Vitamin E δ-Tocotrienol Augments the Antitumor Activity of Gemcitabine and Suppresses Constitutive NF-κB Activation in Pancreatic Cancer

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Abstract

The NF-κB transcription factor functions as a crucial regulator of cell survival and chemoresistance in pancreatic cancer. Recent studies suggest that tocotrienols, which are the unsaturated forms of vitamin E, are a promising class of anticancer compounds that inhibit the growth and survival of many cancer cells, including pancreatic cancer. Here, we show that tocotrienols inhibited NF-κB activity and the survival of human pancreatic cancer cells in vitro and in vivo. Importantly, we found the bioactivity of the four natural tocotrienol compounds (α-, β-, δ-, and γ-tocotrienol) to be directly related to their ability to suppress NF-κB activity in vitro and in vivo. The most bioactive tocotrienol for pancreatic cancer, δ-tocotrienol, significantly enhanced the efficacy of gemcitabine to inhibit pancreatic cancer growth and survival in vitro and in vivo. Moreover, we found that δ-tocotrienol augmentation of gemcitabine activity in pancreatic cancer cells and tumors is associated with significant suppression of NF-κB activity and the expression of NF-κB transcriptional targets (Bcl-X<sub>L</sub>, X-linked inhibitor of apoptosis, and survivin). Our study represents the first comprehensive preclinical evaluation of the activity of natural vitamin E compounds in pancreatic cancer. Given these results, we are conducting a phase I trial of δ-tocotrienol in patients with pancreatic cancer using pancreatic tumor cell survival and NF-κB signaling components as intermediate biomarkers. Our data also support future clinical investigation of δ-tocotrienol to augment gemcitabine activity in pancreatic cancer. Mol Cancer Ther; 10(12); 2363–72. ©2011 AACR.

Introduction

Pancreatic cancer is a leading cause of cancer mortality with less than 5% of patients surviving 5 years after diagnosis (1). Gemcitabine is a mainstay treatment for pancreatic cancer (2). However, tumor resistance to gemcitabine therapy is common, making this a critical challenge for pancreatic cancer management.

Prosurvival signaling mediated by the transcription factor NF-κB is a key player in gemcitabine resistance in pancreatic cancer (3–11). Therefore, targeting dysregulated NF-κB signaling is an important strategy to improve the efficacy of gemcitabine therapy and thereby improve outcomes for patients with pancreatic cancer. Several studies have combined natural compounds that inhibit NF-κB, such as genistein, curcumin, fisetin, and green tea, with gemcitabine to investigate synergy in treating pancreatic cancer (11–14). However, translation of these studies to the clinic has been challenging due to the low bioavailability of some of these natural compounds in humans.

Tocotrienols, a group of 4 (α-, β-, δ-, and γ-tocotrienol) unsaturated naturally occurring vitamin E compounds (Fig. 1A), have received increasing attention for their potential as nontoxic dietary anticancer agents (15, 16). Our group recently showed that oral administration of 100 mg/kg/d of δ-tocotrienol to mice resulted in levels that were 10 times higher in pancreas than in subcutaneously implanted tumor tissue, suggesting that these compounds will have reasonable bioavailability for pancreatic tumor intervention (17). In this study, we investigated the potential of the 4 natural tocotrienols to inhibit pancreatic cancer and NF-κB activation in vitro and in vivo. In addition, we investigated the potential of the most bioactive tocotrienol to augment gemcitabine activity in vitro and in vivo.

Materials and Methods

Chemicals and cell lines

All chemicals and reagents were purchased from Sigma-Aldrich unless otherwise specified. Tocotrienols (α, β, γ, and δ) and α- and δ-tocopherol were obtained from Davos Life Ltd. Gemcitabine-HCl was purchased from Eli Lilly and...
and Company. l-Glutamine, penicillin, streptomycin, and HEPES buffer were purchased from Mediatech. FBS was purchased from HyClone. Dulbecco’s Modified Eagle’s Medium (DMEM), RPMI-1640, keratinocyte serum-free medium, sodium pyruvate, trypsin-EDTA, and PBS were purchased from Invitrogen. Ethanol (100%) was purchased from Aaper Alcohol and Chemical. Pancreatic cancer cell lines MiaPaCa-2 and AsPc-1 were obtained from American Type Culture Collection (ATCC). Human pancreatic ductal epithelial cells (HPDEe C7) and HPDE6 C7-KRas cells were gifts from Dr. Tsao, Ontario Cancer Institute, University of Toronto, Toronto, Ontario, Canada. These cells were authenticated by morphologic, cell proliferation, and mycoplasma tests, as recommended in ATCC Technical Bulletin No. 8 (2007).

**Cell culture and growth**

HPDE6 C7 and HPDE6 C7-KRas cells were grown in keratinocyte growth media (Invitrogen) supplemented with human epidermal growth factor and bovine pituitary extract. MiaPaCa-2 and AsPc-1 cells were grown in monolayers with DMEM and RPMI media, respectively, supplemented with 10% FBS, 2 mmol/L l-glutamine, penicillin (50 IU/mL), and streptomycin (50 mg/mL). RPMI medium was also supplemented with 10^{-2} mol/L HEPES buffer and 10^{-3} mol/L sodium pyruvate. Cells were cultured at 37°C in a humidified atmosphere of 5% CO_2 and 95% O_2.

**Cell proliferation MTT assay**

Cells were seeded in 96-well plates at a density of 3,000 cells per well and allowed to attach overnight. Cells were then incubated for 72 hours with various concentrations of α- , β- , γ- , and δ-tocotrienol and α-tocopherol (10^{-5} to 10^{-4} mol/L). In other experiments, cells were incubated for 72 hours with gemcitabine and δ-tocotrienol (10^{-5} to 10^{-4} mol/L) and their combination or ethanol (3%) in PBS as vehicle control. Media were aspirated and replaced with 20 μL of 1 mg/mL MTT and incubated for 2 to 4 hours at 37°C in a humidified atmosphere of 5% CO_2.
aspirated, 200 μL of dimethyl sulfoxide was added to each well, plates were incubated for 5 minutes with shaking, and absorbance was read at 540 nm.

Isobologram analysis
Gemcitabine and δ-tocotrienol were combined at ratios of 1:1 and 1:2 of their IC₅₀ values to plot the isobologram using fraction effects and combination index (CI) through CalcuSyn software (Biosoft). Constant ratio (IC₅₀ ratio) of the 2-drug combination is used. The dose range (different fraction of the IC₅₀ values) and effects (proliferation) are entered in CalcuSyn, which displays the parameters (Dₑ, m, and r) as well as isobologram using CI, where Dₑ is the median effect dose signifying the potency, m is measurement of the sigmoidicity (shape) of the dose–effect curve, and r is linear correlation coefficient of the median effect plot. The software analyzes the quantitative measure of the degree of drug interactions in terms of additive effect (CI = 1), synergism (CI < 1), or antagonism (CI > 1), based on a published method (18).

Trypan blue dye exclusion assay
Treated cells were trypsinized and washed with PBS, and cell suspension (50 μL) was mixed with 50 μL of trypan blue dye and incubated for 2 minutes at room temperature. A 10-μL volume was loaded onto a hemocytometer, and cells were scored as live or dead on the basis of trypan blue exclusion.

Cell death assay
Cytoplasmic DNA fragments and histone were detected in cells using Cell Death Detection ELISA kit from Roche Diagnostic.

Colonogenic survival (anchorage-independent) growth assay
The standard soft agar colony formation assay was conducted in MiaPaCa-2 cells. Cells were seeded at a density of 5,000 per well in 12-well plates in 0.3% agar over a 0.6% bottom agar layer. Colonies were fed with growth media and α, β, γ, and δ-tocotrienol or α/δ-tocopherol (5 × 10⁻⁵ mol/L), and colony formation growth was observed for 14 days. In other experiments, colonies were fed with growth media and gemcitabine (2 × 10⁻⁵ mol/L) and δ-tocotrienol (5 × 10⁻⁵ mol/L) and their combination, and colony formation growth was observed for 14 days. Colonies were photographed after overnight incubation with 1 mg/mL MTT in the wells. Colonies were counted under stereomicroscope and compared with controls. Experiments were done at least twice, each in triplicate.

NF-κB (p65) binding activity assay
NF-κB binding activities in nuclear and cytosolic fractions of MiaPaCa-2 cells were determined using the Trans AM ELISA Kit from Active Motif, according to manufacturer’s instructions.

Caspase enzyme activity assay
Treated cells were lysed with lysis buffer (0.5 mmol/L Tris/pH 8.0, 5 mmol/L EDTA/pH 8, 0.15 mmol/L NaCl, 0.5% NP-40). The enzymatic activities of caspase-3, 8, and 9 were determined using specific fluorogenic substrates. The liberated fluorescent 7-amido-4-methyl-coumarin groups were quantified using a multiwell plate VersaFluor fluorometer at 355-nm excitation and 460-nm emission wavelengths (Bio-Rad).

Cell lysis and protein determination
Cells were washed 3 times in cold PBS (pH 7) and then lysed in mammalian protein extraction reagent lysis buffer (Pierce) containing EDTA and protease inhibitor cocktail. Protein concentration was determined using BCA reagents (Pierce) according to manufacturer’s instructions.

Western blot analysis
Extracted proteins from cells and tumor tissues (40 μg) were resolved on 12.5% SDS-PAGE running gel and 5% stacking gel. Proteins were then electrotransferred onto nitrocellulose membranes. After blocking in 5% nonfat powdered milk for 1 hour, membranes were washed and treated with antibodies to CK18, PARP-1, NF-κB subunits (p65/p50), 1xBo, p-1xBo, Bcl-XL, X-linked inhibitor of apoptosis (XIAP), survivin, and β-actin (1:1,000 and 1:5,000) overnight at 4°C (Axzora; Santa Cruz Biotechnology; Cell Signaling). After they were washed, blots were incubated with horseradish peroxidase–conjugated secondary antibody IgG (1:5,000 and 1:10,000) for 1 hour at room temperature. Washed blots were then treated with SuperSignal West Pico chemiluminescent substrate (Pierce) for positive antibody reaction. Membranes were exposed to X-ray film (Kodak) for visualization and densitometric quantization of protein bands using AlphaEaseFC software (Alpha Innotech).

Animals and treatments
Female NIH severe-combined immunodeficient (SCID) nude mice (4–5 weeks old, 20–25 g) were obtained from Charles River and kept in our Center’s animal facility for 1 week for quarantine. Mice (n = 25) were injected with AsPc-1 cells (one million) with Matrigel (100 μL) to both flanks. When tumor volume reached 100 mm³, mice were randomly divided into the following 5 treatment groups: (i) normal controls: 100 μL oral gavage of ethanol extracted olive oil (vehicle) twice daily for 4 weeks, (ii) α-tocotrienol treated, (iii) β-tocotrienol treated, (iv) γ-tocotrienol treated, and (v) δ-tocotrienol treated. Tocotrienols were administered at 200 mg/kg oral gavage twice daily for 4 weeks. In other experiments, mice (n = 20) were injected with AsPc-1 cells (one million) with Matrigel (100 μL) to both flanks. When tumor volume reached 100 mm³, mice were randomly divided into the following 4 treatment groups: (i) normal controls: 100 μL oral gavage of ethanol extracted olive oil (vehicle) twice daily for 4 weeks, (ii) δ-tocotrienol treated (200 mg/kg oral gavage twice daily for 4 weeks), (iii) gemcitabine treated...
(100 mg/kg intraperitoneally twice a week for 4 weeks), and (iv) δ-tocotrienol + gemcitabine treated (200 mg/kg oral gavage daily plus gemcitabine at 100 mg/kg intraperitoneally twice a week for 4 weeks). Tumor volumes were measured every other day. Animal studies were approved by our Institutional Laboratory Animal Care and Use Committee and were conducted per the guidelines of the NIH.

Statistical analysis
Data are expressed as means ± SEM and were analyzed statistically using unpaired t tests or one-way ANOVA, where appropriate. ANOVA was followed by Duncan multiple range tests using SAS statistical software for comparison between different treatment groups. Significance was set at \( P < 0.05 \).

Results

Effect of tocotrienols on growth and survival of pancreatic cancer cells in vitro
Using the MTT assay, we found that natural tocotrienols have variable inhibitory effects on human pancreatic cancer cells, with δ-tocotrienol and γ-tocotrienol exhibiting the most significant inhibitory effects (cell viability reduced up to 60% with 50 μmol/L and β-tocotrienol having a moderate inhibitory effect (cell viability reduced up to 40% with 50 μmol/L; Fig. 1B).

Tumor volumes in the β-δ- and γ-tocotrienol groups were also significantly lower from day 15 \((P < 0.05)\) to end of treatment \((P < 0.01)\) for β- and γ-tocotrienol and \(P < 0.001\) for δ-tocotrienol). On day 34, δ-tocotrienol significantly reduced tumor volume by 50% \((P < 0.001)\), γ-tocotrienol reduced tumor volume by 42% \((P < 0.01)\), and β-tocotrienol reduced tumor volume by 32% \((P < 0.01)\). In contrast, α-tocotrienol did not significantly decrease tumor growth.

Effect of tocotrienols on NF-κB activation in pancreatic cancer cells
Because previous studies have shown that γ-tocotrienol can suppress constitutive NF-κB activation in pancreatic cancer cells \((19)\), the possibility that tocotrienol bioactivity in pancreatic cancer is related to NF-κB suppression was considered. As illustrated in Fig. 3A, tocotrienol treatment suppressed constitutive NF-κB activation in a tocotrienol compound-dependent manner. The extent of NF-κB activity inhibition was found to be significant for γ- and δ-tocotrienol in the nuclear extract and for β-, γ-, and δ-tocotrienol in the cytosolic extract. Interestingly, α-tocotrienol and α-tocopherol had no effect on NF-κB activity. These results were further confirmed by immunoblotting experiments in AsPC-1 and MiaPaCa-2 cells (Fig. 3B) and in tumor tissues of mice xenografted with AsPC-1 cells (Fig. 3C). A crucial step in the activation of NF-κB proteins is the phosphorylation of IκBα freeing NF-κB complexes to translocate to the nucleus where they induce target gene expression, including prosurvival factors such as Bcl-2, survivin, and XIAP. As shown in Fig. 3B and C, δ-tocotrienol consistently suppressed NF-κB/p65 and phosphorylated IκBα expression in pancreatic cancer cells and tumor tissues, consistent with downregulation of Bcl-2, survivin, and XIAP in pancreatic cancer cells and tumor tissues. Consistent with a previous report,
\(\gamma\)-tocotrienol also suppressed NF-\(\kappa\)B proteins and their target genes (19). However, \(\alpha\)- and \(\beta\)-tocotrienol did not suppress the NF-\(\kappa\)B proteins, p-I\(\kappa\)B or Bcl-X\(L\), survivin, and XIAP, in a consistent fashion.

**\(\delta\)-Tocotrienol augments inhibition of pancreatic cancer cell proliferation by gemcitabine**

Recently, \(\gamma\)-tocotrienol was reported to augment gemcitabine activity and to inhibit NF-\(\kappa\)B activation in pancreatic cancer cells (19). Because we observed that both \(\gamma\)- and \(\delta\)-tocotrienol significantly inhibited NF-\(\kappa\)B activation, we investigated whether \(\delta\)-tocotrienol augmented gemcitabine inhibition of pancreatic cancer growth. The effects of \(\delta\)-tocotrienol and gemcitabine alone and in combination on AsPc-1 and MiaPaCa-2 cell proliferation were determined by MTT. Cells were treated with vehicle, \(\delta\)-tocotrienol, gemcitabine, or \(\delta\)-tocotrienol + gemcitabine at (0–100 \(\mu\)mol/L) for 72 hours (Fig. 4A). At 10 to 100 \(\mu\)mol/L, \(\delta\)-tocotrienol + gemcitabine significantly augmented gemcitabine inhibition of cell proliferation. Furthermore, to confirm synergism, we determined CI values for 2 combination treatment groups. Our results show that cells treated with gemcitabine + \(\delta\)-tocotrienol at a ratio of 1:1 had additive/antagonistic loss of cell viability (CI = 1.32), whereas cells treated with gemcitabine + \(\delta\)-tocotrienol at 1:2 showed synergistic loss of cell viability (CI = 0.89; Fig. 4B). We further investigated the effects of gemcitabine and \(\delta\)-tocotrienol alone and in combination on anchorage-independent growth of MiaPaCa-2 cells using soft agar colony formation assay (Fig. 4D). Gemcitabine (20 \(\mu\)mol/L) alone inhibited colony formation by 84%; \(\delta\)-tocotrienol (50 \(\mu\)mol/L) alone inhibited colony formation by 67%. Gemcitabine (20 \(\mu\)mol/L) plus \(\delta\)-tocotrienol (50 \(\mu\)mol/L) resulted in 99% inhibition of anchorage-independent growth.

**\(\delta\)-Tocotrienol augments gemcitabine-induced apoptosis in pancreatic cancer cells**

We next compared whether enhanced cytotoxicity by gemcitabine + \(\delta\)-tocotrienol was mediated by apoptosis. Figure 4C shows that, relative to single-agent gemcitabine, combination with \(\delta\)-tocotrienol elicited a significantly (\(P < 0.001, P < 0.01\)) higher percentage of cell death in pancreatic cancer cell lines, suggesting that the loss of viable cells is due to the induction of cell death pathway. We confirmed this by measuring the fold increase in apoptosis in MiaPaCa-2 cells using the cell death ELISA and the caspase-3 activity assay. While treatment of MiaPaCa-2 cells with gemcitabine and \(\delta\)-tocotrienol as single agents increased apoptosis, gemcitabine + \(\delta\)-tocotrienol significantly augmented the fold increase in apoptosis. Caspase-3 activity was also

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**Figure 2.** A. effect of in vivo tocotrienols on AsPc-1 pancreatic tumor growth in SCID nude mice. B. tumor volume in \(\delta\)-, \(\gamma\)-, and \(\beta\)-tocotrienol groups was significantly decreased compared with vehicle. Points, means; bars, SE; \(n = 10\); \(P < 0.05\); \(P < 0.01\); \(P < 0.001\); \(P < 0.0001\). C, expression of apoptosis marker CK18 and proapoptotic Bax protein in AsPc-1 cells (\(n = 3\)) by Western blot analysis. D, CK18 and Bax expression in mouse tumor tissues (\(n = 5\)) by Western blot analysis. V, vehicle.
observed to be significantly elevated ($P < 0.001$) in the combination treatment group. PARP-1, a 116-kDa nuclear PARP-1, is one of the main cleavage targets of caspase-3 in vivo, serving as a marker of cells undergoing apoptosis (20). Our data confirm induction of apoptosis by gemcitabine, $\delta$-tocotrienol, and the combination of the 2 agents in AsPc-1 and MiaPaCa-2 cells.

**$\delta$-Tocotrienol downregulates constitutively activated NF-$\kappa$B in gemcitabine-treated pancreatic cancer cells**

MiaPaCa-2 cells were exposed to 50 $\mu$mol/L $\delta$-tocotrienol, 20 $\mu$mol/L gemcitabine, or their combination for 72 hours, and their nuclear extracts were subjected to NF-$\kappa$B DNA binding activity assay (ELISA). We found that gemcitabine alone did not significantly affect NF-$\kappa$B DNA binding activity (Fig. 5A). Interestingly, treatment with $\delta$-tocotrienol significantly inhibited binding activity, with combined gemcitabine and $\delta$-tocotrienol significantly inhibiting NF-$\kappa$B DNA binding activity more than either drug alone. These results were further confirmed by Western immunoblotting in AsPc-1 and MiaPaCa-2 cells. As shown in Fig. 5B, expression levels of NF-$\kappa$B/p65 and NF-$\kappa$B/p50 proteins were significantly depleted in cells treated with $\delta$-tocotrienol and in those treated with gemcitabine + $\delta$-tocotrienol. In
addition, we assessed the antiapoptotic molecules Bcl-XL, survivin, and XIAP. Relative to control and gemcitabine alone, Bcl-XL, survivin, and XIAP expression levels were downregulated in cells exposed to δ-tocotrienol alone and in cells exposed to gemcitabine + δ-tocotrienol. These results strongly suggest that the augmentation of gemcitabine activity in pancreatic cancer cells by δ-tocotrienol is, in part, due to the inactivation of NF-κB and its downstream genes by δ-tocotrienol.

δ-Tocotrienol enhances the in vivo therapeutic effects of gemcitabine in a pancreatic tumor model in SCID nude mice

On the basis of our in vitro results, we designed studies to determine the effects of δ-tocotrienol and gemcitabine in a human model of pancreatic tumor in SCID nude mice (Fig. 6A). The dose of δ-tocotrienol was determined from our previous studies of δ-tocotrienol pharmacokinetics in mice (17); our in vitro data indicated that a 2:1 ratio of δ-tocotrienol +
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Figure 5. A, effect of gemcitabine (Gem) and δ-tocotrienol alone and in combination on NF-κB/p65 DNA binding activity in nuclear compartment of MiaPaCa-2 cells. Gemcitabine was refractory to p65 binding to DNA, whereas δ-tocotrienol significantly decreased p65 binding to DNA (*, P < 0.01) compared with vehicle. However, the combination resulted in greater inhibition of p65 binding to DNA than vehicle (**, P < 0.001) or gemcitabine alone (***, P < 0.01). Bars (means) ± SE (n = 3). B, expression of NF-κB subunit and NF-κB-regulated antiapoptotic proteins (n = 3).

AsPc-1 cells were implanted in the subcutaneous tissue of flanks of SCID nude mice. Mice were randomly assigned to the 4 treatment groups (see Materials and Methods), with treatment continued per experimental protocol for 23 days. Animals were euthanized on the last day of the therapy. To determine the effects of treatment on tumor development, we assessed tumor volume on days 0 to 23 of treatment. As shown in Fig. 6B, on day 12, tumor volumes in the δ-tocotrienol alone and δ-tocotrienol + gemcitabine groups were significantly lower than tumor volumes in vehicle and gemcitabine alone treatment groups (P < 0.01 and P < 0.001). From treatment day 17, tumor volumes in mice treated with δ-tocotrienol + gemcitabine were significantly reduced compared with those shown in mice treated with gemcitabine or δ-tocotrienol alone. The results are in accordance with the in vitro results.

We next examined the cleavage of PARP-1, a marker of apoptosis, in the tumor tissues of mice as well as the expression of the proapoptotic protein Bax. As shown in Fig. 6C, δ-tocotrienol, gemcitabine, and δ-tocotrienol + gemcitabine induced PARP-1 cleavage in mouse tumors. Bax expression was significantly induced in the δ-tocotrienol alone and the gemcitabine + δ-tocotrienol tumors compared with vehicle and gemcitabine alone.

Effect of δ-tocotrienol + gemcitabine treatment on NF-κB activation and NF-κB-regulated gene products

We further investigated whether the effects of combining δ-tocotrienol and gemcitabine on tumor growth in mice were associated with inhibition of NF-κB activation. Our Western blot analysis results clearly show that NF-κB/p65 and NF-κB/p50 proteins and the NF-κB transcriptional targets Bcl-XL, survivin, and XIAP were moderately downregulated by δ-tocotrienol alone. Similar to our in vitro studies, gemcitabine alone did not affect the expression of NF-κB or NF-κB–regulated gene products. However, similar to our in vitro studies, constitutively active NF-κB was almost completely suppressed in tumor samples of mice treated with δ-tocotrienol + gemcitabine (Fig. 6D). Tumors also revealed downregulation of important NF-κB–regulated proapoptotic proteins (Bcl-XL, survivin, and XIAP).

Discussion

Our results clearly show that the 4 natural tocotrienols have different abilities to inhibit cancer growth and survival. We show that δ- and γ-tocotrienol consistently inhibited cancer growth and survival in vitro and in vivo. In contrast, α- and β-tocotrienol and α-tocopherol do not inhibit growth and survival of pancreatic cancer cells. Our data agree with the results reported by Hussein and Mo (21) who showed that δ-tocotrienol suppressed the proliferation of Panc-1, MiaPaCa-2, and BxPc-3 human pancreatic cancer cells. Our results are also in agreement with Kunnumakkara and colleagues (19) who reported that γ-tocotrienol inhibited the growth and survival of Panc-1, MiaPaCa-2, and BxPc-3 human pancreatic cancer cells. Our data provide the first report of a direct comparison of the effects of all 4 of the vitamin E tocotrienol compounds on human pancreatic cancer cells in vitro and in vivo. The results indicate that δ-tocotrienol is the most bioactive tocotrienol against human pancreatic cancer cells and provide the rationale for selecting δ-tocotrienol as the lead tocotrienol compound for further studies of the use of tocotrienols for pancreatic cancer prevention and treatment.

Our in vitro and in vivo results show that the bioactivity of tocotrienols in pancreatic cancer cells was directly related to inhibition of NF-κB activity. Our results agree with Kunnumakkara and colleagues (19) who reported...
that γ-tocotrienol inhibited NF-κB activity in vitro and in vivo. We show for the first time that δ-tocotrienol also inhibited NF-κB activity and the expression of NF-κB-regulated gene products. In contrast, α- and β-tocotrienol had no significant effect on NF-κB activity. These results strongly suggest that the bioactivity of tocotrienols against cancer cells is due, in part, to inhibition of the activity of the transcription factor NF-κB. Because numerous studies have shown that inhibition of NF-κB can enhance gemcitabine activity in pancreatic cancer cells (3, 8, 9, 19, 22), we investigated whether δ-tocotrienol could enhance the activity of gemcitabine against human pancreatic cancer. We found that δ-tocotrienol augmented gemcitabine inhibition of cell viability, as well as induction of apoptosis in pancreatic cancer cells. We also found that δ-tocotrienol augmented gemcitabine inhibition of growth of human pancreatic AsPc-1 tumors in SCID nude mice. Augmentation of gemcitabine activity by δ-tocotrienol is associated with inhibition of constitutively active NF-κB and NF-κB-regulated gene products. Our results are in agreement with Kunnumakkara and colleagues (19) who showed that γ-tocotrienol inhibition of constitutively active NF-κB and NF-κB-regulated gene products was associated with γ-tocotrienol potentiation of gemcitabine-induced apoptosis, as well as γ-tocotrienol potentiation of the effects of gemcitabine against human pancreatic tumors in nude mice.

Several mechanisms by which tocotrienols exert their anticancer effects have been reported. Suppression of inflammatory transcription factor NF-κB, which is involved in tumorigenesis, and inhibition of 3-hydroxy-3-methyl-glutaryl CoA (HMG-CoA) reductase, mammalian DNA polymerase, and certain protein kinases are potential targets to tocotrienols (16). In this study, we found that the in vitro and in vivo anti–pancreatic cancer activity of tocotrienols can be attributed to inhibition of NF-κB signaling. Additional studies are being designed to clarify the mechanisms of inhibition of NF-κB signaling by δ-tocotrienol in pancreatic cancer cells. One possibility is that δ-tocotrienol inhibits the degradation of the protein that inhibits NF-κB, the inhibitor of NF-κB (IκB). IκB sequesters NF-κB in the cytoplasm, and phosphorylation of IκB makes it a target for ubiquitination. The added ubiquitin molecules render IκB susceptible to degradation by proteasomes. We observed that δ-tocotrienol treatment resulted in a decrease of phosphorylated IκB. Whether δ-tocotrienol affects the kinase that phosphorylates IκB is unknown.

In summary, this is the first report evaluating the effects of all of the natural vitamin E tocotrienol compounds on pancreatic cancer cells. Our results show that δ- and γ-tocotrienol inhibited NF-κB activity, cell growth, cell survival, and tumor growth in nude mice. We further show that δ-tocotrienol augmented gemcitabine activity
in vitro and in vivo. These results suggest that inhibition of NF-κB signaling by δ-tocotrienol may be an effective approach for the prevention and treatment of pancreatic cancer. Our findings suggest evaluation of NF-κB signaling compounds as an endpoint biomarker in our ongoing phase I trial of δ-tocotrienol in patients with pancreatic tumors (ClinicalTrials.gov. Identifier: NCT00985777).

Disclosure of Potential Conflicts of Interest

M.P. Malafa and S.M. Sebti are named as inventors on US Patent “Delta-tocotrienol Treatment and Prevention of Pancreatic Cancer” (June 26, 2007; OTML docket number 06A069) but do not have financial interest in the companies that have licensed this patent. No potential conflicts of interest were disclosed by other authors.

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