Zerumbone Enhances TRAIL-Induced Apoptosis through the Induction of Death Receptors in Human Colon Cancer Cells: Evidence for an Essential Role of Reactive Oxygen Species

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Abstract
Identification of the active component and mechanisms of action of traditional medicines is highly desirable. We investigated whether zerumbone, a sesquiterpene from tropical ginger, can enhance the anticancer effects of tumor necrosis factor–related apoptosis-inducing ligand (TRAIL). We found that zerumbone potentiated TRAIL-induced apoptosis in human HCT116 colon cancer cells and that this correlated with the up-regulation of TRAIL death receptor (DR) 4 and DR5. Induction of DRs occurred at the transcriptional level, and this induction was not cell-type specific, as its expression was also up-regulated in prostate, kidney, breast, and pancreatic cancer cell lines. Deletion of DR5 or DR4 by small interfering RNA significantly reduced the apoptosis induced by TRAIL and zerumbone. In addition to up-regulating DRs, zerumbone also significantly down-regulated the expression of cFLIP but not that of other antiapoptotic proteins. The induction of both DRs by zerumbone was abolished by glutathione and N-acetylcysteine (NAC), and this correlated with decreased TRAIL-induced apoptosis, suggesting a critical role of reactive oxygen species. Inhibition of extracellular signal-regulated kinase 1/2 and p38 mitogen-activated protein kinase but not of Jun NH2-terminal kinase abolished the effect of zerumbone on DR induction. Zerumbone also induced the p53 tumor suppressor gene but was found to be optional for DR induction or for enhancement of TRAIL-induced apoptosis.

Introduction
Many traditional medicines have been used for thousands of years, and although they are safe and affordable, neither the active components nor the mechanisms of action are understood. Moreover, as many as 70% of all drugs approved by the U.S. Food and Drug Administration in the past 25 years have been based on natural products. Zerumbone, a sesquiterpene, was first isolated from the rhizome of a subtropical wild shampoo ginger (Zingiber zerumbet) and determined to be an anti-inflammatory agent (1). It was found to have anticancer activity against a wide variety of tumor cells, including colon cancer (1, 2), leukemia (3), myeloid cancer (4), and liver cancer (5), and to inhibit phorbol ester–induced EBV activation (6). In vivo, this agent was found to suppress azoxymethane-induced colonic aberrant crypt foci in rats (2, 7), dextran sodium sulfate–induced colitis in mice (8), skin tumor initiation and promotion in mice (9), myeloid tumors in mice (4), cholecytokinin-induced acute pancreatitis in rats (10), CXCR4-mediated invasion of breast and pancreatic tumor cells (11), colon and lung carcinogenesis in mice (12), and human breast cancer–induced bone loss in nude mice (13). How zerumbone mediates all these effects is not understood, but suppression of constitutive and inducible nuclear factor-κB activation and nuclear factor-κB–regulated gene products has been shown by different groups (12, 14). In contrast, zerumbone has been found to have very little or no cytotoxic effect on the normal human endothelial cells (3) and dermal fibroblasts (1). The cytotoxic effect of zerumbone on leukemia cells was found to be mediated through the induction of Fas receptors (3), leading to activation of caspase-8. Whether zerumbone has any effect on apoptosis mediated through other death receptor (DR) is not known.

Tumor necrosis factor–related apoptosis-inducing ligand (TRAIL), a member of the tumor necrosis factor superfamily, is believed to regulate tumor cells killing through five different receptors, but only two of them, DR4 and DR5, are transmembrane receptors and mediate apoptosis. Engagement of DR4 and DR5 leads to the activation of caspase-8, which then leads to activation of caspase-9 and caspase-3 (15–17). The activation of caspase-8, also called FLICE, is inhibited by FLICE-interacting protein (cFLIP). The evidence that TRAIL may have an anticancer role also stems from the report that TRAIL deficiency accelerates the progression of hematologic malignancies (18). Because of its selectivity toward tumor cells, both TRAIL and agonistic antibodies against its receptor are currently in clinical trials for cancer treatment in combination with various chemotherapeutic agents (17).

Some tumor cells have been shown to be resistant to TRAIL, and this resistance appears to be mediated through the loss of TRAIL receptors, enhanced expression of caspases inhibitors such as cFLIP, X-linked inhibitor of apoptosis protein, cellular inhibitor of apoptosis protein, and survivin, or alternations in expression of the Bcl-2 family proteins (19). Thus, agents that can up-regulate TRAIL receptors and down-regulate antiapoptotic proteins have the potential to enhance the apoptotic effects of TRAIL. In this study, we sought to determine the effect of zerumbone on TRAIL-induced apoptosis in colon cancer cells. Our results show that zerumbone can potentiate the apoptosis induced by TRAIL...
through the up-regulation of DR4 and DR5 expression and the down-regulation of cFLIP.

Materials and Methods

Materials. Zerumbone was kindly supplied by Dr. Akira Murakami (Kyoto University). Soluble recombinant human TRAIL/Apo2L was purchased from PeproTech. Penicillin, streptomycin, DMEM, RPMI 1640, and fetal bovine serum were obtained from Invitrogen. All antibodies were obtained from Santa Cruz Biotechnology, BD Biosciences, or Cell Signaling. Small interfering RNA (siRNA) for DR5, DR4, and extracellular signal-regulated kinase (ERK) 1 were synthesized or purchased from Qiagen.

Cell lines. Human cell lines HCT116 (colon adenocarcinoma), HT29 (colon adenocarcinoma), H1299 (lung adenocarcinoma), A293 (embryonic kidney carcinoma), PC3 (prostate adenocarcinoma) and DU145 (prostate adenocarcinoma), MDA-MB-231 (breast adenocarcinoma) and MCF-7 (breast adenocarcinoma), and AsPC-1 (pancreatic adenocarcinoma) were obtained from the American Type Culture Collection. HCT116 variants with deletions in p53, p21, and bax were kindly supplied by Dr. Bert Vogelstein (John Hopkins University). The colon cancer cells (HCT116 and HT29) were cultured in McCoy's 5A medium with 10% fetal bovine serum and penicillin/streptomycin (Invitrogen). A293, MDA-MB-231, and MCF-7 were cultured in DMEM, and other cell lines were cultured in RPMI 1640 with 10% fetal bovine serum and penicillin/streptomycin.

Live/Dead Assay. This assay was done as described previously (14).

Cytotoxic assay. The effects of zerumbone on the cytotoxic effects of TRAIL agents were determined by the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide uptake method as described (20).

Clonogenic assay. Treated and untreated cells were seeded in 100 mm Petri dishes, allowed to form colonies for 14 days, and then stained as described (21).

Analysis of cell surface expression of DR4 and DR5. Treated and untreated cells were stained with phycoerythrin-conjugated mouse monoclonal anti-human DR5 or DR4 (R&D Systems) for 45 min at 4°C according to the manufacturer's instructions, resuspended and analyzed.
by flow cytometry with phycoerythrin-conjugated mouse IgG2B as an isotype control.

**Propidium iodide staining for DNA fragmentation.** Cells were pretreated with zerumbone for 12 h and then exposed to TRAIL for 24 h. Propidium iodide staining for DNA content analysis was done as described elsewhere (22).

**RNA analysis and reverse transcription-PCR.** Total RNA was extracted from the treated cells according to the manufacturer’s instructions (Invitrogen) and RT-PCR was done as described (11).

**Transfection with siRNA.** HCT116 cells were plated in each well of 6-well plates and allowed to adhere for 24 h. On the day of transfection, 12 μL Hiperfect transfection reagent (Qiagen) was added to 50 nmol/L siRNA in a final volume of 100 μL culture medium. After 48 h of transfection, cells were treated with zerumbone for 12 h and then exposed TRAIL for 24 h.

**Western blot analysis.** To determine the levels of protein expression, we prepared whole-cell extracts and analyzed by Western blot as described previously (14). To measure activation of mitogen-activated protein kinase (MAPK), whole-cell extracts from treated cells were subjected to Western blotting for phosphorylated ERK1/2, p38, and Jun NH2-terminal kinase (JNK). The same blots were stripped and reprobed with ERK1/2, p38, and JNK to ensure equal loading.

**Results**

The present studies were designed to investigate the effect of zerumbone on TRAIL-induced apoptosis. HCT116 colon cancer cells were used for most studies, but other cell types were also used to determine the specificity of this effect.

**Zerumbone sensitizes colon cancer cells to TRAIL-mediated apoptosis.** We determined whether zerumbone enhances TRAIL-induced apoptosis in HCT116 colon cancer cells. For this, cells were pretreated with zerumbone (20 μmol/L) for 12 h, washed with PBS to remove zerumbone, and then exposed to TRAIL (25 ng/mL) for 24 h. The results indicated that zerumbone and TRAIL treatment alone induced 11% and 5% apoptosis, respectively. Combination treatment with both zerumbone and TRAIL enhanced apoptosis to 79% (Fig. 1A). When apoptosis was examined using propidium iodide staining, we found that apoptosis was induced at 10.9% by zerumbone, 18.7% by TRAIL, and 57.9% by the combination of the two (Fig. 1B, left).

Whether zerumbone enhances the effect of TRAIL in long-term colony formation assay was also examined. We found that, under the conditions when zerumbone or TRAIL alone had minimal effect on colony formation of HCT116 cells, the combination treatment completely suppressed the colony-forming ability of these tumor cells (Fig. 1B, right).

We also examined the effect of zerumbone on TRAIL-induced cytotoxicity using the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide method, which detects the mitochondrial activity. For this experiment, cells were pretreated with various concentrations of zerumbone and then exposed to TRAIL. The results showed that the combination treatment with zerumbone and TRAIL significantly inhibited cell proliferation compared to the control group (Fig. 1C).

**Figure 2.** Zerumbone-induced DR5 and DR4 expression. A, HCT116 cells were treated with indicated doses of zerumbone at the indicated times. Whole-cell extracts were prepared and analyzed for DR4 and DR5 expression by Western blotting. B, zerumbone-induced DR5 gene expression. HCT116 cells were treated with zerumbone for 24 h, and total RNA was extracted and examined for expression of DR5 by RT-PCR. Glyceraldehyde-3-phosphate dehydrogenase (GAPDH) was used as an internal control to show equal RNA loading. C, HCT116 cells were treated with 20 μmol/L zerumbone for 24 h and then harvested for analysis of cell surface DR4 and DR5 by immunofluorescent staining and subsequent flow cytometry. Filled gray peaks, cells stained with a matched control phycoerythrin-conjugated IgG isotype antibody. D, cells were treated with 20 μmol/L zerumbone for 24 h, and whole-cell extracts were prepared and analyzed by Western blotting using. Equal protein loading was evaluated by β-actin.
Next, we examined the effect of zerumbone, TRAIL, and the combination on the activation of caspase-8, caspase-9, caspase-3, and poly(ADP-ribose) polymerase (PARP) cleavage. We found that although zerumbone and TRAIL had little effect on the caspases and PARP, the two together were highly effective (Fig. 1D). Together, our results indicate that zerumbone can enhance TRAIL-induced apoptosis.

**Zerumbone induces the expression of TRAIL receptors DR4 and DR5 in cancer cell lines.** To determine how zerumbone potentiates TRAIL-induced apoptosis, we investigated its effect on TRAIL receptors (DR4 and DR5). For this, HCT116 cells were treated with different concentrations of zerumbone for 24 h, and whole-cell extracts were prepared and examined for expression of DR4 and DR5 proteins. Zerumbone induced both DR4 (Fig. 2A, top left) and DR5 (Fig. 2A, top right) in a dose-dependent manner, with optimum induction occurring at around 20 to 30 μmol/L. Whether this induction of the DRs was dependent on time was also examined. Zerumbone induced both DR4 (Fig. 2A, bottom left) and DR5 (Fig. 2A, bottom right) in a time-dependent manner.

To determine whether induction of TRAIL receptors by zerumbone occurs at the transcriptional level, we examined mRNA for DR5 expression after cells had been treated with various concentrations of zerumbone. As shown in Fig. 2B, zerumbone induced the transcript for DR5 in a dose-dependent manner, thus suggesting that zerumbone acts at the transcriptional level.

Whether zerumbone enhances the expression of DRs on cell surface was also examined. For this, we analyzed cell surface expression of DR5 and DR4 in cells exposed to zerumbone. We found that zerumbone increased cell surface levels of DR5 and DR4 (Fig. 2C). The level of DR4 cell surface expression induced by zerumbone was lower than that of DR5. Collectively, these results indicate that zerumbone up-regulated the expression of both DRs on the cell surface.

We also investigated whether up-regulation of DR5 and DR4 by zerumbone was specific to HCT116 or also occurs in other cell types. For this, colon cancer cells (HT29 and HCT116), prostate cancer cells (PC3 and DU145), pancreatic cancer cells (AsPC-1), embryonic kidney cells (A293), and breast cancer cells (MDA-MB-231 and MCF-7) were exposed to zerumbone (20 μmol/L) for 24 h and then examined for DR5 and DR4 protein expression. Zerumbone induced the expression of DR5 (Fig. 2D, top) in HCT116, PC3, DU145, AsPC-1, A293, and MCF-7 cells. The sesquiterpene induced the expression of DR4 (Fig. 2D, middle) in HCT116, AsPC-1, A293, and MCF-7 cells. No significant induction of DR4 was noted in prostate cancer cell lines PC3 and DU145 (Fig. 2D). Induction of either DR4 or DR5 was minimal in breast cancer MDA-MB-231 and colon cancer HT29 cells after exposure to zerumbone. Together, these findings suggest that the up-regulation of DR5 and DR4 by zerumbone is not cell type specific.

**DR induction by zerumbone is needed for TRAIL-induced apoptosis.** To determine the role of DR5 and DR4 in TRAIL-induced apoptosis, we used siRNA specific to DR5 and DR4 to down-regulate the expression of these receptors. Transfection of cells with siRNA for DR5 but not with the control siRNA reduced zerumbone-induced DR5 expression (Fig. 3A). Similarly, transfection of cells with siRNA for DR4 reduced the zerumbone-induced DR4 expression (Fig. 3A). However, DR4 siRNA had minimal effect on the zerumbone-induced up-regulation of DR5.

We next examined whether the suppression of DR5 or DR4 by siRNA could abrogate the sensitizing effects of zerumbone on TRAIL-induced apoptosis using an esterase staining assay (the

concentrations of zerumbone for 12 h and then exposed to TRAIL for 24 h. HCT116 cells were moderately sensitive to either zerumbone or TRAIL alone. However, pretreatment with zerumbone enhanced TRAIL-induced cytotoxicity (Fig. 1C).
Live/Dead Assay). The results reveal that the effect of zerumbone on TRAIL-induced apoptosis was effectively abolished in cells transfected with either DR5 or DR4 siRNA (Fig. 3B), whereas treatment with control siRNA had no effect (Fig. 3B). Silencing of DR5 had more dramatic effect on TRAIL-induced apoptosis than that of DR4. The silencing of both receptors abolished the apoptosis as much as silencing of DR5 alone, thus suggesting that DR5 is a major player in TRAIL-induced apoptosis.

**Zerumbone down-regulates the expression of cFLIP but has no effect on X-linked inhibitor of apoptosis protein, survivin, and Bel-2 family proteins.** We examined whether zerumbone has any effect on the expression of any of the antiapoptotic proteins. Cells were exposed to different concentrations of zerumbone for 24 h and then examined for expression of cFLIP, X-linked inhibitor of apoptosis protein, survivin, Bcl-xL, and Bcl-2 expression. Zerumbone down-regulated the expression of both forms of cFLIP but had little effect on the other antiapoptotic proteins (Fig. 3C). Thus, it is possible that zerumbone affects TRAIL-induced apoptosis not only through induction of DR4 and DR5 but also through the down-regulation of cFLIP, an inhibitor of caspase-8.

**Zerumbone-induced up-regulation of TRAIL receptors is dependent on reactive oxygen species.** There has been a report that TRAIL-induced apoptosis is regulated by reactive oxygen species (ROS; ref. 23). Another study suggested that induction of DR5 by agents such as curcumin requires ROS and exposure of renal cancer cells to peroxide induces DR5 (24). We sought to determine whether zerumbone-induced TRAIL receptors are also regulated by ROS. As shown in Fig. 4A, pretreating HCT116 cells with the ROS scavenger N-acetylcysteine (NAC) reduced the zerumbone-induced up-regulation of both DR5 and DR4 expression in a dose-dependent manner. We also examined the effect of glutathione on the zerumbone-induced expression of TRAIL receptors and found that glutathione pretreatment abolished the induction of DR4 and DR5 by zerumbone in a dose-dependent manner (Fig. 4B). This suggests the critical role of ROS in the induction of TRAIL receptors by zerumbone.

We next examined whether scavenging of ROS could attenuate the TRAIL-induced cell death enhanced by zerumbone. As shown in Fig. 4C, zerumbone significantly enhanced TRAIL-induced apoptosis in colon cancer cells, and pretreatment of cells with...
NAC markedly reduced this zerumbone-induced enhancement from 73% to 20%.

Then we determined whether NAC pretreatment also attenuates the zerumbone-induced increase in activation of caspase-8, caspase-3, and PARP cleavage (Fig. 4D). We found that zerumbone enhanced TRAIL-induced cleavage of procaspase-8, procaspase-3, and PARP and that NAC abolished this increase, again suggesting the critical role of ROS.

Up-regulation of TRAIL receptors by zerumbone is reversed by inhibitors of MAPK. MAPKs, including ERK1/2, p38 MAPK, and JNK, have been shown to mediate the up-regulation of DR5 by bisindolylmaleimide and LY303511 (25, 26). We investigated whether these MAPKs have any role in zerumbone-induced TRAIL receptors. As shown in Fig. 5A, pretreatment of cells with an ERK1/2 inhibitor (PD98059) suppressed the zerumbone-induced up-regulation of DR4 and DR5 in a dose-dependent manner.

Pretreatment of cells with a p38 inhibitor (SB202190) also reduced zerumbone-induced DR4 up-regulation but to a lesser extent (Fig. 5A, middle). No effect of the p38 inhibitor was observed on zerumbone-induced DR4 and DR5 expression. Compared with inhibitors of ERK and p38 MAPK, JNK inhibitor had no effect on zerumbone-induced DR4 or DR5 expression (Fig. 5A, bottom).

We also examined whether zerumbone can activate ERK, p38 MAPK, and JNK. We found that zerumbone activated ERK in a time-dependent manner (Fig. 5B, top). Zerumbone activated p38 MAPK transitorily between 1 and 2 h and declined thereafter (Fig. 5B, middle). No effect of zerumbone was observed on the activation of JNK. Thus, the activation of these various MAPKs is consistent with the results obtained with the effect of their inhibitors on the zerumbone-induced expression of TRAIL receptors.

Zerumbone-induced activation of MAPK is dependent on ROS. Thus far, our data indicated that ERK and ROS are involved in expression of DR by zerumbone. Whether zerumbone-induced activation of MAPK is also dependent on ROS production was examined. To do this, cells were exposed to antioxidant NAC (20 mmol/L) for 1 h and then treated with 20 μmol/L zerumbone for 24 h. Whole-cell extracts were prepared and analyzed by Western blotting using DR4 and DR5 antibodies.

B. zerumbone-activated ERK. Cells were treated with 20 μmol/L zerumbone and whole-cell extracts were subjected to Western blotting for phosphorylated ERK1/2, p38, and JNK. The same blots were stripped and reprobed with ERK1/2, p38, and JNK to ensure equal loading. C. zerumbone-induced ERK activation is dependent on ROS. Cells were pretreated with NAC (20 mmol/L) for 1 h and then exposed to 20 μmol/L zerumbone for the indicated times. Whole-cell extracts were prepared and subjected to Western blotting using relevant antibodies. D. blockade of ERK reversed effect of zerumbone on TRAIL-mediated cell death. Cells were transfected with either ERK1 siRNA or control siRNA. After 48 h, cells were treated with 20 μmol/L zerumbone for 24 h, and whole-cell extracts were subjected to Western blotting (left). Right. cells and siRNA-transfected cells were pretreated with 20 μmol/L zerumbone for 12 h and then incubated with 25 ng/mL TRAIL for further 24 h. Cell death was determined by the PARP cleavage. Equal protein loading was evaluated by β-actin.
indicate that zerumbone-induced activation of MAPK is dependent on ROS.

Silencing of ERK blocks DR up-regulation and TRAIL sensitization. We next determined whether silencing of ERK blocks DR up-regulation and inhibits TRAIL sensitization. To examine this, HCT116 cells were transfected with control and specific siRNA against ERK1. After 48 h, cells were then exposed to zerumbone for 24 h and harvested, and lysates were subjected to Western blotting. The result indicates that the expression of ERK1 was significantly reduced in cells treated specific siRNA when compared with cells left untreated or treated with control siRNA (Fig. 5A, left). The reduction in expression of ERK1 by the siRNA correlated with suppression of zerumbone-induced up-regulation of DR5 and DR4 (Fig. 5A, left).

Furthermore, siERK1 significantly inhibited the enhancement of TRAIL-induced PARP cleavage by zerumbone. However, control siRNA had no effect (Fig. 5D, right).

Zerumbone can induce p53 but is not required for expression of TRAIL receptors. Numerous reports have suggested that p53 can induce DRs (27, 28). We examined whether zerumbone can induce p53 and, if so, whether this action mediates the induction of TRAIL receptors. As shown in Fig. 6A, zerumbone induced p53 expression in a dose- and time-dependent manner.

To determine whether p53 is needed for zerumbone-induced DRs induction, we used H1299 lung cancer cells that are deficient in p53 protein expression. As shown in Fig. 6B (left), zerumbone induced DR5 but not DR4 in p53-deficient H1299 cells, although these cells do not express p53 protein. To clarify the difference between results using colon and lung cancer cell lines, we also used a HCT116 variant in which p53 is deleted. Again, we found that zerumbone induced DR5 as well as DR4 in both wild-type and p53-deleted cells, thus indicating that p53 has no role in the induction of either DR by zerumbone (Fig. 6B, right).

To determine whether deletion of p53 modulates the apoptotic effect of zerumbone on TRAIL-induced apoptosis, we examined PARP cleavage. Enhanced apoptosis was observed when TRAIL was combined with zerumbone in wild-type cells, but this was unaffected in p53-deleted cells, suggesting that p53 induction plays little role in TRAIL-induced apoptosis (Fig. 6C, left). The enhancement of apoptosis by zerumbone, however, was abolished in cells in which either p21 (Fig. 6C, middle) or bax was deleted (Fig. 6C, right), suggesting the critical role of these two proteins.

Figure 6. A, zerumbone increased p53 expression. HCT116 cells were treated with various concentrations and times. Whole-cell extracts were prepared and analyzed by Western blotting using p53 antibody. B, effect of p53 on zerumbone-induced DR expression. H1299 cells (p53-null cells; left) and HCT116 and p53 variant cells (right) were treated with zerumbone for 24 h. Whole-cell extracts were prepared and analyzed by Western blotting using relevant antibodies. C, cells were pretreated with zerumbone for 12 h and exposed to TRAIL for 24 h. Whole-cell extracts were prepared and analyzed by Western blotting using indicated antibodies. D, HCT116 and bax variant cells were treated with zerumbone for 24 h. Whole-cell extracts were prepared and analyzed by Western blotting using relevant antibodies. Equal protein loading was evaluated by β-actin. wt, wild-type.
Deletion of bax has no effect on up-regulation of DR by zerumbone. Whether the deletion of bax modulates the expression of DR by zerumbone in HCT116 cells was examined. The effect of bax on the expression of DR5 and DR4 induced by zerumbone was investigated using bax-deleted cells. Results show that zerumbone increased the expression of bax, DR5, and DR4 in wild-type cells, but deletion of bax had no effect on the induction of these receptors by zerumbone (Fig. 6D). These results suggest that bax is not linked to the up-regulation of DR expression by zerumbone.

Discussion

In the present report, we show that zerumbone, a component of wild ginger, can enhance the apoptotic effects of TRAIL against colon cancer cells. The mechanism by which zerumbone mediates its effects on TRAIL-induced apoptosis appears to involve the induction of TRAIL receptors and down-regulation of cFLIP, an inhibitor of caspase-8. We found that the induction of DRs by zerumbone was not cell type specific but was observed in a wide variety of cell types, including colon, breast, prostate, kidney, and pancreatic cancer cells. Induction of TRAIL receptors in some cells, however, was much more pronounced than that in other cell types. We found that zerumbone had no effect on human breast cancer MDA-MB-231 and colon cancer HT29 cells. Both of these cell lines are known to express mutant p53 (29, 30). Our results, however, show that the lack of induction of receptors by zerumbone is not due to mutation in p53. The mechanism by which this sesquiterpene induces DR5 appears to occur at the transcriptional level. We also found that zerumbone induces TRAIL receptors through the generation of ROS as shown by our results that NAC and glutathione abolished the induction of DRs. The results regarding the induction of DRs by zerumbone through ROS are consistent with those in previous reports regarding curcumin (24), inactive phosphatidylinositol 3-kinase inhibitor LY303511 (26), proteasome inhibitors (28), H2O2 (31), baicalein (32), and 15-deoxy-A12,14-prostaglandin J2 (33). We found that an increase in TRAIL-induced apoptosis by zerumbone was also reversed by NAC and glutathione. Apoptosis induced by TRAIL alone is also resistant to TRAIL. Whether the deletion of bax modulates the expression of DRs by zerumbone is an open question. We found that zerumbone induced p53 protein expression. Although p53 expression has been implicated in the expression of DR5 (28, 42), we found that zerumbone-induced DR5 expression was mediated through a p53-independent mechanism. No induction of DR4, however, was observed in p53-null cells. That p53 plays a role in the up-regulation of DR4 has already been shown (43). Thus, it is possible that the role of p53 in the induction of DR4 and DR5 depends on the nature of the stimulus and the cell type. We found that the ability of zerumbone to enhance TRAIL-induced apoptosis was unaffected by a lack of p53 expression in cells.

Overall, we conclude that zerumbone can enhance TRAIL-induced apoptosis through the up-regulation of DRs and the down-regulation of cFLIP. Considering that zerumbone when used alone is highly safe and exhibits anticancer activities in vitro (1–5) and in vivo (1, 2, 7, 9, 12) against a wide variety of tumors, we suggest that it can be also used in combination with TRAIL that is in clinical trials currently. Thus, these studies have an implication in treatment of cancer by TRAIL, especially tumors that develop resistance to TRAIL.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

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