0026-895X/11/8001-136–146$25.00
MOLECULAR PHARMACOLOGY
Copyright © 2011 The American Society for Pharmacology and Experimental Therapeutics
Mol Pharmacol 80:136–146, 2011

Vol. 80, No. 1
71316/3697494
Printed in U.S.A.

Synergistic Effect of Curcumin and Cisplatin via Down-Regulation of Thymidine Phosphorylase and Excision Repair Cross-Complementary 1 (ERCC1)[S]

Min-Shao Tsai, Shao-Hsing Weng, Ya-Hsun Kuo, Yu-Fan Chiu, and Yun-Wei Lin

Molecular Oncology Laboratory, Department of Biochemical Science and Technology, National Chiayi University, Chiayi, Taiwan

Received January 18, 2011; accepted April 14, 2011

ABSTRACT

Curcumin (diferuloylmethane), a phenolic compound obtained from the rhizome of *Curcuma longa*, is known to have antiproliferative and antitumor properties. Thymidine phosphorylase (TP), an enzyme of the pyrimidine salvage pathway, is considered an attractive therapeutic target, and its expression could suppress cancer cell death induced by DNA damage agents. Excision repair cross-complementary 1 (ERCC1) is a protein involved the process of nucleotide excision repair. The ERCC1 gene is expressed at high levels in cancers and has been associated with resistance to platinum-based chemotherapy. In this study, the effects of curcumin on TP and ERCC1 expression induced by cisplatin in non–small-cell lung cancer (NSCLC) cell lines was investigated. Exposure of the NSCLC cells to various concentrations of curcumin (5–40 μM) down-regulates the mRNA and protein levels of TP and ERCC1 through destabilization of the mRNA and proteins via a mechanism involving inactivation of MKK1/2-extracellular signal-regulated kinase (ERK1/2). Depletion of endogenous TP or ERCC1 expression by transfection with specific small interfering RNAs significantly decreases cell viability in curcumin-exposed NSCLC cells. Curcumin enhances the sensitivity of cisplatin treatment for NSCLC through inactivation of ERK1/2 and by decreasing the TP and ERCC1 protein levels. Enhancement of ERK1/2 signaling by constitutively active MKK1/2 causes an increase in TP and ERCC1 protein levels and promotes cell viability after cotreatment with curcumin and cisplatin. Enhancement of the cytotoxicity to cisplatin by administration of curcumin is mediated by down-regulation of the expression levels of TP and ERCC1 and by inactivation of ERK1/2.

Introduction

Lung cancer is a leading global cause of morbidity and mortality (Jemal et al., 2006). Cisplatin-based chemotherapy has been widely used for the treatment of non–small-cell lung cancer (NSCLC). Cisplatin exerts cytotoxic effects through the formation of covalent adducts and interferes with DNA replication, leading to cell death (Furuta et al., 2002). However, the efficacy of this chemotherapy is frequently attenuated owing to drug resistance in the advanced stage of NSCLC (Sève and Dumontet, 2005). The mechanisms of cisplatin resistance have been proposed, including enhancement of DNA repair and intracellular antioxidant activity, which block the induction of apoptosis (Rosell et al., 2002; Rudin et al., 2003). This leads to overproduction of proinflammatory mediators triggered by cancer cells and decreased drug accumulation (Siddik, 2003; Ohmichi et al., 2005). Because of these mechanisms, there is increased expression of excision repair cross-complementation 1 (ERCC1), a structure-specific DNA repair endonuclease responsible for incision at the 5′ site of damaged DNA (Niedernhofer et al., 2004). This increased expression of ERCC1 in cancer cells has been associated with more efficient removal of DNA adducts induced by cisplatin, leading to clinical drug resistance (Altaha et al., 2004). Therefore, in NSCLC, treatment with adjuvant cis-

This work was supported by the National Science Council of Taiwan [Grant NSC 99-2320-B-415-001-MY3].

Article, publication date, and citation information can be found at http://molpharm.aspetjournals.org.

doi:10.1124/mol.111.071316.

[S] The online version of this article (available at http://molpharm.aspetjournals.org) contains supplemental material.

ABBREVIATIONS: NSCLC, non–small-cell lung cancer; ERCC1, excision repair cross-complementation 1; NF-κB, nuclear factor-κB; AP-1, activator protein-1; MAPK, mitogen-activated protein kinase; TP, thymidine phosphorylase; MG132, *N*-benzoyloxycarbonyl (*Z*)-Leu-Leu-leucinal; U0126, 1,4-diamino-2,3-dicyano-1,4-bis(methylthio)butadiene; PCR, polymerase chain reaction; GAPDH, glyceraldehyde 3-phosphate dehydrogenase; MTS, (4,5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2*H*-tetrazolium; CI, combination index; MKK, mitogen-activated protein kinase kinase 1/2; ERK, extracellular signal-regulated kinase; RT, reverse transcription; siRNA, small interfering RNA; MKK1/2-CA, constitutively active MKK1/2.

platin-based chemotherapy significantly prolonged the survival rate among patients with ERCC1-negative tumors, relative to ERCC1-positive patients (Azuma et al., 2007).

Curcumin (diferuloylmethane), a well known chemopreventive agent, has been reported to possess antioxidant, anti-inflammatory, antiproliferative, and anticarcinogenic activities in several different cancers (Shishodia et al., 2005). It has been reported that among the multiple biological effects of curcumin is an ability to suppress several intracellular signaling molecules, including NF-κB and AP-1 as well as the members of the MAPK family signaling pathways (Chen and Tan, 1998; Han et al., 2002). The sensitizing effect of curcumin on cancer cell apoptosis has been reported for a variety of chemotherapeutic agents (Du et al., 2006; Weir et al., 2007) that are related to inactivation of NF-κB, modulation of p38 MAPK and AKT, and up-regulation of death receptor 5 (Deeb et al., 2004; Jung et al., 2005; Weir et al., 2007). However, it is unclear whether curcumin could enhance the sensitivity of cisplatin through modulation of MKK1/2-ERK1/2 signaling in NSCLC.

Thymidine phosphorylase (TP) is an enzyme of the pyrimidine salvage pathway, which is up-regulated in cancers. TP expression is correlated with reduced apoptosis induced by DNA damage agents, microtubule-interfering agents, hypoxia, and Fas ligands (Mori et al., 2002; Ikeda et al., 2003; Jeung et al., 2005). Elevated levels of TP are associated with poor prognosis and shorter patient survival (Mori et al., 2000). However, it should be explored whether curcumin has the ability to regulate TP expression, and the detailed molecular mechanism involved in this process should be characterized.

Curcumin has no adverse health effects and is therefore an excellent candidate for development of potential therapeutic strategies for treatment of cancer. In the present study, we have investigated the molecular mechanisms of curcumin alone and in combination with cisplatin for generation of cytotoxic effects in three different NSCLC cell lines. The evidence indicates that by down-regulating TP and ERCC1 expression and inactivation of MKK1/2-ERK1/2 signaling in NSCLC cell lines, curcumin exerts a cytotoxic effect that is synergistic with the effect of cisplatin.

Materials and Methods

Cell Lines and Reagents. Human lung bronchioloalveolar adenocarcinoma A549, lung squamous cell carcinoma H520, and lung carcinoma H1975 cell lines were obtained from the American Type Culture Collection (Manassas, VA) and cultured at 37°C in a humidified atmosphere containing 5% CO_2 in RPMI-1640 complete medium supplemented with sodium bicarbonate [2.2% (w/v)] and *l*-glutamine [0.03% (w/v)], penicillin (100 units/ml), streptomycin (100 μg/ml), and fetal calf serum (10%).

Curcumin, cisplatin, cycloheximide, and actinomycin D were obtained from Sigma (St. Louis, MO). *N*-Benzoyloxycarbonyl (*Z*)-Leu-Leu-leucinal (MG132), lactacystin, and 1,4-diamino-2,3-dicyano-1,4-bis(methylthio)butadiene (U0126) were purchased from Calbiochem-Novabiochem (San Diego, CA). Actinomycin D, MG132, lactacystin, and U0126 were dissolved in dimethyl sulfoxide (DMSO). Cycloheximide was dissolved in Milli-Q-purified water (Millipore, Billerica, MA).

Western Blot Analysis. After the different treatments, equal amounts of protein from each set of experiments were subjected to Western blot analysis as described previously (Ko et al., 2010). The specific phospho-ERK1/2 (Thr202/Tyr204) and phospho-MKK1/2 (Ser217/Ser221) antibodies were purchased from Cell Signaling Technology (Danvers, MA). The PD-ECGF(PGF-44C), ERCC1(FL-297), ubiquitin(P4D1), ERK2(K-23), HA(F-7), and Actin(I-19) antibodies were purchased from Santa Cruz Biotechnology (Santa Cruz, CA).

The relative protein blot intensities were determined using a computing densitometer equipped with the ImageQuant analysis program (GE Healthcare, Chalfont St. Giles, Buckinghamshire, UK). The relative fold under each blot was calculated by averaging the results of three independent experiments and was normalized by arbitrarily setting the densitometry of control cells to 1.

Immunoprecipitation. After treatment, equal amounts of proteins were immunoprecipitated using an anti-ubiquitin antibody and collected with protein G-Sepharose beads (GE Healthcare). The immunoprecipitate was then washed three times with ice-cold lysis buffer and subjected to immunoblot analysis.

Small Interfering RNA Transfection. The sense-strand sequences of siRNA used were as follows: TP, 5′-AUAGACUCCAGCUUAUCCA-3′; ERCC1, 5′-GGAGCUGGCUAAGAUGUGU-3′, and scrambled (as a control), 5′-GCGCGCUUUGUAGGATTCG-3′ (Dharmacon Research, Lafayette, CO). Cells were transfected with siRNA duplexes (200 nM) with Lipofectamine 2000 (Invitrogen, Carlsbad, CA) for 24 h.

Plasmid and Transfection. Plasmid transfection of MKK1-CA (a constitutively active form of MKK1, ΔN3/S218E/S222D) and MKK2-CA (a constitutively active form of MKK2, ΔN4/S222E/S226D) was achieved as described previously (Ko et al., 2010). Exponentially growing human lung cancer cells (10^6) were plated for 18 h, and the MKK1/2-CA expression vectors were transfected into cells using Lipofectamine (Invitrogen) before curcumin and cisplatin treatment.

Reverse Transcription-PCR. Total RNA was extracted from drug-treated NSCLC cells with TRIzol reagent (Invitrogen). cDNA was synthesized by using random hexamers following the Moloney murine leukemia virus reverse transcriptase cDNA synthesis system (Invitrogen). The final cDNA was used for subsequent PCRs. TP was amplified by using the primers with the sequence 5′-GGCATGGATCTGGAGGAGAC-3′ (forward) and 5′-CTCTGACCCACGATACAGCA-3′ (reverse) in conjunction with a thermal cycling program consisting of 40 cycles of 95°C for 30 s, 59°C for 30 s, and 72°C for 30 s. ERCC1 was amplified using primers with the sequence of 5′-CCCTGGGAATTTGGCGACGTAA-3′ (forward) and 5′-CTCCAGGTACCGCCCAGCTTCC-3′ (reverse) in conjunction with a thermal cycling program consisting of 26 cycles of 95°C for 30 s, 61°C for 30 s, and 72°C for 60 s. Glyceraldehyde 3-phosphate dehydrogenase (GAPDH) was amplified as an internal control. The GAPDH primers were 5′-CTACATGGTTTACATGTTCC-3′ (forward) and 5′-GTGAGCTTCCCGTTCAGCTCA-3′ (reverse). Expression of GAPDH was used as a control to measure the integrity of the RNA samples.

Quantitative Real-Time PCR. PCRs were performed using an ABI Prism 7900HT according to the manufacturer's instructions (Applied Biosystems, Foster City, CA). Amplification of specific PCR products was detected using the SYBR Green PCR Master Mix (Applied Biosystems). The designed primers in this study were as follows: TP: forward primer, 5′-AGCTGGAGTCTATTCCTGGATT-3′; reverse primer, 5′-GGCTGCATATAGGATTCCGTC-3′; ERCC1: forward primer, 5′-GGGTGACTGAATGTCTGACCA-3′; reverse primer, 5′-GGGTACTTTCAAGAAGGGCTC-3′; GAPDH: forward primer, 5′-CATGAGAAGTATGACAACAGCCT-3′; reverse primer, 5′-AGTCCTTCCACGATACCAAAGT-3′. For each sample, the data were normalized to the housekeeping gene GAPDH.

Measurement of Cell Viability. In vitro (4,5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2*H*-tetrazolium (MTS) assay was carried out essentially according to the procedure described previously (Ko et al., 2010). The principle of this convenient method is based on the conversion of 3-MTS into a chromatic, soluble formazan by a mitochondrial enzyme, NAD-dependent dehydrogenase, in live cells. In brief, cells were cultured at 5000 per well in 96-well

tissue culture plates. To assess cell viability, drugs were added after plating. At the end of the culture period, 20 μl of MTS solution (CellTiter 96 Aqueous One Solution Cell Proliferation Assay; Promega, Madison, WI) was added, the cells were incubated for a further 2 h, and the absorbance was measured at 490 nm using an ELISA plate reader (Bio-Rad Technologies, Hercules, CA).

Combination Index Analysis. The cytotoxicity induced by the combined treatment with curcumin and cisplatin was compared with the cytotoxicity induced by each drug using the combination index (CI), where CI <0.9, CI = 0.9 to 1.1, and CI >1.1 indicate synergistic, additive, and antagonistic effects, respectively. The combination index analysis was performed using CalcuSyn software (Biosoft, Oxford, UK). The mean of CI values at a fraction affected of 0.90 and 0.75 were averaged for each experiment, and the values were used to calculate the mean between the three independent experiments.

Colony-Forming Ability Assay. Immediately after the drug treatment, cells were washed with phosphate-buffered saline and trypsinized for the determination of cell numbers. The cells were plated at a density of 500 cells on a 60-mm diameter Petri dish in triplicate for each treatment. The cells were cultured for 10 to 14 days, and the cell colonies were stained with 1% crystal violet solution in 30% ethanol. Cytotoxicity was determined by the number of colonies in the treated cells divided by the number of colonies in the untreated control.

Trypan Blue Dye Exclusion Assay. Cells were treated with curcumin and/or cisplatin for 24 h. In each preparation, the cell viability of lung cancer cells was determined by the trypan blue dye exclusion assay; this dye was excluded by living cells and only penetrated the cell membrane of dead cells. The proportion of dead cells was determined by using a hemocytometer to count the number of stained cells.

Statistical Analyses. For each protocol, three or four independent experiments were performed. Results were expressed as the mean ± S.E.M. Statistical calculations were performed using SigmaPlot 2000 (Systat Software, San Jose, CA). Differences in measured variables between experimental and control groups were

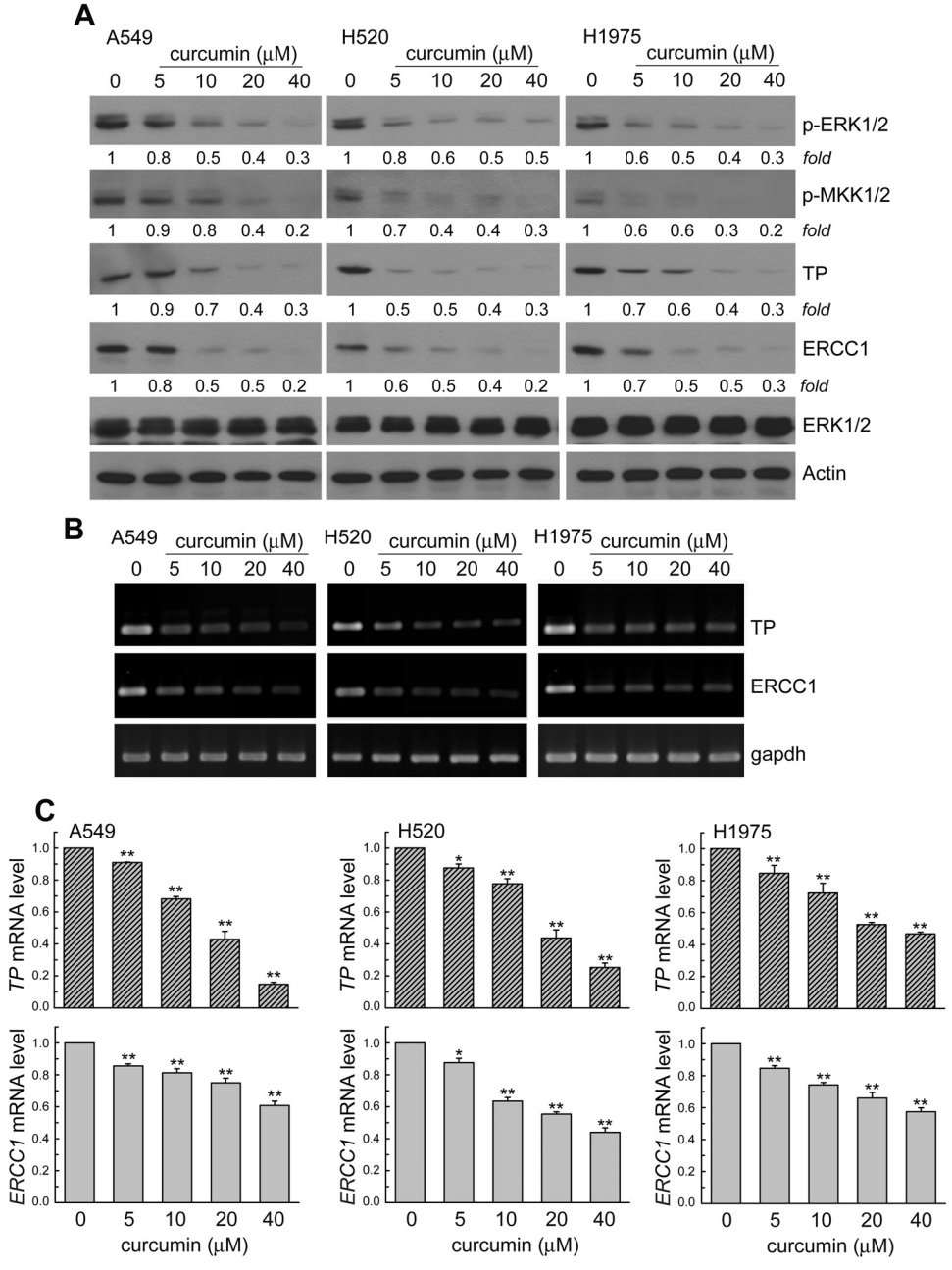

Fig. 1. Protein levels of phospho-MKK1/2, phospho-ERK1/2, TP, and ERCC1 were decreased by treatment with curcumin. A, NSCLC cell lines (A549, H520, or H1975) were treated with curcumin (5–40 μM) in complete medium for 24 h. Cells were then extracted for the determination of phospho-MKK1/2, phospho-ERK1/2, TP, ERCC1, ERK1/2, and actin protein levels by Western blotting. B and C, after the same treatment described in A, total RNA was isolated and subjected to RT-PCR and real-time PCR for TP and ERCC1. **, $P < 0.01$; *, $P < 0.05$, using the Student's t test for the comparison between cells treated with or without curcumin in NSCLC cells.

assessed by unpaired t test. $P < 0.05$ was considered statistically significant.

Results

TP and ERCC1 Protein and mRNA Levels Are Decreased after Curcumin Exposure. To evaluate the role of TP and ERCC1 in regulating the curcumin-induced cytotoxicity in NSCLC cell lines, A549, H520, and H1975 cells were treated with concentrations of curcumin ranging from 5 to 40 μM for 24 h and then examined for expression of TP and ERCC1 by Western blot analysis. Figure 1A demonstrated that curcumin significantly decreased the cellular TP and ERCC1 protein levels. Actin controls showed that the levels of actin protein were unaffected under these conditions. Moreover, Western blot analysis using phosphospecific antibodies indicated a decrease of MKK1/2-ERK1/2 phosphorylation after curcumin treatment of the three cell lines (Fig. 1A). No differences in levels of endogenous unphosphorylated ERK1/2 were observed. To elucidate the mechanisms responsible for the elevated TP and ERCC1 expression levels observed in NSCLC cell lines, we first confirmed the expression of TP and ERCC1 mRNA by reverse transcription-PCR (RT-PCR) and real-time PCR. As shown in Fig. 1, B and C, curcumin significantly and dose-dependently reduced the steady-state levels of TP and ERCC1 mRNA in NSCLC cell lines.

Curcumin Treatment Down-Regulates the Protein and mRNA Stability of TP and ERCC1 in NSCLC Cell Lines. Next, we examined the possible mechanisms for post-transcriptional regulation of TP and ERCC1 transcripts under curcumin treatment. To evaluate the mRNA stability of TP and ERCC1 in curcumin-exposed lung cancer cells, we treated these cells with curcumin (10 μM) for 9 h in the presence of actinomycin D to block de novo RNA synthesis for 3, 6, or 9 h and then measured the levels of the existing TP and ERCC1 mRNA by RT-PCR. As shown in Fig. 2A, curcumin treatment produced lower levels of TP and ERCC1 mRNA after cotreatment with actinomycin D relative to control cells. This indicates that curcumin decreases the stability of TP and ERCC1 mRNAs.

Furthermore, we investigated the mechanism of modulation of protein levels of TP and ERCC1 by curcumin by exploring the possibility that curcumin enhances the rate of TP and ERCC1 protein degradation. These cells were treated with curcumin for 9 h, followed by the addition of cycloheximide (an inhibitor of de novo protein synthesis) for 3, 6, and 9 h to evaluate the rate of degradation of the TP and ERCC1 proteins. In Fig. 2B, it can be seen that upon treatment of NSCLC cell lines with curcumin, the rates of degradation of TP and ERCC1 proteins were markedly increased relative to the untreated cells. The curcumin-mediated down-regulation of the TP and ERCC1 mRNA and protein expression occurs through a decrease in the stabilities of the mRNAs and proteins.

Lactacystin and MG132 Block the Curcumin-Induced Down-Regulation of TP and ERCC1 Protein. To investigate whether the 26S proteasome is involved in the curcumin-induced degradation of TP and ERCC1 proteins, lactacystin or MG132, both 26S proteasome inhibitors, was added with curcumin to the NSCLC cells. As shown in Fig.

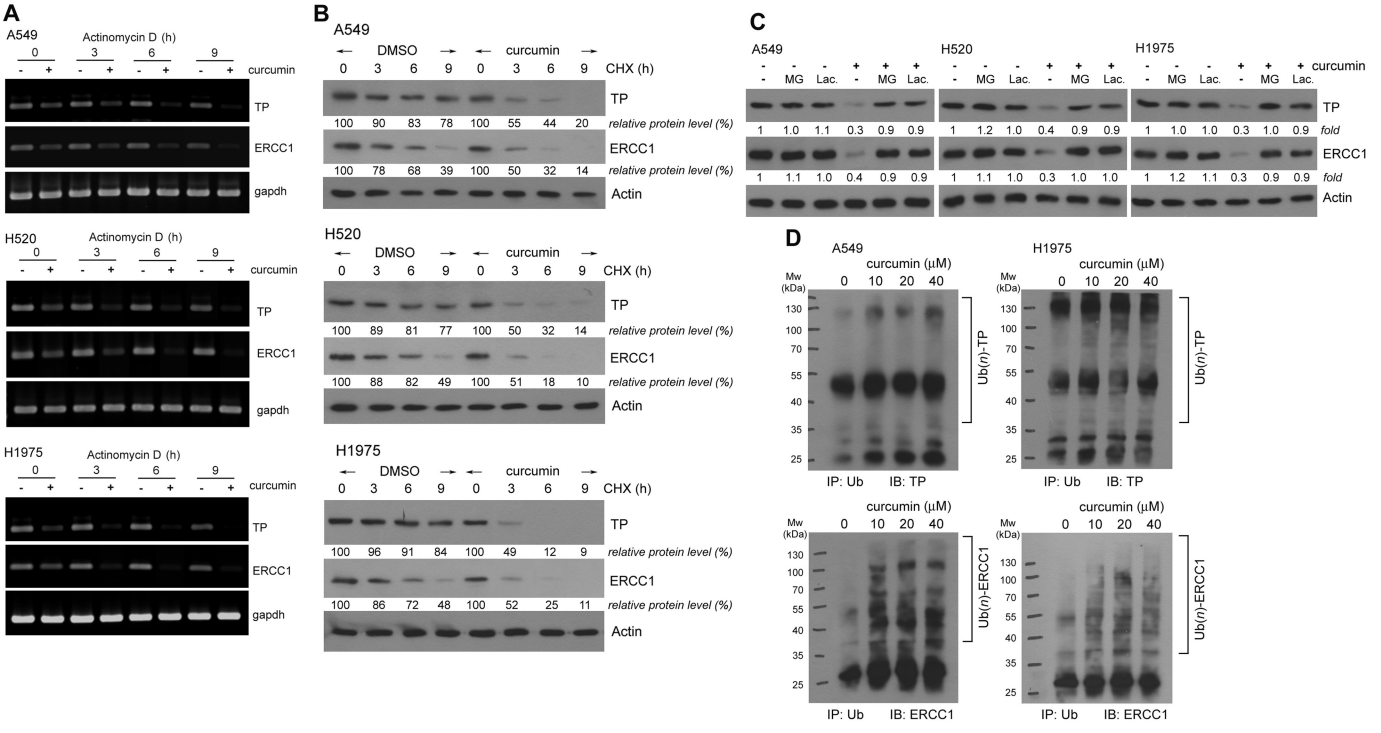

Fig. 2. Treatment with curcumin decreased the cellular TP and ERCC1 mRNA and protein stability in NSCLC cells. A, cells were exposed to curcumin (10 μM) for 9 h in the presence of actinomycin D (2 μg/ml) for 3, 6, or 9 h. After the treatment, total RNA was extracted and analyzed by RT-PCR. TP and ERCC1 mRNA levels were normalized against GAPDH in three separate treatments. B, cells were treated with curcumin (10 μM) for 9 h, followed by the addition of cycloheximide (60 μg/ml) for 3, 6, and 9 h. C, cells were treated with curcumin (40 μM) for 18 h, and then with MG132 (10 μM) or lactacystin (10 μM) for 6 h. Whole-cell extracts were collected for Western blot analysis of TP and ERCC1 protein levels. D, as described above, equal amounts of protein in each cell extract was subjected to immunoprecipitation (IP) with an antiubiquitin antibody. The immunoprecipitates were analyzed by immunoblot (IB) analysis using an anti-TP or an anti-ERCC1 antibody.

2C, both lactacystin and MG132 prevented the curcumin-induced down-regulation of TP and ERCC1. In addition, we examined the levels of ubiquitin conjugates on TP and ERCC1. In Fig. 2D, curcumin treatment increased the levels of ubiquitin-conjugated TP and ERCC1 in NSCLC cell lines. These results indicate that curcumin decreases the levels of TP and ERCC1 protein via the ubiquitin-mediated 26S proteasome degradation pathway in NSCLC cells.

ERK1/2 Inactivation Is Correlated with Decreased Expression of Tp and Ercc1 by Curcumin. Next, we determined whether the MKK1/2-ERK1/2 signaling pathway inactivation is involved in the down-regulation of TP and ERCC1 protein expression in curcumin-exposed NSCLC cells. The NSCLC cells were transfected with constitutive active MKK1 (MKK1-CA) vectors, and then treated with curcumin (10–40 μM) for 24 h. As shown in Fig. 3A, the phosphorylation levels of ERK1/2 were higher in MKK1-CA–transfected A549 and H1975 cells than in pcDNA3-transfected cells. It was found that MKK1-CA transfection could also restore the phosphorylated ERK1/2, TP, and ERCC1 protein levels, which were decreased by curcumin treatment (Fig. 3A). Moreover, MKK1/2-CA was also found to be able to rescue the TP mRNA down-regulation by curcumin, as determined by reverse transcription-PCR and real-time PCR analyses (Fig. 3, B and C). These results collectively suggest that inhibition of ERK1/2 activity by curcumin reduces TP and ERCC1 expression in NSCLC cells.

Knockdown of Either TP or ERCC1 Expression by siRNA Transfection Sensitizes NSCLC Cells to Curcumin. To evaluate the importance of TP and ERCC1 in the

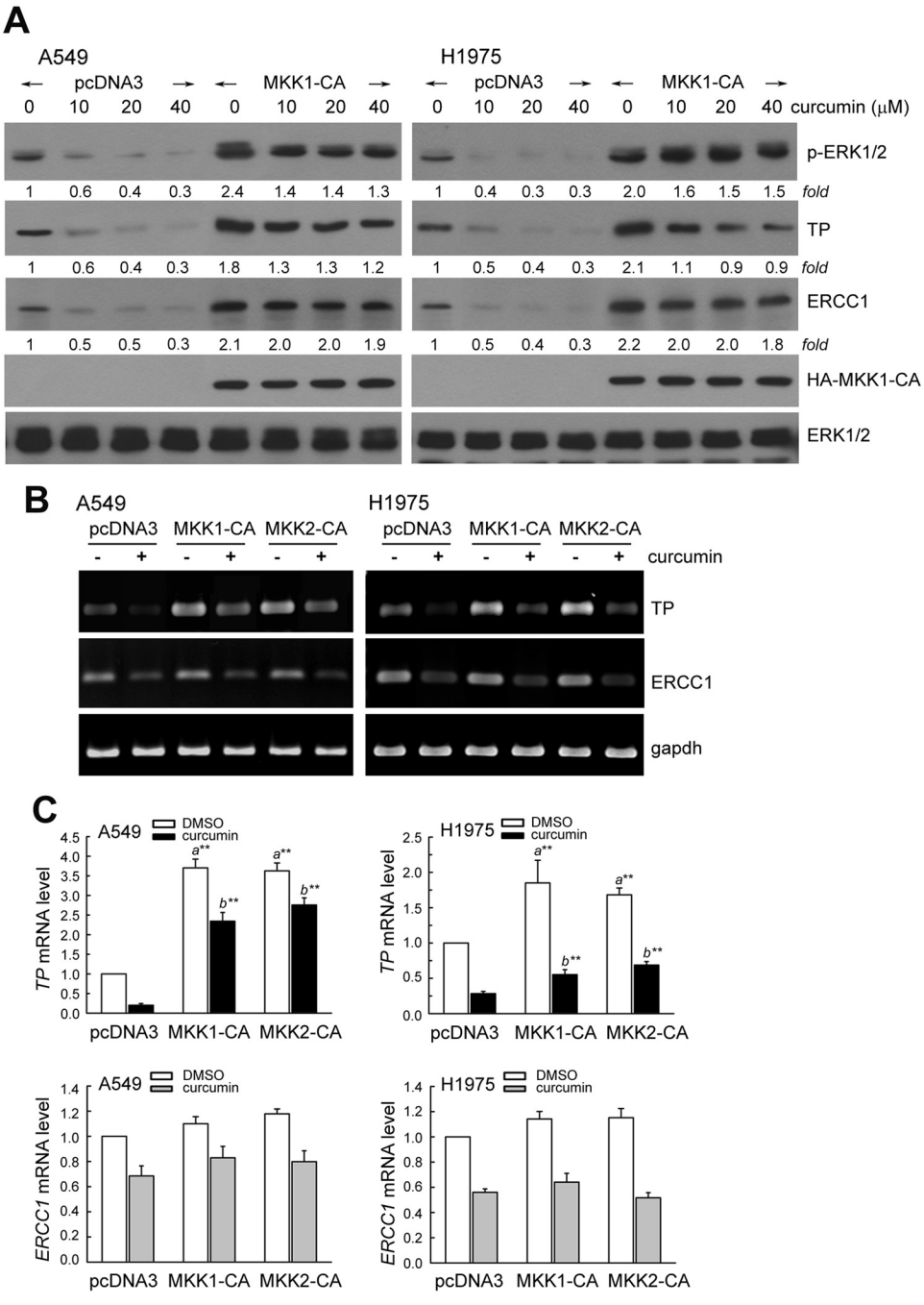

Fig. 3. Transfection of MKK1-CA vector expression restored the TP and ERCC1 protein levels that were decreased by curcumin. A, MKK1-CA expression vectors were transfected into A549 and H1975 cells by using Lipofectamine 2000. After transfection, the cells were treated with curcumin (10–40 μM) for 24 h. Whole-cell extracts were collected for Western blot analysis of TP and ERCC1 protein levels. B and C, as described above, total RNA was isolated and subjected to RT-PCR and real-time PCR for TP and ERCC1. a^{**}, $P < 0.01$ using the Student's t test for comparison between the cells transfected with MKK1/2-CA or pcDNA3 vectors. b^{**}, $P < 0.01$ (Student's t test). Comparison between the cells transfected with MKK1/2-CA or pcDNA3 vectors in curcumin treated cells.

curcumin-induced cytotoxic effect in NSCLC cells, specific siRNAs against TP and ERCC1 were used to knock down TP and ERCC1 expression in curcumin-treated cells. We found that TP and ERCC1 expression became significantly decreased 24 h after treatment with 200 nM siRNA in curcumin-exposed A549 and H1975 cells (Fig. 4A). Furthermore, curcumin-decreased ERK1/2 phosphorylation was not affected in cells transfected with TP or ERCC1 siRNA. Cell viability was determined by MTS and the colony-forming ability assay, as shown in Fig. 4, B and C. The effect of curcumin-induced cytotoxicity was significantly enhanced by transfection with siRNAs against TP and ERCC1 relative to transfection of the curcumin-treated group with the scrambled siRNA (**, $P < 0.01$; Fig. 4, B and C).

U0126 Enhances the Curcumin-Induced Cytotoxicity in NSCLC Cells. The MKK1/2 inhibitor U0126 was investigated to determine whether complete inhibition of ERK1/2 activation would promote down-regulation of TP and ERCC1 by curcumin. The A549 and H1975 cells were treated with various concentrations of MKK1/2 inhibitor U0126 (2.5–10 μM) and curcumin (5 μM). As shown in Fig. 4D, curcumin decreased the extent of ERK1/2 phosphorylation, and the TP and ERCC1 protein levels were significantly further decreased by treatment with U0126 relative to the control DMSO-treated cells. Next, we evaluated whether ERK1/2 inactivation is required for curcumin-induced cytotoxicity in NSCLC cell lines. The cells were cotreated with various concentrations of curcumin and U0126 for 24 h. Cell viability was assessed by the MTS assay. In Fig. 4E, U0126 enhanced the cytotoxicity in curcumin-exposed NSCLC cells. These results indicate that inactivation of MKK1/2–ERK1/2 signal by curcumin suppresses TP and ERCC1 expression and decreases the viability of the NSCLC cells.

Curcumin Decreases the Protein Levels of Phosphorylated ERK1/2, TP, and ERCC1 Induced by Cisplatin. Next, we examined the combined effects of curcumin and

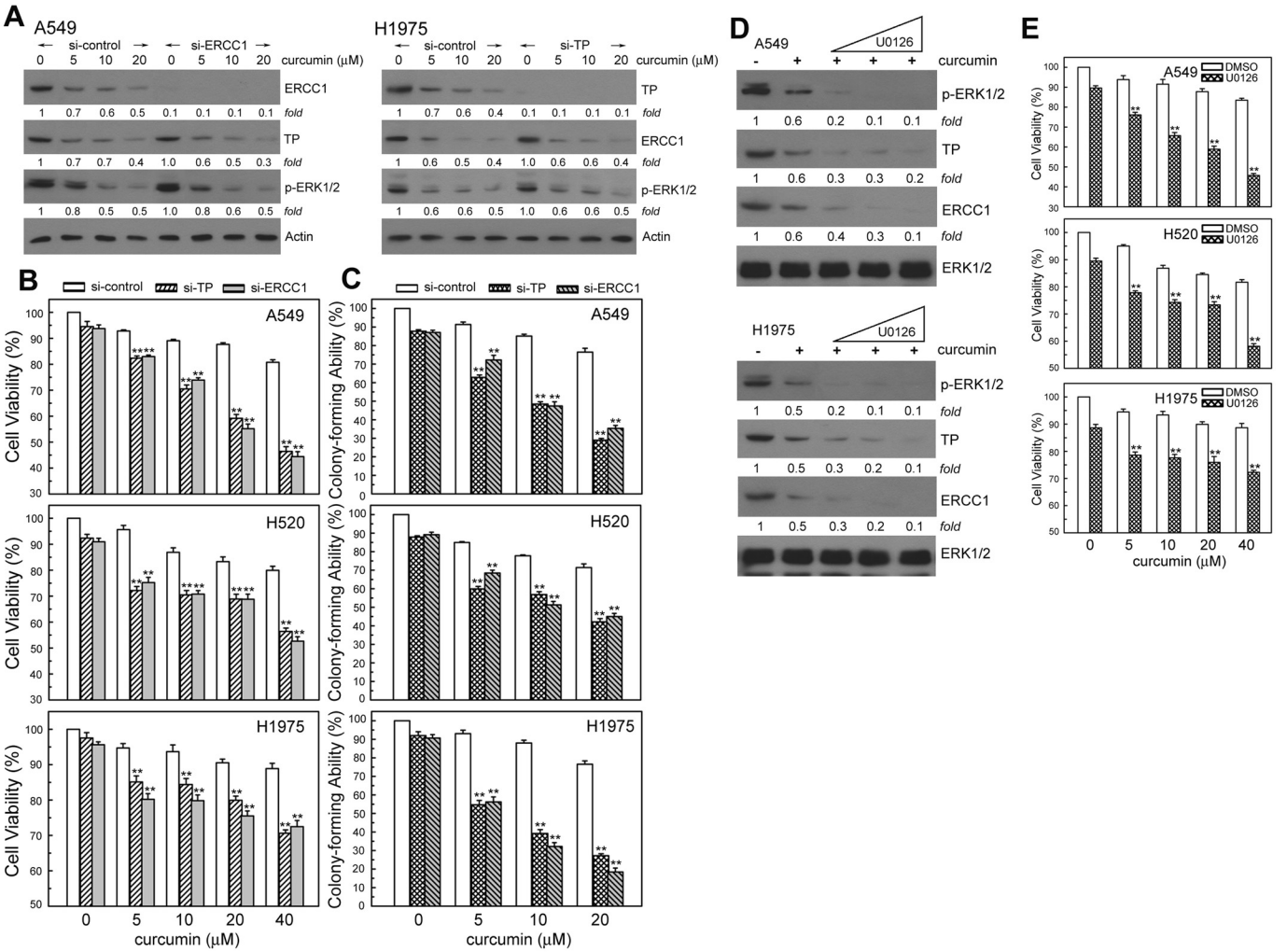

Fig. 4. Knockdown of TP and ERCC1 expression by siRNA transfection enhances curcumin-induced cell death. A, A549 and H1975 cells were transfected with siRNA duplexes (200 nM) specific to TP, ERCC1, or a scrambled control in complete medium for 24 h before treatment with curcumin (5–40 μM) for 24 h. Whole-cell extracts were collected for Western blot analysis using specific antibodies against TP, ERCC1, phospho-ERK1/2, and actin. B and C, cell viability was determined using the MTS and colony-forming ability assay. The results (mean ± S.E.M.) were obtained from three independent experiments. **, $P < 0.01$, using the Student's t test for the comparison between cells treated with curcumin in combination with the siRNA against TP RNA, the siRNA against ERCC1 RNA, and the scrambled siRNA. D, A549 and H1975 cells were exposed to curcumin (5 μM) and U0126 (2.5, 5, and 10 μM) for 24 h. Cells were then extracted for Western blotting. E, after the treatment described in D, the cell viability was determined using the MTS assay. The results (mean ± S.E.M.) were obtained from three independent experiments. **, $P < 0.01$, using the Student's t test for the comparison between the curcumin-treated cells cotreated with U0126 and the control cells that were not treated with U0126.

cisplatin on the expression of TP and ERCC1 compared with the results of each separate treatment. As shown in Fig. 5, cisplatin increased the levels of phosphorylated ERK1/2 in a dose-dependent manner, and curcumin suppressed this activation. No effect on the levels of unphosphorylated ERK1/2 was noted. Moreover, curcumin was found to decrease the cisplatin-elicited up-regulation of TP and ERCC1 protein expression in A549 and H1975 cells (Fig. 5). Furthermore, we examined the changes in mRNA levels of TP and ERCC1 after treatment with curcumin and cisplatin combination by using RT-PCR and real-time PCR analyses. In Fig. 6, A and B, it can be seen that the combination of cisplatin and curcumin produced significantly lower TP and ERCC1 mRNA levels relative to cisplatin alone. Next, to evaluate the possible mechanisms for post-translational and post-transcriptional regulation of TP and ERCC1 expression, which occur upon cotreatment with curcumin and cisplatin, the protein and mRNA stability of TP and ERCC1 were examined. As shown in Fig. 6, C and D, curcumin decreased the mRNA and protein stability of TP and ERCC1 in cisplatin-treated NSCLC cell lines. Taken together, these results indicate that curcumin down-regulates cisplatin-elicited ERK1/2 activation as well as the expression of TP and ERCC1.

Curcumin Potentiates the Cytotoxicity of Cisplatin toward NSCLC Cells. Furthermore, we used dose-inhibition studies to test whether curcumin could sensitize NSCLC cell lines to cisplatin. The viable cells were evaluated by the MTS assays. In Fig. 7A, cotreatment with curcumin and cisplatin caused a significant decrease in cell viability. This indicates increased cisplatin sensitivity (from an IC_{50} of ~20 to 10 μg/ml) with the addition of 20 μM curcumin to A549 cells. Similar phenomena were observed when cell death was assessed using the trypan blue exclusion assay (Fig. 7B). In addition, the mean values of the CI indicate that the curcumin-cisplatin treatment has a synergistic effect (Fig. 7C). Moreover, NSCLC (A549, H520, and H1975) cancer cells were exposed to curcumin and/or cisplatin, and their proliferation was determined over 1 to 4 days after exposure to the drugs. Curcumin alone (20 μM) has an antiproliferative effect on NSCLC. However, curcumin was found to significantly enhance the inhibition of cell growth by cisplatin in NSCLC cells (Fig. 7D). The combination of curcumin and cisplatin together was more effective than either treatment alone.

Influence of ERK1/2 Inactivation on the Regulation of TP and ERCC1 Protein Expression and Cell Viability under Curcumin and Cisplatin Cotreatment. We next tested whether curcumin-dependent ERK1/2 inactivation is essential for synergistic cytotoxicity induced by curcumin and cisplatin. The NSCLC cells were transfected with MKK1/2-CA (constitutively active MKK1/2) vectors, and then treated with curcumin and cisplatin for 24 h. Cell viability was assessed by the MTS assay. Figure 8A shows that the expression of the MKK1/2-CA vectors rescued the TP and ERCC1 protein levels that were decreased by the curcumin and cisplatin combination. It is noteworthy that transfection with MKK1/2-CA vectors also enhanced cell survival, which was suppressed by curcumin and/or cisplatin in NSCLC cells

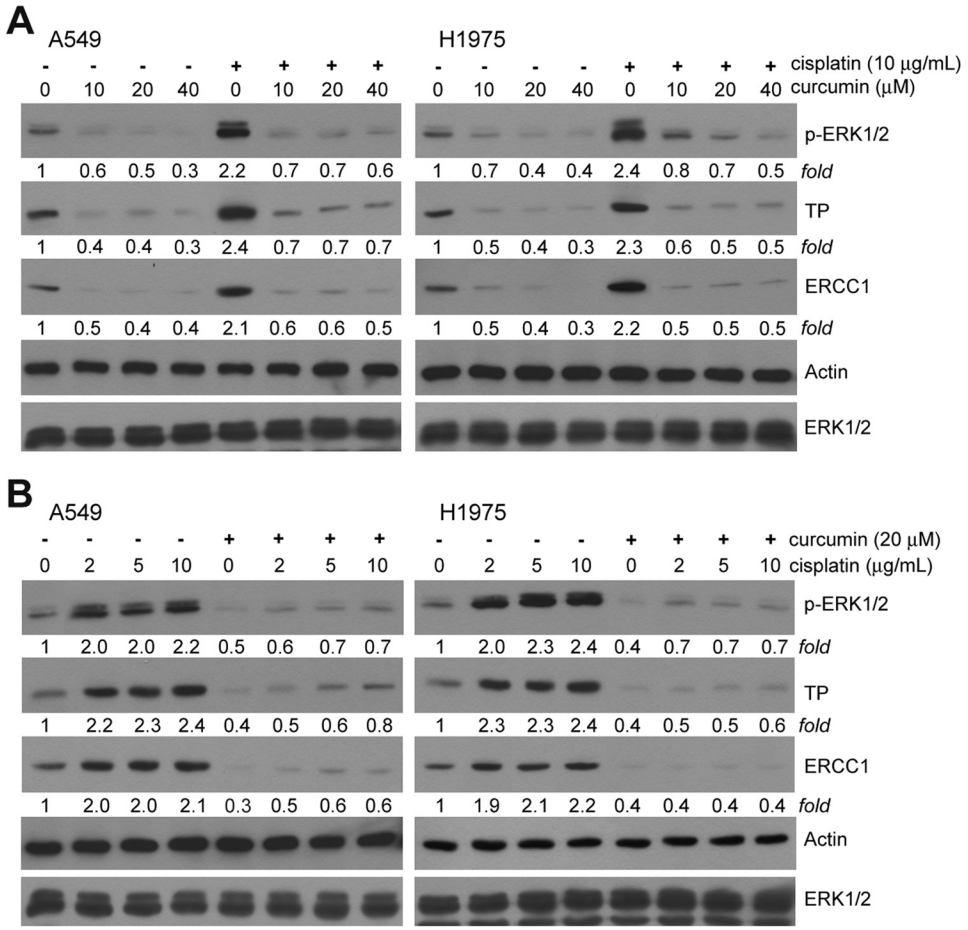

Fig. 5. Curcumin decreases cisplatin-induced protein levels of phopho-ERK1/2, TP, and ERCC1. A, A549 or H1975 cells (10^6) were cultured in complete medium for 18 h and then exposed to curcumin (10–40 μM) and cisplatin (10 μg/ml) for 24 h in complete medium. B, cells were exposed to various concentrations of cisplatin and curcumin (20 μM) for 24 h. After treatment, cell extracts were examined by Western blots to determine the phospho-ERK1/2, TP, and ERCC1 protein expression levels. **, $P < 0.01$, using the Student's t test for the comparison between cells treated with cisplatin/curcumin alone and the cells co-treated with these two drugs.

(Fig. 8B). Therefore, curcumin enhances the cytotoxicity of cisplatin against NSCLC cells through a mechanism that depends upon inactivation of MKK1/2–ERK1/2.

Discussion

The results of our study have identified an additional mechanism through which curcumin induces cytotoxic effects in NSCLC cells via decreasing the expression of TP and ERCC1. Previous studies indicated that NF-κB (Aggarwal et al., 2006), AKT, and AP-1 (Tomita et al., 2006) participate in the mediation of the antiproliferative effects of curcumin. The number of signaling pathways and molecular targets involved is continuously growing; consequently, the mechanism is becoming more complex. The mechanism is cell type-specific and dose-dependent. Curcumin inhibits cell proliferation and induces apoptosis in human cancer cells as a result of the induction of proapoptotic proteins and the inhibition of antiapoptotic proteins as well as inhibition of survival pathways (Dorai et al., 2001; Radhakrishna Pillai et al., 2004). For example, curcumin induces apoptosis in human renal cells through the down-regulation of Bcl-xL and IAP, the release of cytochrome *c*, and the inhibition of AKT (Woo et al., 2003). The inhibitory effect of curcumin on ERK1/2 activation, and the proliferation of pancreatic stellate cells is mediated by inducing the expression of the heme oxygenase-1 gene (Schwer et al., 2008). We have found that curcumin inactivates the MKK1/2–ERK1/2 signal in NSCLC cell lines. Enforced expression of MKK-CA rescues the TP and ERCC1 protein levels that were decreased by curcumin. In contrast, addition of the MKK1/2 inhibitor U0126 enhances the curcumin-elicited down-regulation of TP and ERCC1. Knockdown of TP and ERCC1 expression significantly decreases the cell viability in curcumin-exposed NSCLCs. To our knowledge, the results of this study provide the first indication that curcumin decreases the expression of TP and ERCC1 by inactivation of MKK1/2–ERK1/2. The expression of TP and ERCC1 plays a protective role in curcumin-treated NSCLC cells.

In pancreatic cancer cells, curcumin was shown to augment the cytotoxic effect of gemcitabine through down-regulation of ERK1/2 activation (Lev-Ari et al., 2007). Curcumin also inhibits the phosphorylation of AKT and enhances the phosphorylation of p38 MAPK. In addition, curcumin inhibits the proliferation of cisplatin-resistant ovarian cancer cells by inducing the generation of superoxide ions, G_2/M arrest, and apoptosis (Weir et al., 2007). Our study also shows that curcumin, as an ERK1/2 inhibitor, decreases cisplatin-induced ERK1/2 activation. Moreover, MKK1/2-CA transfection rescues the decreased phospho-ERK1/2 levels and improves cell viability, which was decreased by the cisplatin and curcumin cotreatment. Collectively, these results lead us

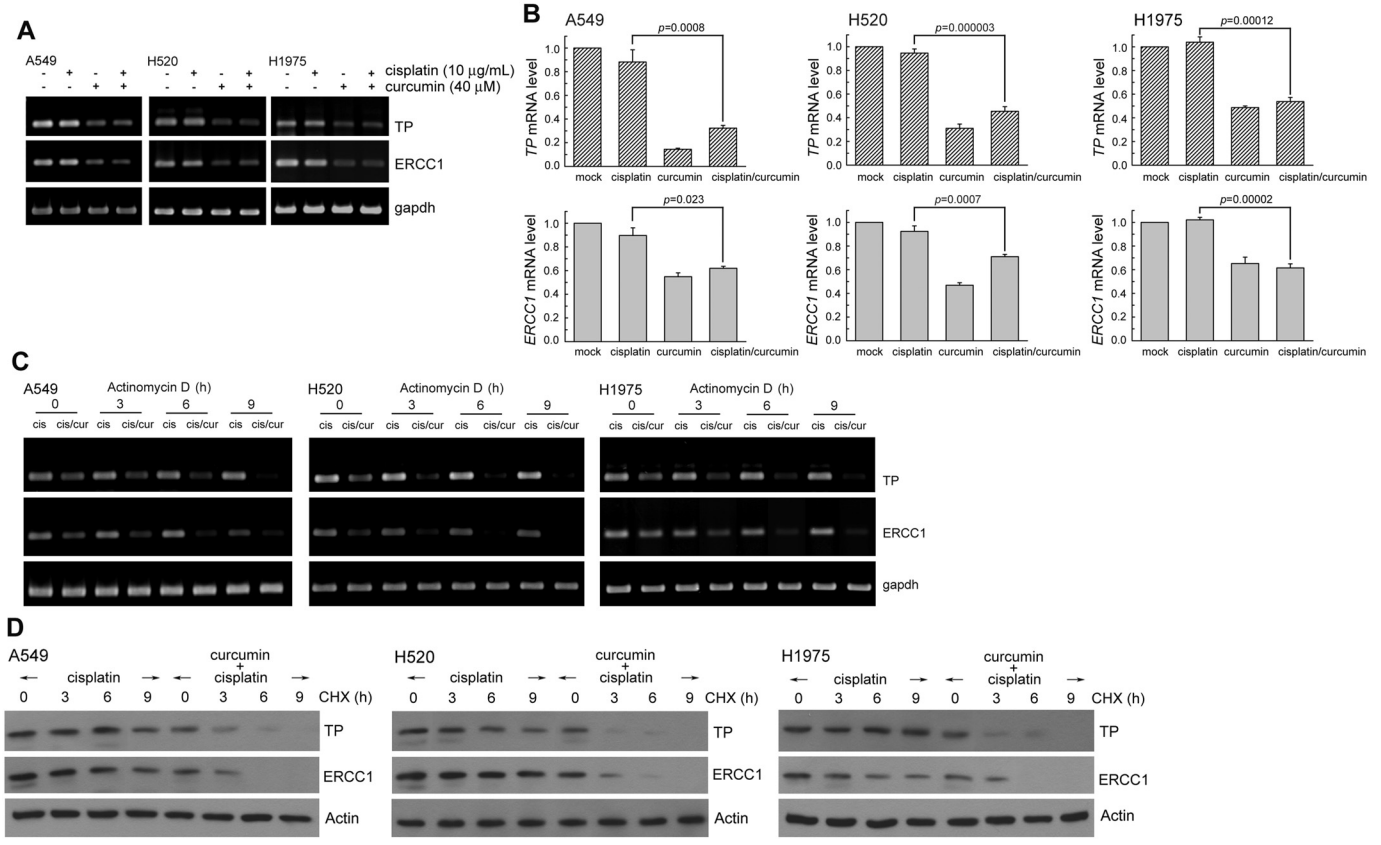

Fig. 6. TP and ERCC1 transcripts are decreased by the combination of curcumin and cisplatin in NSCLC cells. A and B, A549 or H1975 cells were treated with curcumin (40 μM) and/or cisplatin (10 μg/ml) for 24 h. Total RNA was isolated and expression levels of TP and ERCC1 genes were determined by RT-PCR and real-time PCR. **, $P < 0.01$, using the Student's *t* test for the comparison between cells treated with cisplatin alone and the cells cotreated with curcumin. C, cells were exposed to cisplatin (10 μg/ml) with or without curcumin (20 μM) for 9 h in the presence or absence of actinomycin D (2 μg/ml) for 3, 6, or 9 h. After the treatment, total RNA was isolated and subjected to RT-PCR for TP and ERCC1 transcripts. D, A549, H520, and H1975 cells were treated with cisplatin (10 μg/ml) alone or cotreated with curcumin (40 μM) for 9 h, followed by the addition of cycloheximide (60 μg/ml) for 3, 6, and 9 h. Whole-cell extracts were collected for Western blot analysis of TP and ERCC1 protein levels.

to conclude that the antiproliferative effects of the curcumin and cisplatin combination observed in NSCLC cells are mediated, at least in part, by inactivation of ERK1/2.

Curcumin seems to potentiate the cytotoxic effects of the other chemotherapeutic agents in several different types of cancer cells. For example, curcumin suppresses paclitaxel-induced expression of the antiapoptotic proteins XIAP, IAP-1, IAP-2, Bcl-2, and Bcl-xL and the proliferative proteins cyclooxygenase 2, c-Myc, and cyclin D1 (Aggarwal et al., 2005). Furthermore, curcumin suppresses the paclitaxel-induced NF-κB pathway in breast cancer cells and inhibits the metastasis of human breast cancer to the lungs in nude mice (Aggarwal et al., 2005). The combination of curcumin with paclitaxel augments the anticancer effects of paclitaxel against HeLa cells (Bava et al., 2005). This synergistic effect is related, in part, to the down-regulation of paclitaxel-induced NF-κB activation and phosphorylation of AKT pathways by curcumin. In this study, we also found that curcumin could enhance cisplatin sensitivity in human fibroblasts and human embryonic kidney 293 cells (Supplemental Fig. S1). Therefore, curcumin has a large potential in cancer therapy.

Many mechanisms of cisplatin resistance have been proposed, including changes in cellular uptake and efflux of the drug, inhibition of apoptosis, and increased DNA repair (Ohmichi et al., 2005). Tumor DNA repair capacity is frequently increased as an inherent cellular mechanism for evading cell death as a result of administration of chemotherapeutic drugs. This study and other previous studies show that curcumin could decrease the expression of DNA repair enzymes that are frequently associated with chemoresistance (Dhandapani et al., 2007). It has been found that curcumin can sensitize glioma cells to the action of cisplatin via a mechanism involving down-regulation of expression of DNA repair enzymes [methylguanine-DNA methyltransferase (MGMT),

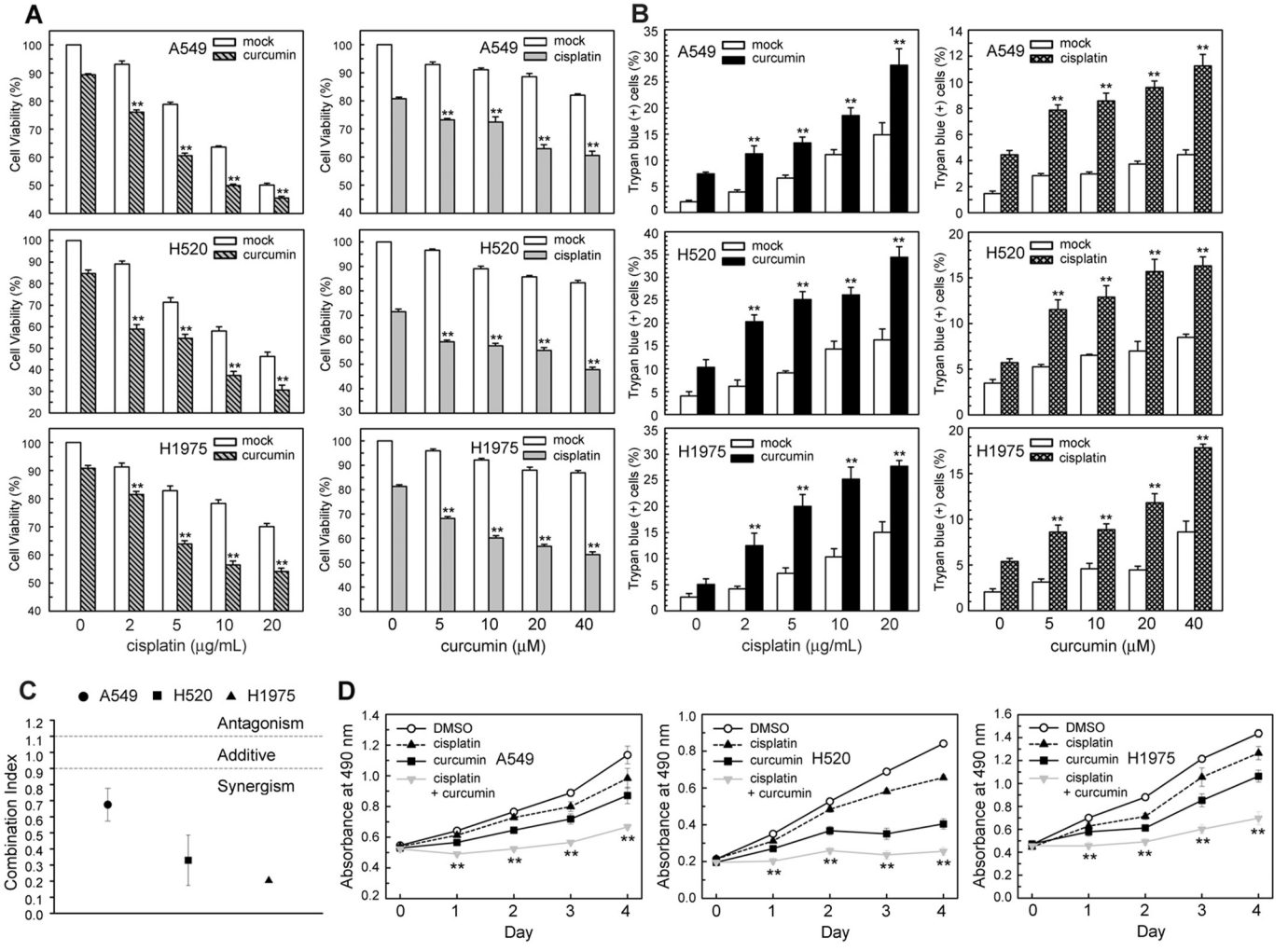

Fig. 7. Curcumin enhances the cisplatin-induced cytotoxic effects of NSCLC cell lines. A, cells were treated with curcumin (5–40 μM) and cisplatin (2–20 μg/ml) for 24 h. The cell viability was determined using the MTS assay. The results (mean ± S.E.M.) were obtained from three independent experiments. B, after the treatment described above, unattached and attached cells were collected and stained with trypan blue dye. The stained dead cells were counted manually. The columns indicate the percentage of trypan blue-positive cells, representing the population of dead cells. The bars indicate the SEM from three independent experiments. The results from the different cell lines treated with curcumin or cisplatin alone and the combination of these two drugs were compared. **, $P < 0.01$ (Student's t test). C, the mean of CI values for the curcumin–cisplatin combination treatment in A549, H520, and H1975 cells. CI values were averaged for each experiment and the values were used to calculate the mean between the experiments as described in *Materials and Methods*. The points and columns indicate the mean values obtained from three independent experiments. The bars indicate the S.E.M. D, cells were treated with cisplatin (0.5 μg/ml) and/or curcumin (20 μM) for 1 to 4 days. The viable cells were determined by the MTS assay on each day in triplicate. The results (mean ± S.E.M.) were from four independent experiments. **, $P < 0.01$, using the Student's t test for the comparison between cells treated with cisplatin alone or cotreated with curcumin.

DNA-PK, Ku70, Ku80, and ERCC-1] (Dhandapani et al., 2007). Moreover, curcumin-mediated inhibition of the Fanconi anemia/BRCA pathway sensitizes tumor cells to cisplatin, resulting in apoptotic death of ovarian and breast tumor cell lines (Chirnomas et al., 2006). Here, we have presented the first evidence that curcumin promotes sensitivity of cisplatin to NSCLC via ERK inactivation-mediated ERCC1 down-regulation. Our results support the previous findings that ERCC1 is a promising target for future investigations of treatments or methods to prevent human NSCLC.

Previous studies indicated that protein kinase C or Ras has been suggested to be involved in the activation of ERK1/2 by cisplatin (Woessmann et al., 2002; Basu and Tu, 2005). In this study, we found that cisplatin could activate ERK1/2 in human lung cancer cell lines. However, whether protein kinase C or Ras participate in up-regulating ERK1/2 activity in cisplatin-exposed NSCLC cells need further examined. Furthermore, our results indicated that curcumin could decrease cisplatin-elicited the expression of ERCC1 and enhance the sensitivity of cisplatin treatment for NSCLC. It has been reported that Snail (also known as Snail1) transcription factor up-regulates ERCC1 transcription and contributes to cisplatin resistance in head and neck squamous cell carcinoma cells (Hsu et al., 2010). Consistent with our previous study, depletion of endogenous ERCC1 expression by si-ERCC1 RNA transfection significantly enhance cisplatin's cytotoxic effect (Ko et al., 2010). In addition, both increased AP-1 (activator protein 1) levels and increased levels of Jun phosphorylation contribute to the increased transactivation of ERCC1 expression in cisplatin-treated human ovarian carcinoma cells (Li et al., 1998). In the present study, we have shown that cisplatin could increase TP protein levels in NSCLC cell lines. Previous findings indicated that TP has cytoprotective functions against cisplatin in human leukemia Jurkat cells, which are independent of its enzymatic activity (Ikeda et al., 2003). Moreover, TP confers cytoprotection against DNA-damaging agents (cisplatin, UV, VP-16) on tumor cells and that TP-induced antiapoptotic effects are at least partly mediated through regulation of the phosphatidyl inositol 3-kinase/AKT survival pathways (Jeung et al., 2006). However, the detail molecular mechanisms that cisplatin regulate TP expression in NSCLC cells is under our investigation.

In conclusion, our study indicates that curcumin synergies with cisplatin via down-regulation of TP and ERCC1. This highlights a key aspect of cisplatin resistance in NSCLC. Our results provide valuable insights for the development of future therapies in efforts to overcome cisplatin resistance in the treatment of NSCLC. On the basis of these findings, further investigations of curcumin as a cisplatin sensitizer is warranted and animal studies are ongoing to study the effect

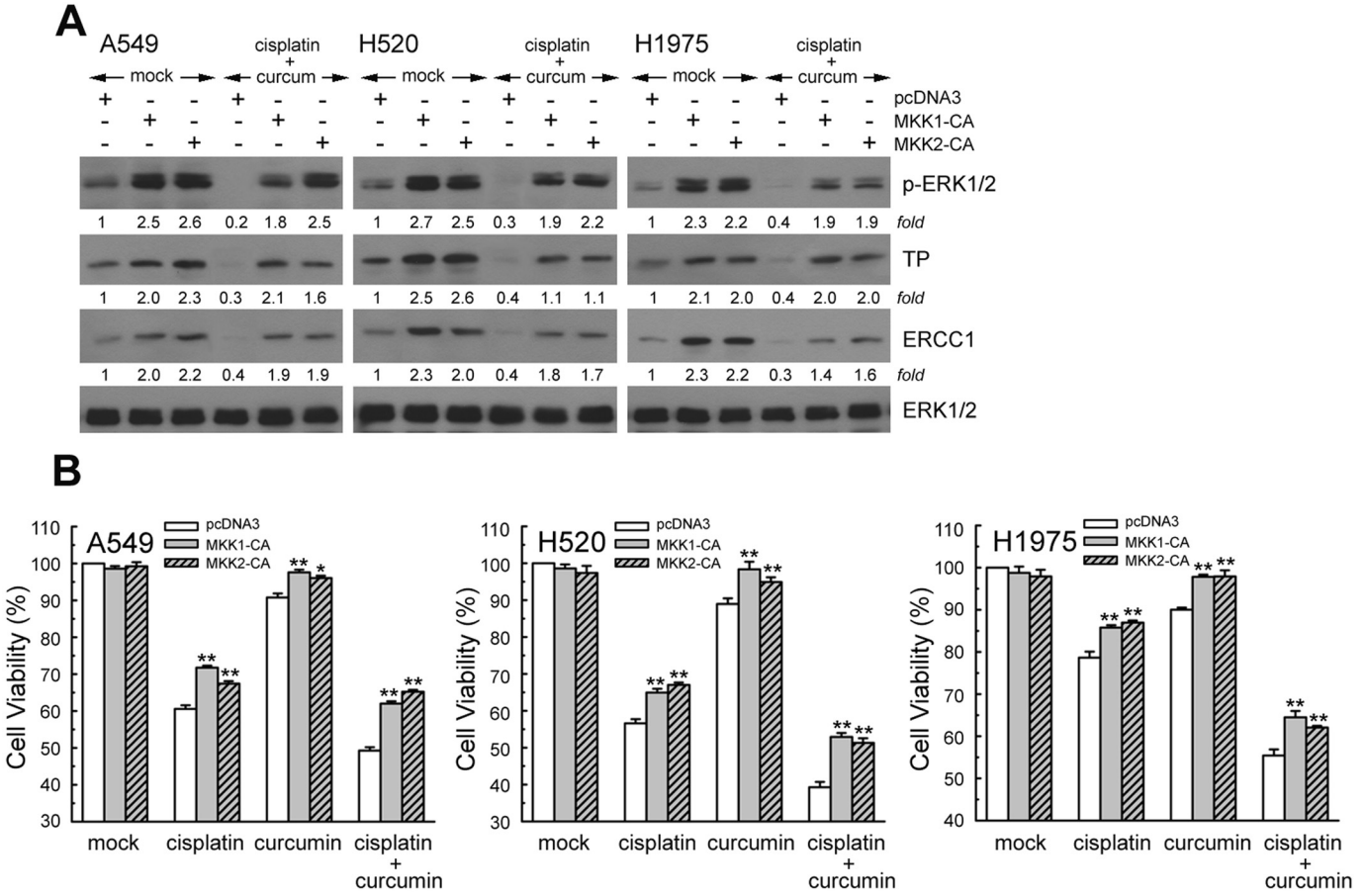

Fig. 8. Enforced expression of MKK1/2-CA vectors decreases the curcumin and cisplatin-induced cytotoxicity. A, cells were transfected with the MKK1/2-CA vectors for 24 h and then treated with cisplatin (10 μg/ml) and curcumin (20 μM) for 24 h. After treatment, cell extracts were examined by Western blot for the determination of phospho-ERK1/2, TP, and ERCC1 protein expression levels. B, cell viability was determined using the MTS assay. The results (mean ± S.E.M.) were from four independent experiments. The results from different cell lines transfected with MKK1/2-CA or pcDNA3 vector were compared. **, $P < 0.01$; *, $P < 0.05$ (Student's t test).

of combination curcumin and cisplatin in mouse models of NSCLC.

Acknowledgments

We thank Drs. Show-Mei Chuang and Jia-Ling Yang for providing us with expression plasmids for transfection.

Authorship Contributions

Participated in research design: Lin.

Conducted experiments: Tsai, Weng, Kuo, Chiu, and Lin.

Contributed new reagents or analytic tools: Tsai, Weng, Kuo, Chiu, and Lin.

Performed data analysis: Lin.

Wrote or contributed to the writing of the manuscript: Lin.

References

Aggarwal BB, Shishodia S, Takada Y, Banerjee S, Newman RA, Bueso-Ramos CE, and Price JE (2005) Curcumin suppresses the paclitaxel-induced nuclear factor-kappaB pathway in breast cancer cells and inhibits lung metastasis of human breast cancer in nude mice. *Clin Cancer Res* **11:**7490–7498.

Aggarwal S, Ichikawa H, Takada Y, Sandur SK, Shishodia S, and Aggarwal BB (2006) Curcumin (diferuloylmethane) down-regulates expression of cell proliferation and antiapoptotic and metastatic gene products through suppression of IkappaBalpha kinase and Akt activation. *Mol Pharmacol* **69:**195–206.

Altaha R, Liang X, Yu JJ, and Reed E (2004) Excision repair cross complementing-group 1: gene expression and platinum resistance. *Int J Mol Med* **14:**959–970.

Azuma K, Komohara Y, Sasada T, Terazaki Y, Ikeda J, Hoshino T, Itoh K, Yamada A, and Aizawa H (2007) Excision repair cross-complementation group 1 predicts progression-free and overall survival in non-small cell lung cancer patients treated with platinum-based chemotherapy. *Cancer Sci* **98:**1336–1343.

Basu A and Tu H (2005) Activation of ERK during DNA damage-induced apoptosis involves protein kinase Cdelta. *Biochem Biophys Res Commun* **334:**1068–1073.

Bava SV, Puliappadamba VT, Deepti A, Nair A, Karunagaran D, and Anto RJ (2005) Sensitization of taxol-induced apoptosis by curcumin involves down-regulation of nuclear factor-kappaB and the serine/threonine kinase Akt and is independent of tubulin polymerization. *J Biol Chem* **280:**6301–6308.

Chen YR and Tan TH (1998) Inhibition of the c-Jun N-terminal kinase (JNK) signaling pathway by curcumin. *Oncogene* **17:**173–178.

Chirnomas D, Taniguchi T, de la Vega M, Vaidya AP, Vasserman M, Hartman AR, Kennedy R, Foster R, Mahoney J, Seiden MV, et al. (2006) Chemosensitization to cisplatin by inhibitors of the Fanconi anemia/BRCA pathway. *Mol Cancer Ther* **5:**952–961.

Deeb D, Jiang H, Gao X, Hafner MS, Wong H, Divine G, Chapman RA, Dulchavsky SA, and Gautam SC (2004) Curcumin sensitizes prostate cancer cells to tumor necrosis factor-related apoptosis-inducing ligand/Apo2L by inhibiting nuclear factor-kappaB through suppression of IkappaBalpha phosphorylation. *Mol Cancer Ther* **3:**803–812.

Dhandapani KM, Mahesh VB, and Brann DW (2007) Curcumin suppresses growth and chemoresistance of human glioblastoma cells via AP-1 and NFkappaB transcription factors. *J Neurochem* **102:**522–538.

Dorai T, Cao YC, Dorai B, Buttyan R, and Katz AE (2001) Therapeutic potential of curcumin in human prostate cancer. III. Curcumin inhibits proliferation, induces apoptosis, and inhibits angiogenesis of LNCaP prostate cancer cells in vivo. *Prostate* **47:**293–303.

Du B, Jiang L, Xia Q, and Zhong L (2006) Synergistic inhibitory effects of curcumin and 5-fluorouracil on the growth of the human colon cancer cell line HT-29. *Chemotherapy* **52:**23–28.

Furuta T, Ueda T, Aune G, Sarasin A, Kraemer KH, and Pommier Y (2002) Transcription-coupled nucleotide excision repair as a determinant of cisplatin sensitivity of human cells. *Cancer Res* **62:**4899–4902.

Han SS, Keum YS, Seo HJ, and Surh YJ (2002) Curcumin suppresses activation of NF-kappaB and AP-1 induced by phorbol ester in cultured human promyelocytic leukemia cells. *J Biochem Mol Biol* **35:**337–342.

Hsu DS, Lan HY, Huang CH, Tai SK, Chang SY, Tsai TL, Chang CC, Tzeng CH, Wu KJ, Kao JY, et al. (2010) Regulation of excision repair cross-complementation group 1 by Snail contributes to cisplatin resistance in head and neck cancer. *Clin Cancer Res* **16:**4561–4571.

Ikeda R, Furukawa T, Mitsuo R, Noguchi T, Kitazono M, Okumura H, Sumizawa T, Haraguchi M, Che XF, Uchimiya H, et al. (2003) Thymidine phosphorylase inhibits apoptosis induced by cisplatin. *Biochem Biophys Res Commun* **301:**358–363.

Jemal A, Siegel R, Ward E, Murray T, Xu J, Smigal C, and Thun MJ (2006) Cancer statistics, 2006. *CA Cancer J Clin* **56:**106–130.

Jeung HC, Che XF, Haraguchi M, Furukawa T, Zheng CL, Sumizawa T, Rha SY, Roh JK, and Akiyama S (2005) Thymidine phosphorylase suppresses apoptosis induced by microtubule-interfering agents. *Biochem Pharmacol* **70:**13–21.

Jeung HC, Che XF, Haraguchi M, Zhao HY, Furukawa T, Gotanda T, Zheng CL, Tsuneyoshi K, Sumizawa T, Roh JK, et al. (2006) Protection against DNA damage-induced apoptosis by the angiogenic factor thymidine phosphorylase. *FEBS Lett* **580:**1294–1302.

Jung EM, Lim JH, Lee TJ, Park JW, Choi KS, and Kwon TK (2005) Curcumin sensitizes tumor necrosis factor-related apoptosis-inducing ligand (TRAIL)-induced apoptosis through reactive oxygen species-mediated upregulation of death receptor 5 (DR5). *Carcinogenesis* **26:**1905–1913.

Ko JC, Su YJ, Lin ST, Jhan JY, Ciou SC, Cheng CM, Chiu YF, Kuo YH, Tsai MS, and Lin YW (2010) Emodin enhances cisplatin-induced cytotoxicity via down-regulation of ERCC1 and inactivation of ERK1/2. *Lung Cancer* **69:**155–164.

Lev-Ari S, Vexler A, Starr A, Ashkenazy-Voghera M, Greif J, Aderka D, and Ben-Yosef R (2007) Curcumin augments gemcitabine cytotoxic effect on pancreatic adenocarcinoma cell lines. *Cancer Invest* **25:**411–418.

Li Q, Gardner K, Zhang L, Tsang B, Bostick-Bruton F, and Reed E (1998) Cisplatin induction of ERCC-1 mRNA expression in A2780/CP70 human ovarian cancer cells. *J Biol Chem* **273:**23419–23425.

Mori K, Hasegawa M, Nishida M, Toma H, Fukuda M, Kubota T, Nagasue N, Yamana H, Hirakawa-Ys Chung K, Ikeda T, et al. (2000) Expression levels of thymidine phosphorylase and dihydropyrimidine dehydrogenase in various human tumor tissues. *Int J Oncol* **17:**33–38.

Mori S, Takao S, Ikeda R, Noma H, Mataki Y, Wang X, Akiyama S, and Aikou T (2002) Thymidine phosphorylase suppresses Fas-induced apoptotic signal transduction independent of its enzymatic activity. *Biochem Biophys Res Commun* **295:**300–305.

Niedernhofer LJ, Odijk H, Budzowska M, van Drunen E, Maas A, Theil AF, de Wit J, Jaspers NG, Beverloo HB, Hoeijmakers JH, et al. (2004) The structure-specific endonuclease Ercc1-Xpf is required to resolve DNA interstrand cross-link-induced double-strand breaks. *Mol Cell Biol* **24:**5776–5787.

Ohmichi M, Hayakawa J, Tasaka K, Kurachi H, and Murata Y (2005) Mechanisms of platinum drug resistance. *Trends Pharmacol Sci* **26:**113–116.

Radhakrishna Pillai G, Srivastava AS, Hassanein TI, Chauhan DP, and Carrier E (2004) Induction of apoptosis in human lung cancer cells by curcumin. *Cancer Lett* **208:**163–170.

Rosell R, Lord RV, Taron M, and Reguart N (2002) DNA repair and cisplatin resistance in non-small-cell lung cancer. *Lung Cancer* **38:**217–227.

Rudin CM, Yang Z, Schumaker LM, VanderWeele DJ, Newkirk K, Egorin MJ, Zuhowski EG, and Cullen KJ (2003) Inhibition of glutathione synthesis reverses Bcl-2-mediated cisplatin resistance. *Cancer Res* **63:**312–318.

Schwer CI, Guerrero AM, Humar M, Roesslein M, Goebel U, Stoll P, Geiger KK, Pannen BH, Hoetzel A, and Schmidt R (2008) Heme oxygenase-1 inhibits the proliferation of pancreatic stellate cells by repression of the extracellular signal-regulated kinase1/2 pathway. *J Pharmacol Exp Ther* **327:**863–871.

Sève P and Dumontet C (2005) Chemoresistance in non-small cell lung cancer. *Curr Med Chem Anticancer Agents* **5:**73–88.

Shishodia S, Sethi G, and Aggarwal BB (2005) Curcumin: getting back to the roots. *Ann NY Acad Sci* **1056:**206–217.

Siddik ZH (2003) Cisplatin: mode of cytotoxic action and molecular basis of resistance. *Oncogene* **22:**7265–7279.

Tomita M, Kawakami H, Uchihara JN, Okudaira T, Masuda M, Takasu N, Matsuda T, Ohta T, Tanaka Y, and Mori N (2006a) Curcumin suppresses constitutive activation of AP-1 by downregulation of JunD protein in HTLV-1-infected T-cell lines. *Leuk Res* **30:**313–321.

Weir NM, Selvendiran K, Kutala VK, Tong L, Vishwanath S, Rajaram M, Tridandapani S, Anant S, and Kuppusamy P (2007) Curcumin induces G_2/M arrest and apoptosis in cisplatin-resistant human ovarian cancer cells by modulating Akt and p38 MAPK. *Cancer Biol Ther* **6:**178–184.

Woessmann W, Chen X, and Borkhardt A (2002) Ras-mediated activation of ERK by cisplatin induces cell death independently of p53 in osteosarcoma and neuroblastoma cell lines. *Cancer Chemother Pharmacol* **50:**397–404.

Woo JH, Kim YH, Choi YJ, Kim DG, Lee KS, Bae JH, Min DS, Chang JS, Jeong YJ, Lee YH, et al. (2003) Molecular mechanisms of curcumin-induced cytotoxicity: induction of apoptosis through generation of reactive oxygen species, down-regulation of Bcl-XL and IAP, the release of cytochrome c and inhibition of Akt. *Carcinogenesis* **24:**1199–1208.

Address correspondence to: Yun-Wei Lin, Molecular Oncology Laboratory, Department of Biochemical Science and Technology, National Chiayi University, Chiayi 600, Taiwan; Telephone: 886-5-271-7770; Fax: 886-5-271-7780; E-mail: linyw@mail.ncyu.edu.tw