of which 2995 genes have been linked with 153 different pathways, and about 350 genes have been linked with any given cancer. Thus cancer, like most diseases exhibits a dysregulation of multiple targets [1] and so drugs that have many targets are needed. In fact most of the drugs recently approved by the FDA are multi-targeted, including sunitinib, sorafenib, and vandetanib, those were once thought to be “dirty”. Traditional medicines are usually safe, naturally multi-targeted and are affordable. Therefore, identification of active components in

natural products and the delineation of the cell signaling pathway they modulate can validate their use in various diseases.

Triptolide, a diterpenoid isolated from the Chinese herb *Tripterygium wilfordii* Hook.f (Fig. 1A), a member of the Celastraceae family of plants, has been used for centuries as anti-inflammatory and immunosuppressive agent including treatment of rheumatoid arthritis [3]. Various studies have also indicated that it exhibits antitumor activities as indicated by suppression of cell growth and induction of apoptosis in a broad range of human cancer cells [4,5]. In addition, triptolide inhibited experimental metastasis in a nude mouse model [6] and sensitized tumors to radiation [7]. How diterpene mediates these effects is not fully understood, but downregulation of various targets such as XIAP [8], COX-2 [9], iNOS [10], uPAR [11], CCR7 [12], and upregulation of death receptor-5 (DR-5) [13], p53 [14], and HSP-70 [15] have all been implicated. Recent studies also showed the role of inhibition of heat shock response [16], JAK/STAT3 [17], bcr-abl [18] and RNA polymerase I and II [19] in the action of triptolide. Thus triptolide is highly multi-targeted. Several of the targets modulated by triptolide are regulated by the transcription factor NF- $\kappa$ B either directly or indirectly. Although triptolide is known to inhibit NF- $\kappa$ B activation induced by various agents including TNF [20], LPS [21] and PMA [11], how these agents inhibit the NF- $\kappa$ B activation pathway is poorly understood.

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**Fig. 1.** Triptolide enhances TNF-induced apoptosis. (A) The chemical structure of triptolide. (B) KBM-5 cells were pretreated with 25 nM triptolide for 6 h and then incubated with 1 nM TNF, 5 nM taxol and 10  $\mu$ g/mL thalidomide for 24 h. The cells were stained with a LIVE/DEAD assay reagent for 30 min and then analyzed under a fluorescence microscope as described under Section 2. The results shown are representative of three independent experiments. (C) Cells were pretreated with 25 nM triptolide for 6 h and then incubated with 1 nM TNF for 24 h. Cells were fixed, stained with TUNEL assay reagent, and then analyzed by flow cytometry for apoptotic effects. (D) Cells were pretreated with 25 nM triptolide for 6 h and then incubated with 1 nM TNF for the indicated times. Whole-cell extracts were prepared and analyzed by Western blotting using an anti-PARP antibody. The results shown are representative of three independent experiments. Equal protein loading was evaluated by  $\beta$ -actin. (E) H1299 cells ( $2.5 \times 10^4$ ) were seeded into the top chamber of a Matrigel invasion chamber system overnight in the absence of serum and then treated with the indicated concentrations of triptolide for 6 h. After incubation, the cells were treated with 1 nM TNF for 24 h in the presence of 1% serum and then assayed for invasion as described in Section 2. Results are expressed as fold activity of the untreated control.

In the current report, we investigated the mechanism by which triptolide inhibits the TNF-induced NF- $\kappa$ B activation pathway. We also investigated the effect of this triepoxide on the expression of various proteins linked to survival, proliferation, inflammation, invasion, and metastasis. Lastly, we investigated whether triptolide can sensitize tumor cells to cytokines and chemotherapeutic agents and modulate invasion.

## 2. Materials and methods

### 2.1. Materials

Triptolide was purchased from ENZO life sciences. A 10 mM solution of triptolide was prepared in 100% dimethyl sulfoxide, stored as small aliquots at  $-20^{\circ}\text{C}$ , and then diluted as needed in cell culture medium. Bacteria-derived recombinant human TNF, purified to homogeneity with a specific activity of  $5 \times 10^7$  U/mg, was kindly provided by Genentech (South San Francisco, CA). Tris, glycine, NaCl, sodium dodecyl sulfate, and bovine serum albumin were purchased from Sigma–Aldrich (St. Louis, MO). Penicillin, streptomycin, Iscove's modified Dulbecco's medium (IMDM), Dulbecco's modified Eagle's medium, RPMI 1640 and fetal bovine serum were obtained from Invitrogen (Carlsbad, CA). Phorbol 12-myristate 13-acetate (PMA), okadaic acid (OA), lipopolysaccharide (LPS), and anti- $\beta$ -actin antibody were purchased from Sigma–Aldrich (St. Louis, MO). The cigarette smoke condensed (CSC) was prepared from the University of Kentucky Reference Cigarette 1R4F (9 mg tar and 0.8 mg nicotine/cigarette). Antibodies against p65, COX-2, I $\kappa$ B $\alpha$ , ICAM-1, c-Myc, cyclin D1, MMP-9, PARP, cIAP-1/2, Bcl-2, and Bcl-x<sub>L</sub> were obtained from Santa Cruz Biotechnology (Santa Cruz, CA). Anti-XIAP antibody was obtained from BD Biosciences (San Jose, CA). Phospho-specific anti-I $\kappa$ B $\alpha$  (serine 32/36), anti-survivin, acetylated-lysine (Ac-K-103), and phospho-specific anti-p65 (serine 276 and 536) antibodies were purchased from Cell Signaling Technology Inc. (Danvers, MA). Anti-IKK- $\alpha$ , anti-IKK- $\beta$  antibodies were kindly provided by Imgenex (San Diego, CA).

### 2.2. Cell lines

Human embryonic kidney A293 cells, human multiple myeloma (RPMI-8226) cells, human T cell leukemia (Jurkat), human lung adenocarcinoma H1299 cells, and human myeloid KBM-5 cells were obtained from the American Type Culture Collection (Manassas, VA). KBM-5 cells were cultured in IMDM supplemented with 15% fetal bovine serum, and A293 cells were cultured in Dulbecco's modified Eagle's medium supplemented with 10% fetal bovine serum. RPMI-8226 cells, H1299 cells, and Jurkat cells were cultured in RPMI 1640 medium supplemented with 10% fetal bovine serum. The mouse embryonic fibroblast (MEF) derived from p65<sup>-/-</sup>C57BL/6J mice and its wild type were kindly provided by Dr. David Baltimore (California Institute of Technology, Pasadena, CA). All media were also supplemented with 100 U/mL penicillin and 100  $\mu\text{g}/\text{mL}$  streptomycin.

### 2.3. Live/dead assay

To measure apoptosis, we used the LIVE/DEAD cell vitality assay kit (Invitrogen), which determines intracellular esterase activity and plasma membrane integrity. We performed this assay as described previously [22]. In brief,  $1 \times 10^5$  cells were incubated with 25 nM triptolide for 6 h and then treated with 1 nM TNF for 24 h at  $37^{\circ}\text{C}$ . Cells were stained with the LIVE/DEAD reagent (5  $\mu\text{M}$  ethidium homodimer and 5  $\mu\text{M}$  calcein-acetoxymethyl ester) and then incubated at  $37^{\circ}\text{C}$  for 30 min. Cells were analyzed under a fluorescence microscope (Labophot-2; Nikon, Tokyo, Japan).

### 2.4. Invasion assay

The membrane invasion culture system was used to assess cell invasion, because invasion through the extracellular matrix is a crucial step in tumor metastasis. The BD BioCoat tumor invasion system is a chamber that has a light-tight polyethylene terephthalate membrane with 8  $\mu\text{m}$  pores and is coated with a reconstituted basement membrane gel (BD Biosciences). A total of  $2.5 \times 10^4$  H1299 cells were suspended in serum-free medium and seeded into the upper wells. After incubation overnight, cells were treated with triptolide and then stimulated with TNF in the presence of 1% fetal bovine serum and triptolide. The cells that invaded through the Matrigel (those that migrated to the lower chamber during incubation) were stained with 4  $\mu\text{g}/\text{mL}$  calcein-AM (Invitrogen) in PBS for 30 min at  $37^{\circ}\text{C}$  and scanned for fluorescence with a Victor 3 multiplate reader (Perkin-Elmer Life and Analytical Sciences); fluorescent cells were counted.

### 2.5. TUNEL assay

We also assayed cytotoxicity by the terminal deoxynucleotidyl transferase-mediated deoxyuridine triphosphate nick end-labeling (TUNEL) method, which examines DNA strand breaks during apoptosis, using the Roche Applied Science (Indianapolis, IN) in situ cell death detection reagent. Briefly,  $1.5 \times 10^6$  cells were incubated with 25 nM triptolide for 6 h and then treated with 1 nM TNF for 24 h at  $37^{\circ}\text{C}$ . Thereafter, cells were plated on a poly-L-lysine-coated glass slide by centrifugation using a Cytospin 4, air-dried, fixed with 4% paraformaldehyde, and permeabilized with 0.1% Triton X-100 in 0.1% sodium citrate. After being washed, cells were incubated with reaction mixture for 60 min at  $37^{\circ}\text{C}$ . Stained cells were mounted with mounting medium purchased from Sigma and analyzed under a fluorescence microscope (Labophot-2).

### 2.6. Electrophoretic mobility shift assay

To assess NF- $\kappa$ B activation, we performed EMSA as described previously. In brief, nuclear extracts prepared from TNF-treated cells ( $1 \times 10^6/\text{mL}$ ) were incubated with  $^{32}\text{P}$ -end-labeled 45-mer double-stranded NF- $\kappa$ B oligonucleotide (15  $\mu\text{g}$  of protein with 16 fmol of DNA) from the HIV long terminal repeat, 5'-TTGTTACAAGG-GACTTTCGCTGGGGACTTTCAGGGAGGCGTGG-3' (boldface indicates NF- $\kappa$ B-binding sites), for 30 min at  $37^{\circ}\text{C}$ , and the DNA-protein complex formed was separated from free oligonucleotide on 6.6% native polyacrylamide gels. A double-stranded mutated oligonucleotide, 5'-TTGTTACAAGTCACTTTCGCTGCTCACTTTCAGG-GAGGCGTGG-3', was used to examine the specificity of binding of NF- $\kappa$ B to the DNA. The specificity of binding was also examined by competition with the unlabeled oligonucleotide. The dried gels were visualized with a Storm 820 PhosphorImager, and radioactive bands were quantitated using ImageQuant software (GE Healthcare, Chalfont St. Giles, Buckinghamshire, UK).

### 2.7. Western blot analysis

To determine the levels of protein expression in the cytoplasm or nucleus, we prepared extracts and fractionated them by SDS-polyacrylamide gel electrophoresis (PAGE). After electrophoresis, the proteins were electrotransferred to nitrocellulose membranes, blotted with the relevant antibody, and detected by ECL reagent (GE Healthcare).

### 2.8. IKK assay

To determine the effect of triptolide on TNF-induced IKK activation, IKK assay was performed by a method we described

previously [22]. In brief, the IKK complex from whole-cell extracts was precipitated with antibody against IKK- $\alpha$  and then treated with protein A/G-agarose beads (Pierce, Rockford, IL). After 2 h, the beads were washed with lysis buffer and then resuspended in a kinase assay mixture containing 50 mM HEPES, pH 7.4, 20 mM  $\text{MgCl}_2$ , 2 mM dithiothreitol, 20  $\mu\text{Ci}$  of  $[\gamma\text{-}^{32}\text{P}]\text{ATP}$ , 10  $\mu\text{M}$  unlabeled ATP, and 2  $\mu\text{g}$  of substrate glutathione transferase-IkBa (amino acids 1–54). After incubation at 30 °C for 30 min, the reaction was terminated by boiling with SDS sample buffer for 5 min. Finally, the protein was resolved on 10% SDS-PAGE, the gel was dried, and the radioactive bands were visualized with a Storm820. To determine the total amounts of IKK- $\alpha$  and IKK- $\beta$  in each sample, 30  $\mu\text{g}$  of whole-cell protein was resolved on 7.5% SDS-PAGE, electrotransferred to a nitrocellulose membrane, and then blotted with either anti-IKK- $\alpha$  or anti-IKK- $\beta$  antibody.

### 2.9. NF- $\kappa$ B-dependent reporter gene expression assay

The effect of triptolide on NF- $\kappa$ B-dependent reporter gene transcription induced by TNF and various genes was analyzed by secretory alkaline phosphatase (SEAP) assay, with the following modification. In brief, A293 cells ( $5 \times 10^5$  cells/well) were plated in six-well plates and transiently transfected by the calcium phosphate method with pNF- $\kappa$ B-SEAP (0.5  $\mu\text{g}$ ). To examine TNF-induced reporter gene expression, we transfected the cells with 0.5  $\mu\text{g}$  of the SEAP expression plasmid and 2  $\mu\text{g}$  of the control plasmid pCMV-FLAG1 DNA for 24 h. We then treated the cells for 6 h with 25 nM triptolide and then stimulated them with 1 nM TNF. The cell culture medium was harvested after 24 h of TNF treatment. To examine reporter gene expression induced by various genes, we transfected A293 cells with 0.5  $\mu\text{g}$  of pNF- $\kappa$ B-SEAP plasmid with 1  $\mu\text{g}$  of an expressing plasmid and 0.5  $\mu\text{g}$  of the control plasmid pCMV-FLAG1 for 24 h, treated them with 25 nM triptolide and then harvested them from culture medium after an additional 24 h of incubation. Culture medium was analyzed for SEAP activity according to the protocol essentially as described by the manufacturer (Clontech, Mountain View, CA) using a Victor 3 microplate reader (PerkinElmer Life and Analytical Sciences).

## 3. Results

### 3.1. Triptolide potentiates the apoptotic effects of TNF, taxol, and thalidomide

Because the activation of NF- $\kappa$ B has been shown to inhibit apoptosis induced by TNF and chemotherapeutic agents, we investigated whether triptolide would modulate the apoptosis induced by TNF and chemotherapeutic agents [23–25]. As examined by the esterase-staining method (LIVE/DEAD assay), triptolide up-regulated TNF-induced apoptosis from 4% to 77% (Fig. 1B, upper). We also found that triptolide enhanced taxol-induced apoptosis from 10% to 57% (Fig. 1B, middle) and thalidomide-induced apoptosis from 7% to 48% (Fig. 1B, lower). Consistent with these results, TUNEL assay demonstrated that triptolide up-regulated TNF-induced early apoptosis (Fig. 1C). Caspase-mediated PARP cleavage likewise showed that triptolide enhanced the apoptotic effect of TNF substantially (Fig. 1D). All these results indicate that triptolide potentiates the apoptotic effects of TNF.

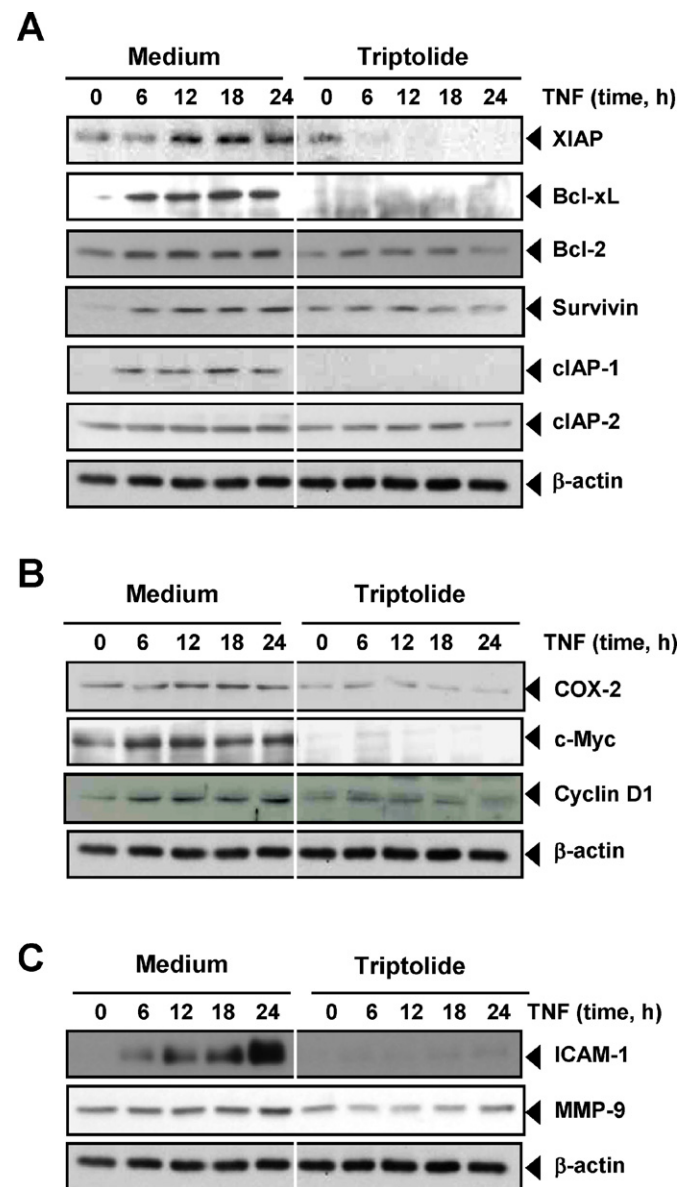
### 3.2. Triptolide suppresses TNF-induced tumor cell invasion activity

TNF can induce the expression of genes involved in tumor metastasis [26]. MMPs, COXs, and adhesion molecules regulated by NF- $\kappa$ B have been linked with tumor invasion [27]. So we

investigated whether triptolide modulates tumor cell invasion activity *in vitro*. Human lung adenocarcinoma H1299 cells, which have high invasive activity, were seeded into the top chamber of the Matrigel invasion chamber with TNF in the presence or absence of triptolide and their invasiveness was examined. The result showed that TNF induced tumor cell invasion by  $\sim 3.2$ -fold, but triptolide suppressed this activity in a dose-dependent manner (Fig. 1E).

### 3.3. Triptolide represses the expression of TNF-induced NF- $\kappa$ B dependent antiapoptotic gene products

We investigated whether potentiation of TNF-induced apoptosis by triptolide is mediated through the downregulation of antiapoptotic gene products. Western blot analysis showed that TNF induced these gene products in a time-dependent manner and



**Fig. 2.** Triptolide inhibits TNF-induced expression of NF- $\kappa$ B-dependent antiapoptotic, proliferative, and metastatic proteins. (A)–(C) KBM-5 cells were incubated with 25 nM triptolide for 6 h and then treated with 1 nM TNF for the indicated times. Whole-cell extracts were prepared and analyzed by Western blotting using the indicated antibodies. The results shown are representative of three independent experiments. Equal protein loading was evaluated by  $\beta$ -actin.



that triptolide suppressed it (Fig. 2A). Thus, the enhancement of apoptosis by triptolide could be due to downregulation of these antiapoptotic proteins.

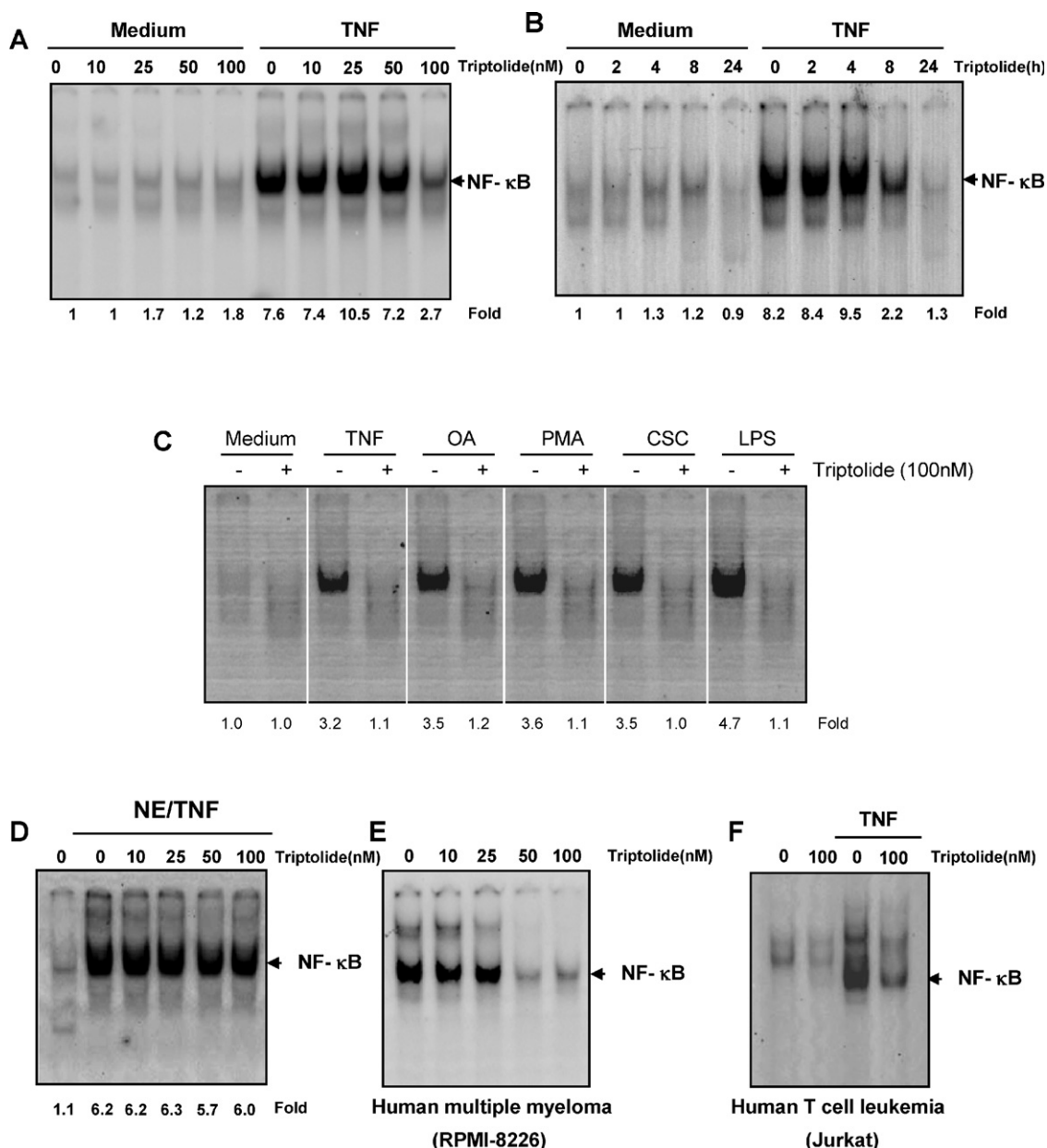
### 3.4. Triptolide suppresses the expression of TNF-induced NF- $\kappa$ B-dependent gene products involved in cell proliferation

A number of gene products that mediate cellular proliferation, such as COX-2, c-myc, and cyclin D1, have NF- $\kappa$ B binding sites in their promoters [28–30]. We investigated whether triptolide could modulate NF- $\kappa$ B regulated gene products involved in the

proliferation of tumor cells. Western blot analysis indicated that TNF induced the expression of these proteins and triptolide abolished it (Fig. 2B).

### 3.5. Triptolide represses the expression of TNF-induced NF- $\kappa$ B dependent gene products involved in metastasis of tumor cells

Because gene products that have been linked with invasion and metastasis are known to be regulated by NF- $\kappa$ B [31], we also investigated whether expression of the genes MMP-9 and ICAM-1 is modulated by triptolide. Western blot analysis indicated that



**Fig. 3.** Triptolide inhibits TNF-induced NF- $\kappa$ B activation. (A) KBM-5 cells were incubated with the indicated concentrations of triptolide for 12 h and treated with 0.1 nM TNF for 30 min. The nuclear extracts were assayed for NF- $\kappa$ B activation by EMSA. The results shown are representative of three independent experiments. (B) KBM-5 cells were preincubated with 100 nM triptolide for the indicated times and then treated with 0.1 nM TNF for 30 min. The nuclear extracts were prepared and assayed for NF- $\kappa$ B activation by EMSA. The results shown are representative of three independent experiments. (C) KBM-5 cells were preincubated with 100 nM triptolide for 12 h and then treated with 0.1 nM TNF, 10  $\mu$ g/mL CSC or 10  $\mu$ g/mL LPS for 30 min; 500 nM OA for 4 h or 25  $\mu$ g/mL PMA for 2 h. The cells were then analyzed for NF- $\kappa$ B activation by EMSA. (D) Nuclear extracts were prepared from untreated cells or cells treated with 0.1 nM TNF and incubated for 30 min with the indicated concentrations of triptolide. They were then assayed for NF- $\kappa$ B activation by EMSA. The results shown are representative of three independent experiments. (E) RPMI-8226 cells were incubated with different concentrations of triptolide for 12 h, the nuclear extracts prepared, and EMSA for NF- $\kappa$ B activation conducted. (F) Jurkat Human T cell leukemia was incubated with 100 nM triptolide for 12 h and then treated with 0.1 nM TNF for 30 min. The nuclear extracts were prepared and assayed for NF- $\kappa$ B activation by EMSA. The results shown are representative of three independent experiments.

TNF induced these gene products and that triptolide suppressed this expression (Fig. 2C).

### 3.6. Triptolide inhibits TNF-induced NF- $\kappa$ B activation in a dose- and time-dependent manner

Because apoptosis and the various gene products noted above are regulated by NF- $\kappa$ B, we investigated whether triptolide could modulate the NF- $\kappa$ B activation pathway. We first determined the dose and duration of exposure to triptolide required to suppress NF- $\kappa$ B activation on human myeloid KBM-5 cells. The EMSA results showed that triptolide inhibited TNF-induced NF- $\kappa$ B activation in a dose-dependent manner (Fig. 3A). However triptolide alone did not activate NF- $\kappa$ B. The suppression of NF- $\kappa$ B activation by triptolide was also found to be time dependent (Fig. 3B).

### 3.7. Suppression of NF- $\kappa$ B activation by triptolide was not unique to TNF

A wide variety of stimuli have been shown to activate NF- $\kappa$ B, including OA, PMA, CSC, and LPS through mechanisms that may differ. We investigated whether triptolide suppresses NF- $\kappa$ B activation by all these agents. EMSA showed that all these agents activated NF- $\kappa$ B and that triptolide abrogated activation (Fig. 3C).

### 3.8. Triptolide does not directly affect binding of NF- $\kappa$ B to DNA

Some NF- $\kappa$ B inhibitors directly modify NF- $\kappa$ B to suppress its DNA binding [32,33]. To determine whether this was the case for triptolide, nuclear extracts from TNF-treated cells were prepared and incubated with triptolide. The EMSA results showed that triptolide did not modify the DNA binding ability of NF- $\kappa$ B proteins prepared from TNF-treated cells (Fig. 3D). These results suggest that triptolide inhibits NF- $\kappa$ B activation by a mechanism different from that of other reagents.

### 3.9. Triptolide inhibits constitutive NF- $\kappa$ B activation

The reason that some cancer cells express constitutive active NF- $\kappa$ B and others do not is not fully understood. Whether triptolide affects constitutive NF- $\kappa$ B activation in human multiple myeloma (RPMI-8226) cells was examined. EMSA showed that triptolide inhibited constitutively active NF- $\kappa$ B in a dose-dependent manner (Fig. 3E), indicating that triptolide can inhibit not only inducible but constitutive NF- $\kappa$ B activation.

### 3.10. Triptolide suppresses NF- $\kappa$ B activation in leukemic cells

Because the signal transduction pathway mediated by NF- $\kappa$ B may be distinct in different cell types, we also determined whether triptolide blocked TNF-induced NF- $\kappa$ B activation in human T cell leukemia (Jurkat). The results showed that TNF-induced NF- $\kappa$ B activation was also blocked in leukemic cells (Fig. 3F), indicating that triptolide-mediated suppression of NF- $\kappa$ B activation is not cell type specific.

### 3.11. Triptolide inhibits TNF-induced I $\kappa$ B $\alpha$ degradation

Because I $\kappa$ B $\alpha$  degradation is required for activation of NF- $\kappa$ B [34], we investigated whether triptolide inhibits TNF-induced NF- $\kappa$ B activation by inhibiting I $\kappa$ B $\alpha$  degradation. We found that TNF induced I $\kappa$ B $\alpha$  degradation in control cells as early as 10 min after treatment, but in triptolide-treated cells TNF-induced I $\kappa$ B $\alpha$  degradation was decreased but not completely reversed (Fig. 4A).

### 3.12. Triptolide inhibits TNF-dependent I $\kappa$ B $\alpha$ phosphorylation and ubiquitination

To determine whether triptolide affects the TNF-induced I $\kappa$ B $\alpha$  phosphorylation and ubiquitination needed for I $\kappa$ B $\alpha$  degradation, we blocked degradation of I $\kappa$ B $\alpha$  with the proteasome inhibitor N-acetyl-leucyl-leucyl-norleucinal (ALLN). Western blot analysis using an antibody that recognizes the serine-phosphorylated form of I $\kappa$ B $\alpha$  showed that TNF-induced I $\kappa$ B $\alpha$  phosphorylation and ubiquitination were strongly suppressed by triptolide (Fig. 4B, upper).

### 3.13. Triptolide inhibits TNF-induced IKK activation

Because triptolide inhibited the phosphorylation and ubiquitination of I $\kappa$ B $\alpha$ , we tested the effect of triptolide on TNF-induced IKK activation, which is required for TNF-induced phosphorylation. As shown in Fig. 4C, triptolide completely suppressed TNF-induced activation of IKK. Neither TNF nor triptolide had any effect on the expression of IKK $\alpha$  and IKK $\beta$ . These results suggest that triptolide modulates TNF-induced IKK activation.

### 3.14. Triptolide did not directly inhibit TNF-induced IKK activation

Whether triptolide suppresses IKK activity directly by binding to the IKK complexes, was examined. The immune complex kinase assay of whole cell extracts from untreated and TNF-treated cells showed that triptolide had no effect on the activity of IKK, suggesting that it modulated TNF-induced IKK activation by inhibiting the upstream kinases (Fig. 4D).

### 3.15. Triptolide inhibits TNF-induced nuclear translocation and phosphorylation of p65

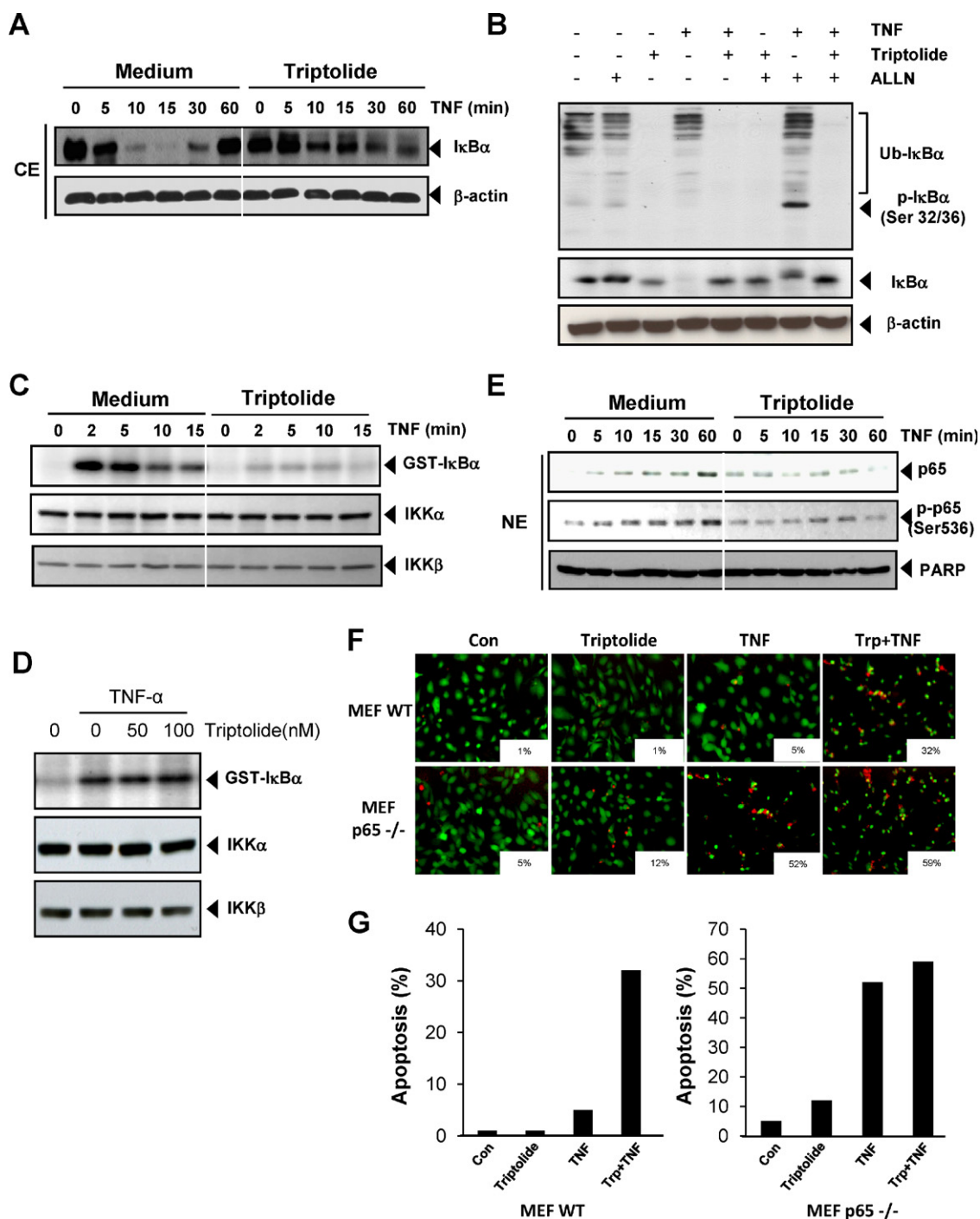
We also tested the effect of triptolide on TNF-induced phosphorylation of p65 (ser 536), which is required for transcriptional activity of p65. TNF induced phosphorylation of p65 in a time-dependent manner, and triptolide abolished it (Fig. 4E, middle). We also examined by Western blot analysis the effect of triptolide on TNF-induced nuclear translocation of p65. As shown in Fig. 4E upper, triptolide inhibited nuclear translocation of p65.

### 3.16. Triptolide does not potentiate TNF-induced apoptosis in p65<sup>-/-</sup> cells

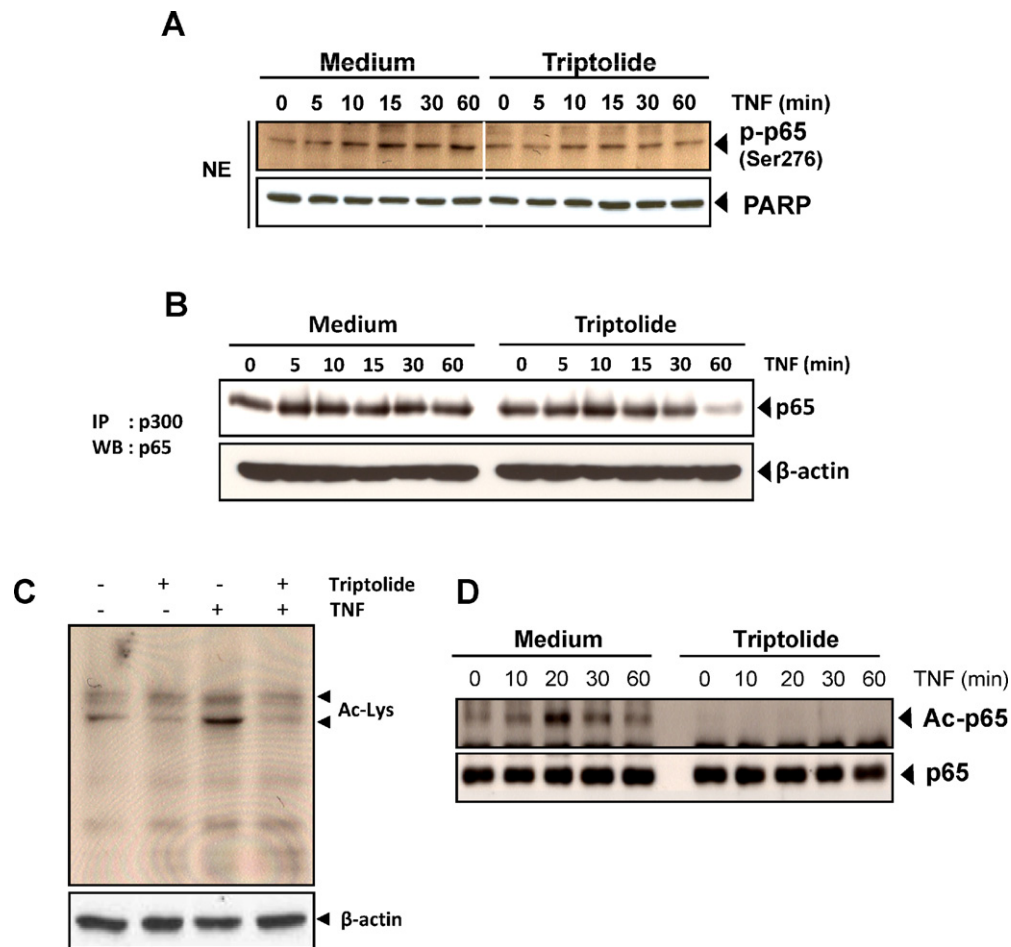
To determine whether inhibition of NF- $\kappa$ B is a major mechanism by which triptolide mediates its effects, we used the wild-type and p65<sup>-/-</sup> cells to compare the apoptosis induced by TNF. Results showed that triptolide potentiated TNF-induced apoptosis from 1% to 32% in wild-type cells. In p65<sup>-/-</sup> cells that lack functional NF- $\kappa$ B, TNF alone could induce apoptosis. We found that triptolide neither had any effect alone nor could it significantly potentiate the apoptotic effect induced by TNF in p65<sup>-/-</sup> cells (Fig. 4F and G).

### 3.17. Triptolide inhibits interaction of p65 with CBP/p300

Triptolide has been shown to inhibit interaction of p65 with CBP/p300 which has been linked to acetylation of p65 [35]. Because ser 276 phosphorylation seems to be highly important considering its crucial role in the interaction with and the engagement of the cofactor CBP/p300 [36], we tested the effect of triptolide on TNF-induced phosphorylation of p65 (ser 276). TNF induced phosphorylation of p65 in a time-dependent manner, and triptolide abolished it (Fig. 5A). Then, we examined the association of p65 and CBP/p300. Immunoprecipitation analysis showed



**Fig. 4.** Triptolide inhibits TNF-induced IκBα degradation, IκBα phosphorylation, p65 phosphorylation, and p65 nuclear translocation. (A) KBM-5 cells were incubated with 50 nM triptolide for 12 h and treated with 0.1 nM TNF for the indicated times. Cytoplasmic extracts were prepared and analyzed by Western blotting using antibodies against anti-IκBα. The results shown are representative of three independent experiments. Equal protein loading was evaluated by β-actin. (B) Cells were preincubated with 50 nM triptolide for 12 h, incubated with 50 μg/mL N-acetyl-leucyl-leucyl-norleucinal (ALLN) for 30 min, and then treated with 0.1 nM TNF for 10 min. Cytoplasmic extracts were fractionated and then subjected to Western blot analysis using phosphospecific IκBα (Ser 32/36) antibody. The same membrane was reblotted with anti-IκBα antibody. Equal protein loading was evaluated by β-actin. (C) KBM-5 cells were preincubated with 50 nM triptolide for 12 h and then treated with 1 nM TNF for the indicated times. Whole-cell extracts were immunoprecipitated with antibody against IKK-α and analyzed by an immune complex kinase assay. To examine the effect of triptolide on the level of expression of IKK proteins, whole cell extracts were fractionated on SDS-PAGE and examined by Western blot analysis using anti-IKK-α and anti-IKK-β antibodies. The results shown are representative of three independent experiments. (D) Whole-cell extracts were prepared from KBM-5 cells treated with 1 nM TNF and immunoprecipitated with anti-IKK-α antibody. The immunocomplex kinase assay was performed in the absence or presence of the indicated concentration of triptolide. (E) KBM-5 cells were either untreated or pretreated with 50 nM triptolide for 12 h and then treated with 0.1 nM TNF for the indicated times. Nuclear extracts were prepared and analyzed by Western blotting using antibodies against phospho-specific p65 (Ser 536) and p65. The results shown are representative of three independent experiments. For loading control of nuclear protein, the membrane was blotted with anti-PARP antibody. (F) and (G) The wild-type and p65<sup>-/-</sup> (10<sup>5</sup>/mL) cells were pretreated with 25 nM triptolide for 12 h and then incubated with 1 nM TNF for 24 h. Cell death was determined by the calcein-AM based Live/Dead assay as described in Section 2. Data are for a representative experiment of three independent ones showing similar results.



**Fig. 5.** Triptolide inhibits TNF-induced p65 acetylation. (A) KBM-5 cells were either untreated or pretreated with 50 nM triptolide for 12 h and then treated with 0.1 nM TNF for the indicated times. Nuclear extracts were prepared and analyzed by Western blotting using antibodies against phospho-specific p65 (Ser 276). The results shown are representative of three independent experiments. For loading control of nuclear protein, the membrane was blotted with anti-PARP antibody. (B) KBM-5 cells were either untreated or pretreated with 50 nM triptolide for 12 h and then treated with 0.1 nM TNF for the indicated times. Whole-cell extracts were immunoprecipitated with antibody against CBP/p300 and analyzed by Western blot analysis using anti-p65 antibody. The results shown are representative of three independent experiments. Equal protein loading was evaluated by  $\beta$ -actin. (C) KBM-5 cells were treated with 100 nM triptolide for 12 h and then exposed to 1 nM TNF for 20 min. Whole cell extracts were prepared and subjected to Western blot analysis using an anti-acetyl-lysine antibody. (D) KBM-5 cells were treated with 100 nM triptolide for 12 h and then exposed to 1 nM TNF. Whole-cell extracts were prepared, immunoprecipitated with an anti-p65 antibody, and subjected to Western blot analysis using an anti-acetyl-lysine antibody. The same blots were re probed with anti-p65 antibody.

significant blockage on the binding of p65 to CBP/p300 in a time-dependent manner (Fig. 5B).

### 3.18. Triptolide inhibits acetylation of p65

Because triptolide has shown to inhibit interaction of p65 with CBP/p300 through suppression of phosphorylation of p65 (ser 276), we determined whether triptolide could also inhibit acetylation of p65. To examine this, whole-cell extracts from cells treated with TNF, triptolide, or both were resolved on SDS-PAGE and then analyzed by Western blot using anti-acetyl lysine antibody. As shown in Fig. 5C, TNF induced acetylation of several proteins, whereas triptolide suppressed the acetylation of these proteins. Then, we examined inhibition of p65 acetylation. Western blot analysis showed that TNF induced the acetylation of p65 and that triptolide blocked the TNF-induced acetylation (Fig. 5D).

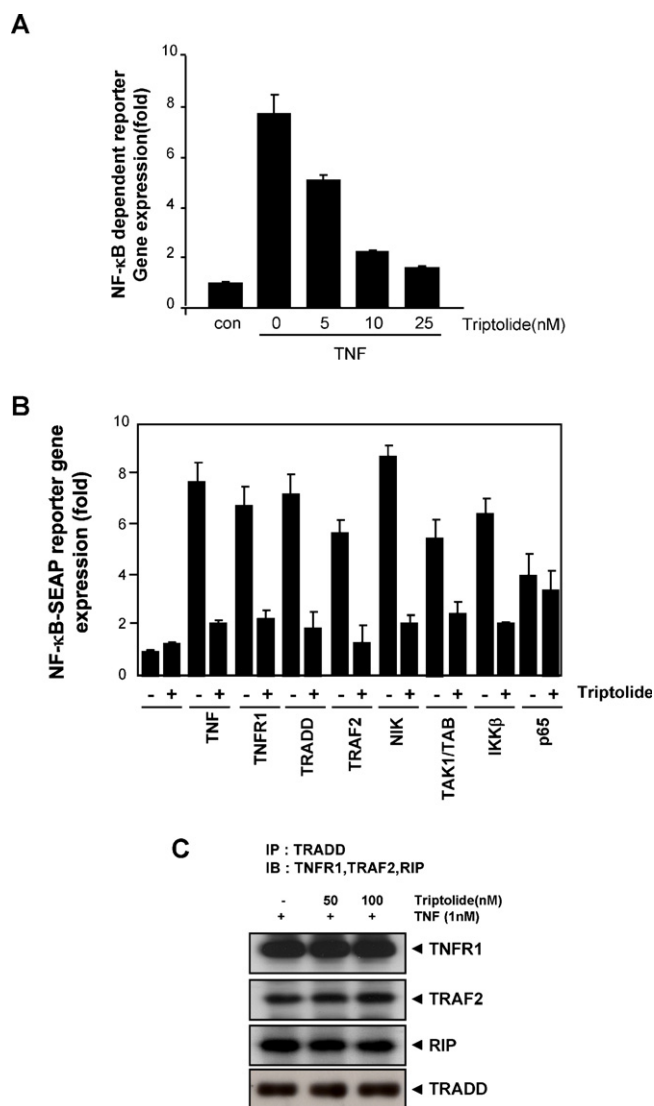
### 3.19. Triptolide represses TNF-induced NF- $\kappa$ B dependent reporter gene expression

Because DNA binding alone does not always correlate with NF- $\kappa$ B dependent gene transcription [37], we also examined

whether triptolide could modulate NF- $\kappa$ B dependent gene transcription by transiently transfecting the cells with the NF- $\kappa$ B. We found that TNF produced ~8-fold increase in SEAP activity over the vector control (Fig. 6A). When the cells were pretreated with triptolide, TNF-induced NF- $\kappa$ B dependent SEAP expression was inhibited in a dose dependent manner. These results showed that triptolide inhibits the NF- $\kappa$ B dependent reporter gene expression by TNF.

It has been reported that TNF-induced NF- $\kappa$ B activation is mediated through the sequential interaction of the TNF receptor with TRADD, TRAF2, NIK, TAK1/TAB1, and IKK, leading to the degradation of I $\kappa$ B $\alpha$  and p65 nuclear translocation [38]. So we also investigated where in the pathway triptolide suppresses gene transcription. Cells were transfected with TNFR1, TRADD, TRAF2, NIK, TAK1/TAB1, IKK $\beta$ , and p65 plasmids, along with the NF- $\kappa$ B-regulated SEAP reporter construct, incubated with triptolide, and then monitored for NF- $\kappa$ B-dependent SEAP expression. Triptolide suppressed SEAP expression induced by all these plasmids, except those transfected with p65 (Fig. 6B). These results suggest that p65 alone is not sufficient for full activation of NF- $\kappa$ B, perhaps some upstream elements, such as phosphorylation and acetylation, are needed.





**Fig. 6.** Triptolide represses NF- $\kappa$ B dependent reporter gene expression induced by TNF and various plasmids. (A) A293 cells were transiently transfected with a NF- $\kappa$ B containing plasmid linked to the SEAP gene and then treated with the indicated concentrations of triptolide. After 24 h in culture with 1 nM TNF, cell supernatants were collected and assayed for SEAP activity as described under Section 2. Results are expressed as fold activity over the activity of the vector control. (B) A293 cells were transiently transfected with an NF- $\kappa$ B containing plasmid alone or with the indicated plasmids. After 24 h, cells were treated with 25 nM triptolide and then incubated with the relevant plasmid for an additional 24 h. For TNF-treated cells, cells were treated with 25 nM triptolide for 6 h and then incubated with 1 nM TNF for 24 h. The supernatants of the culture medium were assayed for SEAP activity as described under Section 2. The results shown are representative of three independent experiments. (C) KBM-5 cells were pretreated with triptolide (50, 100 nM) for 12 h and then incubated with 1 nM TNF for 10 min. Whole-cell extracts were immunoprecipitated using an antibody against TRADD and then analyzed by Western blot using anti-TNFR1, -TRAF2 and -RIP antibodies. Anti-TRADD antibody was used as a loading control.

Whether triptolide modulates TNF $\alpha$ -induced formation of protein complexes between the TNFR1 and the adaptor proteins TRADD, RIP and TRAF2, was investigated. For this, KBM-5 cells were pretreated with 50, 100 nM triptolide for 12 h, then stimulated with TNF for 10 min, immune-precipitated with anti-TRADD and immunoblotted using antibodies against TNFR1, TRAF2 and RIP. As shown in Fig. 6C, triptolide did not interfere with the formation of this complex, suggesting that triptolide does directly interfere with the TNF receptor.

#### 4. Discussion

The present study was designed to investigate the mechanism by which triptolide blocks the TNF-induced NF- $\kappa$ B activation pathway, which has been closely linked to inflammation, tumor cell survival, proliferation, invasion, angiogenesis, and metastasis.

We found that apoptosis induced by TNF, taxol, and thalidomide was potentiated by triptolide. It is highly likely that downregulation of various cell survival gene products is linked to chemosensitization of the tumor cells by triptolide. Chemosensitization of tumor cells to taxol and thalidomide by triptolide has not been examined before. Our results also demonstrate that tumor cell invasion, which is normally mediated through MMP-9, is suppressed by the diterpene.

We found that enhancement of apoptosis by these agents was correlated with inhibition of expression of such gene products as survivin, c-IAP1, c-IAP2, XIAP, Bcl-2, and Bcl-x<sub>L</sub>, which are all known to be antiapoptotic proteins. Downmodulation of XIAP, cIAP-1 and cIAP-2 by triptolide is in agreement with previous reports [39], but our finding of the downmodulation of Bcl-2, and Bcl-x<sub>L</sub> differs from other reports. The precise reason for this difference is not clear but the cell type and inducer used may account for the difference.

Our results also showed for the first time that triptolide suppressed gene products that have been implicated in cell proliferation (COX-2, cyclin D1 and c-Myc). It is also in agreement with Zhu et al. [35] who showed downregulation of constitutive expression of cyclin D1 by triptolide. We further observed that triptolide could downregulate the expression of MMP-9 and ICAM-1, all regulated by NF- $\kappa$ B.

Because apoptosis and the various gene products noted above are regulated by NF- $\kappa$ B, we investigated whether triptolide could modulate the NF- $\kappa$ B activation pathway. Our results indicate that triptolide could suppress NF- $\kappa$ B activation through several novel mechanisms. The diterpene did not block NF- $\kappa$ B activation by direct modification of the p65 subunit of NF- $\kappa$ B, as most agents do [33,40], but by suppressing nuclear translocation of p65. NF- $\kappa$ B activation in response to different stimuli requires IKK activation, which phosphorylates I $\kappa$ B $\alpha$  at serine 32 and 36, leading to degradation of I $\kappa$ B $\alpha$  [34]. We found that this inhibition was in part mediated through the inhibition of IKK by triptolide, which led to the suppression of phosphorylation and the degradation of I $\kappa$ B $\alpha$ .

Besides inducible NF- $\kappa$ B activation, we found that triptolide inhibited constitutive NF- $\kappa$ B activation. Constitutively active NF- $\kappa$ B has been found in a wide variety of leukemic and tumor epithelial cells [41] and is needed for these cells' proliferation [42]. It is not fully understood why tumor cells express constitutively active NF- $\kappa$ B, but IKK has been implicated [42]. Thus, it is possible that triptolide's inhibition of IKK in tumor cells is linked to its ability to suppress constitutive NF- $\kappa$ B activation.

Triptolide has been reported to inhibit the activation of Bcr-Abl kinase and its downstream targets [18]. This kinase has been associated with suppression of TNF-induced NF- $\kappa$ B activation [43]. So our data suggest that inhibition of NF- $\kappa$ B by triptolide might be caused by inhibition of Bcr-Abl. Gleevec has had major effect on chronic myelogenous leukemia (CML) therapy, but resistance to Gleevec is now an emerging problem for CML patients [44]. Thus triptolide may be a promising agent to overcome Gleevec resistance caused by the Bcr-Abl mutation.

We found triptolide blocked phosphorylation of p65 at ser 276 and 536. LPS is known to induce the phosphorylation of p65 at ser 276, which promotes its interaction with p300 [36]. Another study showed that constitutively active NF- $\kappa$ B in thyroid carcinoma is suppressed by triptolide through inhibition of interaction of p65 with p300 [35]. In addition, acetylation of RelA (p65) at lysine 310, one step in the TNF-induced NF- $\kappa$ B activation pathway, is

regulated by prior phosphorylation of serine 276 and 536. Such phosphorylated and acetylated forms of RelA enhanced transcriptional activity [45]. Our data suggest that triptolide may suppress TNF-induced NF- $\kappa$ B activation through inhibition of p65 acetylation.

We investigated how triptolide suppressed IKK activation by examining its effects on several kinases that function upstream of IKK, such as MEKK1, MEKK3, PKC, GSK3 $\beta$ , TAK1, PDK1, NIK, and Akt [46–49]. Recent studies indicate that TAK1 plays a major role in the canonical pathway activated by cytokines through its interaction with TAB1 and TAB2 [50]. TAK1 also has been shown to be recruited by the TNFR1 through TRADD, TRAF2, and receptor-interacting protein. Our results suggest NF- $\kappa$ B-reporter activity induced by TNF, TNFR1, TRADD, TRAF2, NIK, IKK and TAK1 was inhibited by the triepoxide, whereas that by p65 was not blocked. These results suggest that a potential site of action of the drug lies between TAK1 and p65. The pathway upstream of TAK1 is less well understood, however, it is possible that triptolide interacts with multiple targets within in the TNF-induced NF- $\kappa$ B activation pathway.

Thus overall our results provide a novel mechanistic insight into the ability of triptolide to block NF- $\kappa$ B activation. Considering that this agent is active at nanomolar concentrations, it provides a novel opportunity to treat cancer and other proinflammatory diseases. The results presented here provide the basis for animal studies required for clinical trials with this agent.

## Contributions

Byoungduck Park, Bokyoung Sung and Vivek Yadav performed research. Byoungduck Park and Bharat Aggarwal wrote manuscript. Madan Chaturvedi revised manuscript.

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