Identification of a Novel Synthetic Triterpenoid, Methyl-2-cyano-3,12-dioxooleana-1,9-dien-28-oate, That Potently Induces Caspase-mediated Apoptosis in Human Lung Cancer Cells[1]

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Abstract

Lung cancer continues to be the leading cause of cancer-related death in the United States. Therefore, new agents targeting prevention and treatment of lung cancer are urgently needed. In the present study, we demonstrate that a novel synthetic triterpenoid methyl-2-cyano-3,12-dioxooleana-1,9-dien-28-oate (CDDO-Me) is a potent inducer of apoptosis in human non-small cell lung carcinoma (NSCLC) cells. The concentrations required for a 50% decrease in cell survival (IC_{50}) ranged from 0.1 to 0.3 μM. CDDO-Me induced rapid apoptosis and triggered a series of effects associated with apoptosis including a rapid release of cytochrome *c* from mitochondria, activation of procaspase-9, -7, -6, and -3, and cleavage of poly(ADP-ribose) polymerase and lamin A/C. Moreover, the caspase-3 inhibitor Z-DEVD-FMK and the pan caspase inhibitor Z-VAD-FMK suppressed CDDO-Me-induced apoptosis. These results indicate that CDDO-Me induced apoptosis in human NSCLC cells via a cytochrome *c*-triggered caspase activation pathway. CDDO-Me did not alter the level of Bcl-2 and Bcl-x_L proteins, and no correlation was found between cell sensitivity to CDDO-Me and basal Bcl-2 expression level. Furthermore, overexpression of Bcl-2 did not protect cells from CDDO-Me-induced apoptosis. These results suggest that CDDO-Me induces apoptosis in NSCLC cells irrespective of Bcl-2 expression level. In addition, no correlation was found between cell sensitivity to CDDO-Me and p53 status, suggesting that CDDO-Me induce a p53-independent apoptosis. Our results demonstrate that CDDO-Me may be a good candidate for additional evaluation as a potential therapeutic agent for human lung cancers and possibly other types of cancer.

Introduction

In the United States, lung cancer is the leading cause of cancer mortality among both men and women. It has been estimated that there will be 169,500 new cases and 157,400 deaths from lung cancer in 2001 (1). Unfortunately, the severe morbidity of lung cancer and the poor 5-year relative survival rate (only 14%) have not been improved by current treatments. Therefore, intense efforts are being mounted to find effective new agents and treatments against lung cancer.

Triterpenoids, biosynthesized in plants by the cyclization of squalene, are used for medicinal purpose in many Asian countries, and some of them were reported to have anticarcinogenic activity (2–5). Because the biological activities of some of the natural triterpenoids are relatively weak, new analogues of these molecules have been synthesized recently in an attempt to identify more potent agents (6–8). One of these analogues, CDDO,[3] was found to inhibit proliferation of many human cancer cells and to suppress the ability of various inflammatory cytokines, such as IFN-γ, interleukin-1, and tumor necrosis factor-α. CDDO also induce *de novo* formation of the enzymes, inducible nitric oxide synthase, and inducible cyclooxygenase, showing a potential for either chemopreventive or chemotherapeutic activity against malignancy (9). Moreover, CDDO was reported recently to induce apoptosis via a caspase-8-dependent mechanism in human osteosarcoma and myeloid leukemia cells (10, 11).

CDDO-Me is a derivative of CDDO (Fig. 1). This compound was as active as CDDO in suppressing the increased production of nitric oxide by IFN-γ in mouse macrophages (7). Interestingly, CDDO-Me was identified recently as a PPARγ antagonist, whereas CDDO was recognized as a PPARγ agonist (12). In this report, we compared the effects of CDDO and CDDO-Me on the growth of human NSCLC cell lines. We

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[3] The abbreviations used are: CDDO, 2-cyano-3, 12-dioxooleana-1,9-dien-28-oate; CDDO-Me, methyl-2-cyano-3,12-dioxooleana-1,9-dien-28-oate; NSCLC, non-small cell lung carcinoma; PARP, poly(ADP-ribose) polymerase; TUNEL, terminal deoxynucleotidyl transferase (Tdt)-mediated nick end labeling; SRB, sulforhodamine B; PI, propidium iodide; PPARγ, peroxisome-proliferator-activated receptor γ.

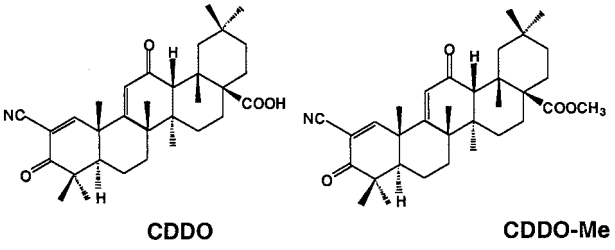

Fig. 1. Chemical structures of CDDO and CDDO-Me.

found that CDDO-Me was much more potent than CDDO in decreasing cell survival. Therefore, we focused additional studies on the induction of apoptosis by CDDO-Me and on some aspects of the mechanism of its action in human NSCLC cells.

Materials and Methods

Reagents. CDDO and CDDO-Me were synthesized at Dartmouth College (Hanover, NH; Ref. 7). They were dissolved in DMSO at a concentration of 10 mM, and aliquots were stored at −80°C. Stock solutions were diluted to the desired final concentrations with growth medium just before use. The caspase inhibitors CBZ-Val-Ala-Asp-Fluoromethyl Ketone (FMK; Z-VAD-FMK) and CBZ-Asp-Glu-Val-Asp-FMK (Z-DEVD-FMK) were purchased from Enzyme System Products (Livermore, CA).

Cell Lines and Cell Culture. H460, H1944, H596, H157, H1792, H522, H292, and H226 were obtained from Dr. Adi Gazdar (University of Texas Southwestern Medical Center, Dallas, TX). Calu-1, SK-MES-1, and A549 were purchased from the American Type Cell Culture (Rockville, MD). H460-Neo (vector control), H460-Bcl2–8 (a transfected clone that expresses a low level of exogenous Bcl-2), and H460-Bcl2–6 (a transfected clone that expresses a high level of exogenous Bcl-2) cell lines were generated as described previously (13). These cells were grown in monolayer culture in a 1:1 (v/v) mixture of DMEM and Ham's F12 medium supplemented with 5% fetal bovine serum at 37°C in a humidified atmosphere consisting of 5% CO_2 and 95% air.

Cell Survival Assay. Cells were seeded at densities ranging from 3×10^3 to 6×10^3 cells/well in 96-well tissue culture plates. On day 2, cells were treated with different concentrations of CDDO or CDDO-Me. Control cultures received the same amount of DMSO as did the treated cultures. At certain times after treatment initiation, cell numbers were estimated by the SRB assay as described previously (14). Cell survival was calculated by using the equation: % cell survival $= (A_t/A_c) \times 100$, where A_t and A_c represent the absorbance in treated and control cultures, respectively. IC_{50}, the drug concentration causing a 50% decrease in cell survival, was determined by interpolation from dose-response curves.

Detection of Apoptosis. Cells were plated on 10-cm diameter dishes 1 day before treatment. After a 24 h-treatment, cells were harvested by trypsinization and counted. One million cells were used for detecting DNA breaks or fragments possessing 3′-hydroxyl ends using an APO-DIRECT TUNEL kit (Phoenix Flow Systems, Inc., San Diego, CA) following the manufacturer's instructions. Another aliquot containing 1×10^6 cells was evaluated using an Annexin V-FITC Apoptosis Detection kit (Oncogene, Cambridge, MA), which measures phosphatidylserine externalized from the inner cytoplasmic layer to the outer surface layer of the cell membrane during apoptosis following the manufacturer's protocols. In this assay, combination of annexin V-FITC, and PI will allow us to distinguish cell populations among viable, early apoptotic, late apoptotic, and necrotic cells. Early apoptotic cells will bind only annexin V-FITC, and late apoptotic cells will be stained with both annexin V-FITC and PI, whereas necrotic cells will be only stained with PI. Additionally, DNA fragmentation was estimated using an ELISA Cell Death Detection kit (Roche Molecular Biochemicals, Indianapolis, IN) that quantitates the amount of cytoplasmic histone-associated DNA fragments increased during apoptosis following the manufacturer's protocols.

Western Blot Analysis. Whole cell lysates from both attached and detached (floating) cells were prepared as described previously (15), and protein concentration was determined using the Protein Assay kit (Bio-Rad, Hercules, CA). Cell lysates (50 μg) were electrophoresed through 7.5–12% denaturing polyacrylamide slab gels and transferred to a PROTRAN nitrocellulose transfer and immobilization membrane (Schleicher & Schuell, Inc., Keene, NH) by electroblotting. The blots were probed or reprobed with the antibodies, and then antibody binding was detected using the Renaissance Western Blot Chemiluminescence Reagent Plus (NEN Life Science Products, Boston, MA) according to the manufacturer's protocol. Mouse monoclonal anti-Bcl-2 (100) and rabbit polyclonal anti-Bcl-$X_{S/L}$ (S-18) antibodies were purchased from Santa Cruz Biotechnology, Inc. (Santa Cruz, CA). Rabbit polyclonal anti-Bax antibody, mouse anticaspase-3 (clone 19), mouse monoclonal anticaspase-7 (clone B94–1), and mouse monoclonal anticaspase-6 (clone 93–4) antibodies were purchased from PharMingen (San Diego, CA). Rabbit polyclonal anticaspase-9 and antilamin A antibodies were purchased from Cell Signaling Technology, Inc. (Beverly, MA). Mouse monoclonal anticaspase-3 antibody was purchased from IMGENEX (San Diego, CA). Rabbit polyclonal anti-PARP (VIC 5) and anti-β-actin antibodies were purchased from Roche Molecular Biochemicals and Sigma Chemical Co. (St. Louis, MO), respectively.

Measurement of Cytochrome *C* Release. Cells were plated onto 10-cm diameter dishes 1 day before treatment. After the cells were exposed to CDDO-Me for the indicated time, both floating and attached cells were harvested for preparation of cytosolic extracts and detection of cytochrome *c* as described previously (16). Mouse monoclonal anticytochrome *c* antibody (clone 7H8.2C12) was purchased from PharMingen.

Results

Effects of CDDO-Me on Cell Survival in Human NSCLC Cells. Lung cancers include small cell lung carcinoma and NSCLC. The latter include three types, adenocarcinoma,

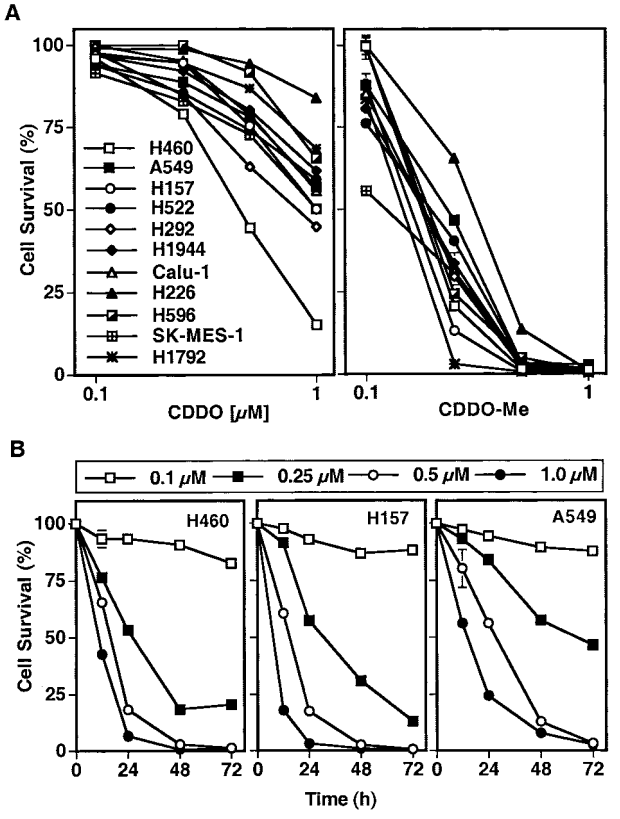

Fig. 2. Effects of CDDO-Me on growth of human NSCLC cells. Concentration- (*A*) and time- (*B*) dependent decrease of cell survival by CDDO-Me, respectively. Cells were seeded in 96-well plates and treated with the indicated concentrations of CDDO-Me for 3 days (*A*) or the indicated times (*B*). Cell numbers were then determined by the SRB assay. *Points,* mean of four replicate determinations; *bars,* ± SD.

epidermoid (or squamous), and large-cell carcinoma, and accounts for >75% of lung cancers (17). Therefore, we focused our study on determining the effects of CDDO-Me on cell growth in NSCLC cells. We first compared and contrasted the effects of CDDO-Me and CDDO on cell survival. As shown in Fig. 2*A,* CDDO-Me decreased survival of all 11 of the human NSCLC cells lines in a concentration-dependent fashion with IC_{50} for different cell lines ranging from 0.13 to 0.31 μM after a 3-day treatment. In contrast, CDDO exhibited much weaker effects than CDDO-Me on the survival of these cell lines with IC_{50} ranging from 0.45 to >1 μM. In fact, the IC_{50} of CDDO for 9 of 11 cell lines (except for H460 and H292) were ≥1 μM. The effects of CDDO-Me on cell survival were also time-dependent (Fig. 2*B*). Its action was very rapid. After a 12- or 24-h treatment, 1 μM of CDDO-Me decreased cell survival by >45% in the three tested cell lines. A549 was apparently less sensitive to CDDO-Me than H460 and H157 were. However, after prolonged treatment (*i.e.,* 3 days), a low dose (*i.e.,* 0.25 μM) of CDDO-Me still decreased cell survival by >50% in this cell line (Fig. 2*B*). We did not find any correlation between cell sensitivity to CDDO-Me and p53 status (Fig. 6*B*). For example, H157 cells carry mutant p53 (18) and were more sensitive to CDDO-Me than A549 cells, which have wild-type p53 (Ref. 18; Fig. 2). These results suggest that the effects of CDDO-Me on cell survival are p53-independent.

Induction of Apoptosis by CDDO-Me in Human NSCLC Cells. To elucidate whether CDDO-Me decreases cell survival through the induction of apoptosis in the NSCLC cells, we then examined the effects of CDDO-Me on apoptosis in three NSCLC cell lines (H157, H460, and A549) using different approaches. Using Annexin V-FITC assay, we detected the increase of both early apoptotic population (Annexin V-positive) and late apoptotic population (Annexin V- and PI-positive) by 50–70% after a 24-h treatment with 1 μM of CDDO-Me (Fig. 3*A*). There was only a small portion of cells undergoing necrosis (PI-positive), which was <5% in all three of the cell lines (Fig. 3*A*). Moreover, we also detected a concentration-dependent increase in apoptotic (*i.e.,* TdT-FITC-positive) cell population in the three NSCLC cell lines using a TUNEL-flow cytometry analysis. After a 24-h treatment, CDDO-Me at 1 μM caused >50% of the cells to undergo apoptosis in these cell lines, which were consistent with the results generated from Annexin V binding assay, whereas CDDO-Me at 0.25 μM did not induce apoptosis in A549 cells. However, ~30% of H157 and H460 cells still underwent apoptosis by 0.25 μM CDDO-Me (Fig. 3*B*). CDDO-Me at 0.5 μM induced apoptosis by 68.6%, 44.8%. and 17.4% in H157, H460, and A549 cells, respectively. It appears that A549 cells were less sensitive than H157 and H460 cells to CDDO-Me-induced apoptosis. Taken together, we conclude that CDDO-Me decreases cell survival through the induction of apoptosis in human NSCLC cells.

Induction of Cytochrome *C*-mediated Caspase Activation by CDDO-Me in Human NSCLC Cells. The cytochrome *c* release from mitochondria that leads to caspase activation represents an important apoptotic pathway, especially for apoptosis induced by cytotoxic agents (19–22). Therefore, we next examined the effects of CDDO-Me on several important events for apoptosis such as cytochrome *c* release, activation of caspases, and cleavage of some vital protein substrates in this pathway. We found that CDDO-Me not only triggered a rapid release of cytochrome *c* from mitochondria (Fig. 4*A*) but also activated procaspase-9 as evidenced by the appearance of a M_r 39,000 caspase-9 band on Western blot gel (Fig. 4*B*). The release of cytochrome *c* occurred as early as 4 h after treatment and, therefore, preceded the activation of procaspase-9, which occurred after a 6-h and a 12-h treatment in H460 and A549, respectively (Fig. 4, *A* and *B*). It is apparent that procaspase-9 was more rapidly activated in H460 than in A549 cells. We noted that low levels of cytochrome *c* were detected in untreated control cells. This could be caused either by spontaneous apoptosis or by a contamination of trace amount of mitochondrial protein during preparation of cytosolic fraction. Nevertheless, a large amount of cytochrome *c* was detected in cytosolic fractions prepared from CDDO-Me-treated cells, which were significantly higher than that from untreated cells (Fig. 4*A*).

Correspondingly, we observed a time-dependent activation of effector caspases including caspase-3, -6, and -7 in both H460 and A549 cells. Activation of these caspases was detected by Western blot analysis, evidenced by the de-

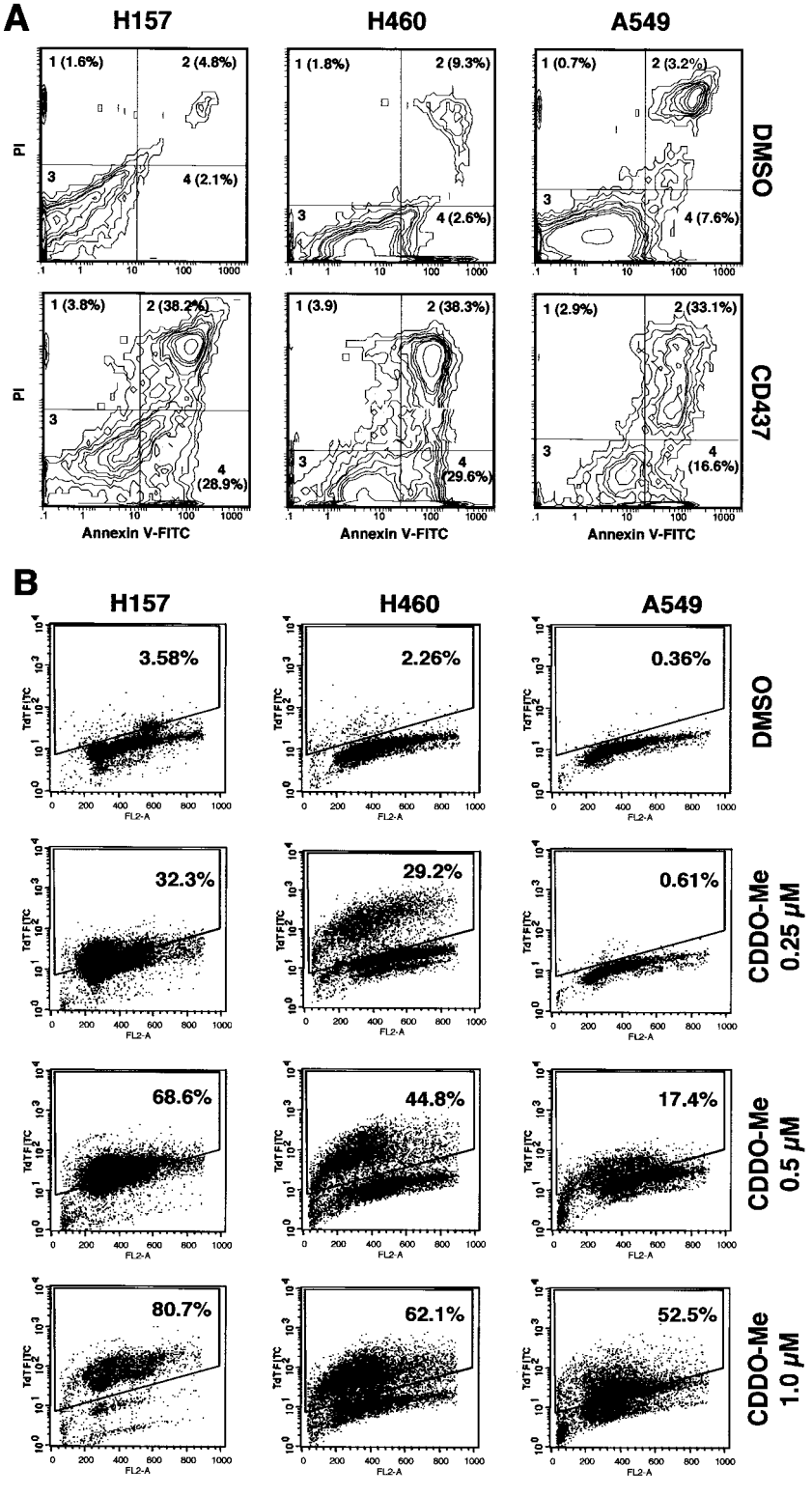

Fig. 3. Induction of apoptosis by CDDO-Me in human NSCLC cells. Cells were seeded in 10-cm diameter dishes and treated with 1 μM (*A*) or the indicated concentrations (*B*) of CDDO-Me for 24 h. Apoptosis was measured by Annexin V assay (*A*) and TUNEL analysis (*B*), respectively, as described in "Materials and Methods." *Gates 1, 2, 3,* and *4* in *A* represent necrotic, late apoptotic, viable, and early apoptotic cells, respectively. The *number in parenthesis of each gate* in *A* represents percentage of cells in the corresponding stage. The *numbers in top gates* in *B* represent percentages of TdT-FITC-positive (apoptotic) cells.

crease of procaspase forms, the appearance of their cleaved bands, and cleavage of their corresponding substrate proteins. As shown in Fig. 4*C,* after the treatment with CDDO-Me, the levels of procaspase-3, -6, and -7 were decreased, and these reductions were accompanied by the increased cleavage of their substrate PARP to an M_r 89,000 fragment in a time-dependent manner. We noted that the cleavage of PARP occurred after a 6-h treatment in H460 cells and after

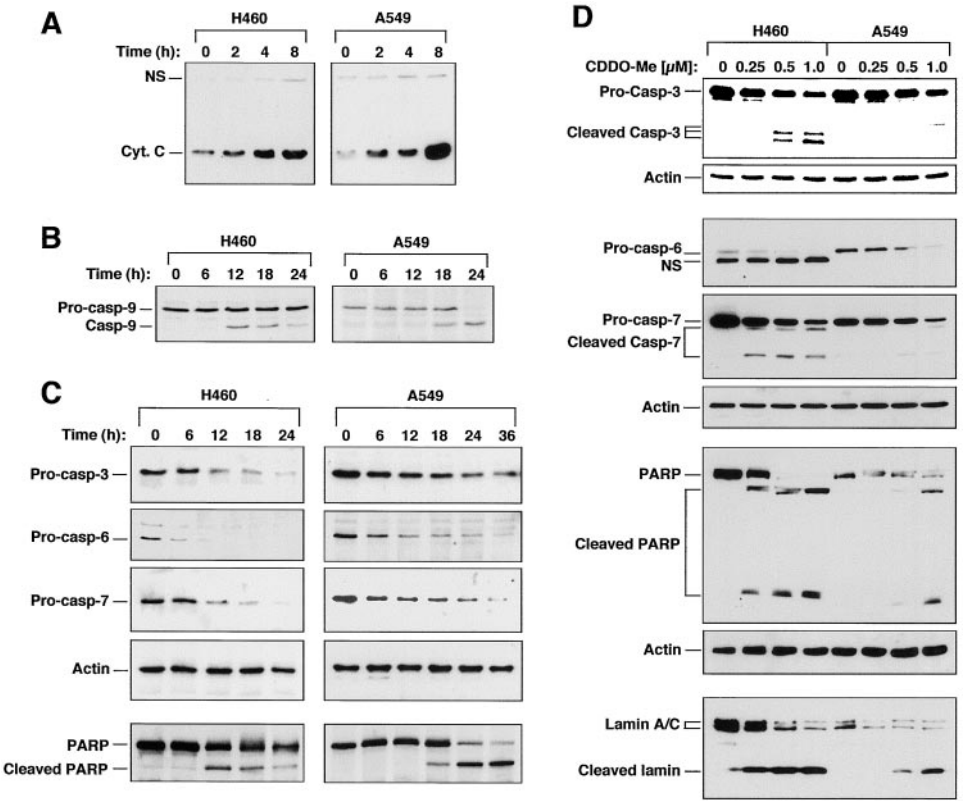

Fig. 4. Effects of CDDO-Me on cytochrome *c* release (*A*) and caspase activation (*B–D*) in human NSCLC cells. *A,* CDDO-Me increased cytochrome *c* release from mitochondria. After cells were exposed to 1 μM of CDDO-Me for the indicated times, they were harvested for the preparation of cytosolic fraction and detection of cytochrome *c* as described in "Materials and Methods." *Cyt. C*, cytochrome C; *NS,* nonspecific band. *B* and *C*, CDDO-Me activated procaspase-9 (*B*) and procaspase-3, -6, and -7 and increased cleavage of PARP (*C*) in a time-dependent fashion. *D*, concentration-dependent activation of procasapse-3, -6, and -7 and cleavage of PARP and lamin A/C. After cells were exposed to 1 μM CDDO-Me for the indicated times (*B* and *C*) or the indicated concentrations of CDDO-Me for 15 h (*D*), both floating and attached cells were harvested, and whole-cell protein lysates were prepared for Western blot analysis as described in "Materials and Methods." *Casp*, caspase.

a 12-h treatment in A549 cells, respectively, indicating that similar to caspase-9 activation, the activation of caspase-3 or -7 also happened more rapidly in H460 cells than in A549 cells. Moreover, we found that CDDO-Me also exerted a concentration-dependent effect on the activation of these effector caspases. As shown in Fig. 4*D,* CDDO-Me at a concentration of 0.25 μM was sufficient to activate caspase-3, -6, and -7 in H460 cells. However, a higher concentration (0.5 μM or higher) was needed to activate these caspases in A549 cells. Apparently, H460 cells were more sensitive than A549 cells to CDDO-Me-induced caspase activation, which is consistent with their responses to the effects of CDDO-Me on cell survival and apoptosis. Using different antibodies, we were able to detect not only a concentration-dependent decrease of the levels of procaspase-3 and -7 but also a concentration-dependent increase in the amount of cleaved bands (active forms of caspase) of caspase-3 and -7. We detected a decrease of procaspase-6 level but failed to detect cleaved forms of caspase-6. However, we could detect the cleavage of lamin A/C, which is a specific substrate of caspase-6 and a marker of caspase-6 activation (Ref. 23; Fig. 4*D*). Thus, CDDO-Me activates not only caspase-3 and -7 but also caspase-6 in both tested lung cancer cell lines. Taken together, these results demonstrate that CDDO-Me targets the mitochondria and activates cytochrome *c*-mediated caspase cascade.

Involvement of Activation of Caspase Cascade in CDDO-Me-induced Apoptosis. To determine whether activation of the caspase cascade is required for CDDO-Me-induced apoptosis, we examined the effect of CDDO-Me on apoptosis induction in the presence of caspase inhibitors. As shown in Fig. 5, the pan-caspase inhibitor Z-VAD-FMK and the caspase-3 inhibitor Z-DEVD-FMK suppressed CDDO-Me-induced apoptosis in both H460 and A549 cells. This indicates that activation of cytochrome *c*-mediated caspase cascade is required for CDDO-Me-induced apoptosis in human NSCLC cells.

CDDO-Me Induces Apoptosis Independent of Bcl-2 Expression Level. The proteins Bcl-2, Bcl-x_L, and Bax are important components of the apoptotic pathway and act as either negative or positive regulators of apoptosis (24). However, as shown in Fig. 6*A,* CDDO-Me did not change the expression level of either Bcl-2 or Bcl-x_L in H460 cells. CDDO-Me also did not change the expression level of Bax-β, but it did increase the level of Bax-α starting from 6 h after CDDO-Me treatment (Fig. 6*A*). Bcl-2 functions as an antiapoptotic protein (24). If Bcl-2 plays any role in CDDO-Me-induced apoptosis, its basal expression level may affect cell sensitivity to CCDO-Me, and overexpression of Bcl-2 should protect cells from apoptosis induced by CDDO-Me. By comparing the basal Bcl-2 expression levels of some NSCLC cell lines with the cytotoxic effects of CDDO-Me (IC_{50}), we found that NSCLC cell lines exhibited a similar sensitivity to CDDO-Me treatment regardless of basal Bcl-2 expression level, indicating that there was no simple correlation between basal Bcl-2 expression level and cell sensitivity to CDDO-Me (Fig. 6*B*). Furthermore, we stably transfected the *Bcl-2* gene or control neo gene into H460 cells and isolated two trans-

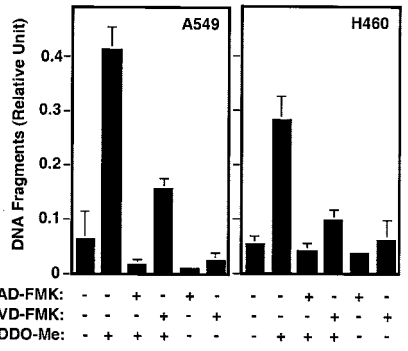

Fig. 5. Suppression of CDDO-Me-induced apoptosis by caspase inhibitors Z-VAD-FMK and Z-DEVD-FMK. Cells were pretreated with 100 μM caspase inhibitors for 30 min and then cotreated with the caspase inhibitors and 1 μM (*A549*) or 0.25 μM (*H460*) CDDO-Me for 24 h. Apoptosis was estimated by an ELISA method as described in "Materials and Methods." *Columns*, means of triplicate determinations; *bars*, $\pm$ SD.

fectants that expressed high (H460-Bcl2–6) and low level (H460-Bcl2–8) of exogenous Bcl-2 protein and a neo-transfected clone (H460-neo) that did not express exogenous Bcl-2 as determined by Western blotting (Fig. 6*C*). These two Bcl-2-overexpressing clones were shown to be resistant to apoptosis induced by tumor necrosis factor-related apoptosis-inducing agent (13), which has been demonstrated recently in several studies to be inactive or less active in inducing apoptosis in Bcl-2-overexpressing cells (25–28). The comparison of the effects of CDDO-Me on the survival of these transfectants indicated that CDDO-Me reduced the survival of the three transfectants to the near same degree, irrespective of the level of exogenous Bcl-2 (Fig. 6*D*). Taken together, these results demonstrate that CDDO-Me induces apoptosis independently of Bcl-2 levels in human NSCLC cells.

Discussion

The triterpenoid CDDO is a potent novel molecule with a wide range of actions, many of which are potentially useful for cancer prevention or treatment (9). More recently, this agent was reported to induce apoptosis in human myeloid leukemia and osteosarcoma cells (10, 11). In the present study, we investigated the effects of another triterpenoid CDDO-Me, a derivative of CDDO, on the cell growth and apoptosis using a panel of human NSCLC cell lines. Although CDDO-Me was found to be as active as CDDO in suppressing the increased production of nitric oxide by IFN-γ in mouse macrophages (7), we have demonstrated that CDDO-Me was much more potent than CDDO in decreasing the survival of human NSCLC cells. Therefore, CDDO-Me may be a better candidate for use as a therapeutic agent for cancer treatment. CDDO-Me decreases the survival of human NSCLC cells through induction of apoptosis. Therefore, our results warrant additional studies on the therapeutic activity of CDDO-Me *in vivo*. It should be pointed out that CDDO-Me inhibited cell growth or decreases cell survival not only in lung cancer cells but also in other types of cancer including human prostate, head and neck, colon, and breast cancer cells.[4]

Caspases play important roles in apoptosis triggered by various proapoptotic signals (19, 20). In general, activation of the caspase cascade requires both initiator caspases such as caspase-8, -9, and -10 and effector caspases such as caspase-3, -6, and -7. The effector caspases cleave several vital substrates such as PARP and DFF45 leading to apoptosis (19, 20). It has been well documented recently that the cytochrome *c* release from mitochondria and its activation of caspase-9 through binding to the protein Apaf-1 is thought to mediate apoptosis triggered by signals such as chemotherapeutic agents (19–22). In this study, CDDO-Me triggered a rapid release of cytochrome *c* from mitochondria to cytosol, activated procaspase-9 and its downstream procaspases including procaspase-3, -6, and -7, followed by the cleavage of their substrate PARP. Moreover, the pancaspase inhibitor Z-VAD-FMK and the caspase-3 inhibitor Z-DEVD-FMK suppressed CDDO-ME-induced apoptosis. Therefore, we conclude that CDDO-Me induces a cytochrome *c*-mediated, caspase-dependent apoptosis in human NSCLC cells.

Bcl-2, Bcl-x_L, and Bax have been implicated as major players in the control of apoptosis (19, 21). Bcl-2 and Bcl-x_L promote cell survival, whereas Bax promotes cell death (24, 29). More recently, these proteins have been found to regulate apoptosis by controlling cytochrome *c* release from mitochondria and activation of caspase-9 (24, 30). CDDO-Me did not alter the expression levels of Bcl-2 and Bcl-x_L, but it did elevate Bax-α level. Whether Bax-α increase plays a role in CDDO-Me-induced apoptosis in human NSCLC cells remains to be elucidated. By comparing the basal Bcl-2 expression levels with the cytotoxic effects of CDDO-Me in these cell lines, we did not find any correlation between the basal Bcl-2 expression level and cell sensitivity to CDDO-Me. Moreover, we found that overexpression of exogenous Bcl-2 failed to protect cells from CDDO-Me-induced apoptosis. Taken together, we conclude that CDDO-Me induces apoptosis independent of Bcl-2 level.

p53 is another important factor that affects the cell response to drug effects on growth inhibition and apoptosis induction (31, 32). The majority of evidence supports the notion that cells with wild-type p53 exhibit increased sensitivity to radiation or chemotherapeutic agents, whereas cells lacking wild-type p53 expression still undergo apoptosis but need a relatively high dose of radiation or chemotherapeutic drugs (31–35). In this study, we found that CDDO-Me decreased cell survival and induced apoptosis regardless of p53 status in human lung cancer cells. Therefore, we conclude that CDDO-Me-induced apoptosis in human cancer cells is p53-independent.

Recent studies have shown that PPARγ ligands induce apoptosis in several types of cancers including human lung cancer cells (36–39). CDDO-Me was reported recently to be a PPARγ antagonist, whereas CDDO is a PPARγ agonist (12). To determine whether CDDO-Me-induced apoptosis is

[4] P. Yue, R. Lotan, and S-Y. Sun, unpublished observations.

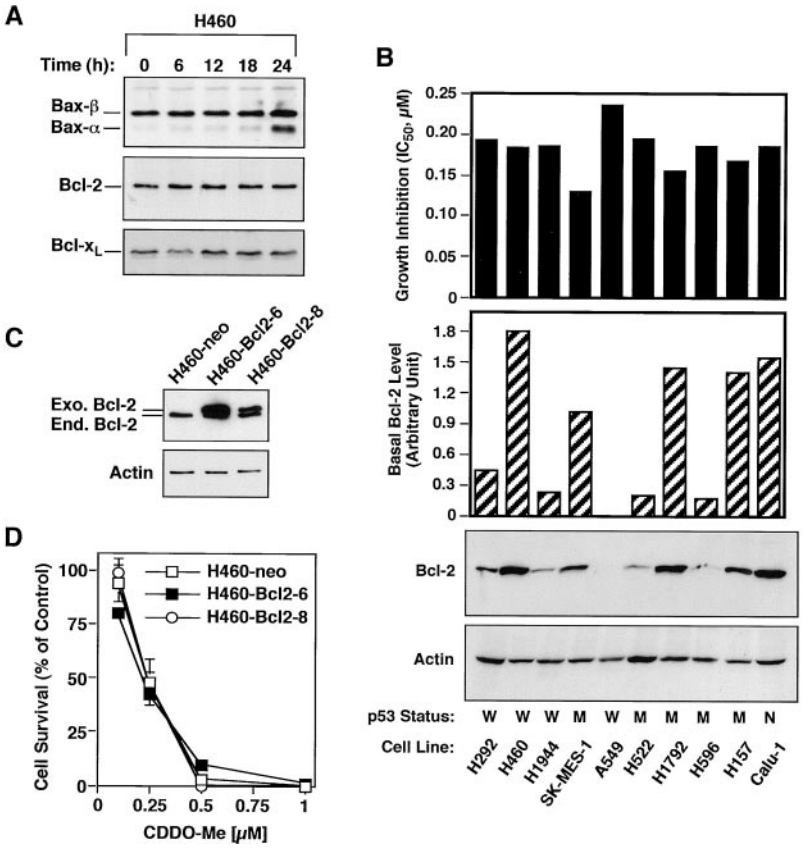

Fig. 6. CDDO-Me induces apoptosis independent of Bcl-2 level as well as p53 status in human NSCLC cells. *A*, effects of CDDO-Me on the levels of Bcl-2 family proteins. The same whole-cell protein lysates from H460 cells used in Fig. 4*B* and *C* were used in this study. *B*, comparison of basal Bcl-2 level, p53 status, and cell sensitivity to CDDO-Me among the NSCLC cells. Whole-cell protein lysates for detection of basal Bcl-2 expression level were prepared from different cell lines with similar density. IC_{50} was calculated based on cell survival results in Fig. 2*A*. p53 status of the NSCLC cell lines were reported previously (18, 31). *W,* wild-type; *M,* mutant; *N,* null. *C*, detection of endogenous and exogenous Bcl-2 expression in neo- and Bcl-2-transfected cells. *End,* endogenous; *Exo,* exogenous. *D,* overexpression of Bcl-2 in H460 cells failed to protect cells from apoptosis induced by CDDO-Me. The transfectants were seeded in 96-well plates and treated with the indicated concentrations of CDDO-Me for 2 days. Cell survival was evaluated by SRB assay described in "Materials and Methods." *Points,* mean of four replicate determinations; *bars,* ± SD.

linked to its antagonistic activity on PPARγ, we examined the apoptosis-inducing activity of CDDO-Me in the presence of several PPARγ agonists including CDDO, ciglitizone, and 15-deoxy-$\Delta^{12,14}$-prostaglandin J_2 (15d-PGJ_2). We speculated that the effect of CDDO-Me on apoptosis induction would be abrogated in the presence of PPARγ agonists if it induces apoptosis through binding to and antagonizing PPARγ. In fact, we found that cotreatment of cells with these PPARγ agonists either did not affect or even enhanced the effect of CDDO-Me on apoptosis depending on used cell lines.[5] These results suggest that the effect of CDDO-Me on apoptosis induction is unlikely to be mediated by antagonism of PPARγ pathway.

In conclusion, we have demonstrated that the novel synthetic triterpenoid CDDO-Me is a potent apoptosis-inducing agent in human NSCLC cells, which acts through a pathway involving cytochrome *c* release from mitochondria and subsequent activation of caspases. Moreover, CDDO-Me induces apoptosis independent of both p53 status and Bcl-2 level. Based on these findings, we suggest that CDDO-Me may be a good candidate for additional evaluation as a cancer therapeutic agent for human lung cancer as well as other types of cancer.

[5] P. Yue, R. Lotan, and S-Y. Sun, unpublished observations.

Acknowledgments

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