Led by Theodore Lawrence,2 and Marc E. Lippman 1

Jianyong Chen,1 James M. Rae,1 Wenhua Tang,1 Meilan Liu,1 Mary Davis,2 Jianyong Chen,1 James M. Rae,1 Theodore Lawrence,2 and Marc E. Lippman1

1Department of Internal Medicine, Division of Hematology and Oncology and 2Department of Radiation Oncology, University of Michigan Comprehensive Cancer Center, University of Michigan, Ann Arbor, Michigan

Abstract
Radioresistance markedly impairs the efficacy of tumor radiotherapy and involves antiapoptotic signal transduction pathways that prevent radiation-induced cell death. The majority of human prostate cancers overexpress the important antiapoptotic proteins Bcl-2 and/or Bcl-xL, which render tumors resistant to radiation therapy. (−)-Gossypol, a natural polyphenol product from cottonseed, has recently been identified as a potent small molecule inhibitor of both Bcl-2 and Bcl-xL. In the current study, we investigated the antitumor activity of (−)-gossypol in prostate cancer and tested our hypothesis that (−)-gossypol may improve prostate cancer’s response to radiation by potentiating radiation-induced apoptosis and thus making cancer cells more sensitive to ionizing radiation. Our data show that (−)-gossypol potently enhanced radiation-induced apoptosis and growth inhibition of human prostate cancer PC-3 cells, which have a high level of Bcl-2/Bcl-xL proteins. Our in vivo studies using PC-3 xenograft models in nude mice show that orally given (−)-gossypol significantly enhanced the antitumor activity of X-ray irradiation, leading to tumor regression in the combination therapy. In situ terminal deoxynucleotidyl transferase–mediated nick end labeling staining showed that significantly more apoptotic cells were induced in the tumors treated with (−)-gossypol plus radiation than either treatment alone. Anti-CD31 immunohistochemical staining indicates that (−)-gossypol plus radiation significantly inhibited tumor angiogenesis. Our results show that the natural polyphenol inhibitor of Bcl-2/ Bcl-xL, (−)-gossypol, can radiosensitize prostate cancer in vitro and in vivo without augmenting toxicity. (−)-Gossypol may improve the outcome of current prostate cancer radiotherapy and represents a promising novel anticancer regime for molecular targeted therapy of hormone-refractory prostate cancer with Bcl-2/Bcl-xL overexpression. [Mol Cancer Ther 2005;4(2):197–205]

Introduction
Radioresistance markedly impairs the efficacy of tumor radiotherapy and involves antiapoptotic signal transduction pathways that prevent radiation-induced cell death (1). Overexpression of the antiapoptotic protein Bcl-2 is observed in 30% to 60% of prostate cancer at diagnosis and in nearly 100% of hormone-refractory prostate cancer (2). Bcl-2 is significantly overexpressed in localized recurrent prostate carcinoma after radiation therapy, suggesting that alterations in the apoptotic pathway may be important in the development of local recurrence (3). Bcl-xL is found to be overexpressed in 80% to 100% of hormone-refractory prostate cancer and is associated with advanced disease, poor prognosis and shortened survival (4). Overexpression of Bcl-2/Bcl-xL antiapoptotic proteins decreases the proapoptotic response to such cellular insults as irradiation, chemotherapy, and androgen withdrawal, leading to resistance to the treatments (5). Thus, inhibition of the antiapoptotic functions of Bcl-2/Bcl-xL represents a novel and promising strategy for overcoming the resistance to current therapy for prostate cancer. Antisense Bcl-2 and Bcl-xL studies have provided important proof-of-the-concept that inhibition of Bcl-2 and Bcl-xL may be an effective new therapeutic strategy for the treatment of advanced prostate cancer (6–8). Recently, Wacheck et al. (9) showed that specific reduction of Bcl-xL protein levels by Bcl-xL antisense oligonucleotides indeed radiosensitized Caco-2 colon cancer cells which have a high level of Bcl-xL and are resistant to radiation. Scott et al. (10) showed that Bcl-2 antisense reduced prostate cancer cell survival following irradiation. Nonpeptide, small-molecule inhibitors of Bcl-2 and Bcl-xL have several major advantages over Bcl-2/Bcl-xL antisense oligonucleotides, antibodies, or peptides, including better bioavailability, better in vivo stability, lower cost, and oral activity (11).
The potential antitumor and chemoprevention activities of some natural polyphenol compounds have been linked to their direct inhibition of antiapoptotic Bcl-2 family proteins, Bcl-2 and Bcl-xL (12). (-)-Gossypol, a natural polyphenol product from cottonseed, has recently been identified as a small-molecule inhibitor of both Bcl-2 and Bcl-xL and potently induces apoptosis in several cancer cell lines (12–14). Because the majority of human prostate cancers overexpress Bcl-2 and/or Bcl-xL, rendering the tumors resistant to radiation therapy, we investigated whether (-)-gossypol can potentiate prostate cancer’s response to radiation and whether this potentiation is accompanied by an increase of radiation-induced apoptosis. Our results show that (-)-gossypol significantly enhances the antitumor activity of radiation therapy in vitro and in vivo without augmenting toxicity and represents a promising new anticancer regime for molecular targeted therapy of hormone-refractory prostate cancer with Bcl-2/Bcl-xL overexpression.

Materials and Methods

Cell Culture and Reagents

All cell lines used were obtained from the American Type Culture Collection (Manassas, VA). Cells were routinely maintained in an improved minimal essential medium (Biofluids, Rockville, MD) with 10% fetal bovine serum and 2 mmol/L L-glutamine. Cultures were maintained in a humidified incubator at 37°C and 5% CO₂. (-)-Gossypol was produced at RTI International (Research Triangle Park, NC) under a National Cancer Institute (NCI) contract to support the RAID Project (D. Yang). For in vitro experiments, (-)-gossypol was dissolved in DMSO at 20 mmol/L as stock solution. For in vivo studies, (-)-gossypol was made fresh before each administration. It was first dissolved in ethanol and then diluted with sterile water within 5 minutes, to a final ethanol concentration of 10%.

Radiation Clonogenic Assay

To investigate the effect of (-)-gossypol on cancer cells’ response to radiation, a standard clonogenic assay was done as described with modification (15, 16). Briefly, 200 to 10,000 PC-3 cells per well in 6-well plates were treated with 1 to 5 μmol/L (-)-gossypol, and the cells were irradiated within one hour with 2 to 8 Gy using 300 kV X-rays. One-milliliter complete medium was added per well in the 6-well plates on day 5. After another 5 to 7 day’s culture, the plates were stained with crystal violet, and the colonies with over 50 cells were counted with a ColCount colony counter (Oxford Optronix, Oxford, United Kingdom). The same amount of solvent DMSO was added in control wells as vehicle control. For each combination treatment, parallel analyses with each agent alone were also done. The cell survival curves were plotted using a linear-quadratic model, and the mean inactivation dose (area under the cell survival curve) was calculated as described previously (17). The cell survival enhancement ratio was calculated as the ratio of the mean inactivation dose in control divided by the mean inactivation dose in treated cells (18).

Apoptosis Assay

For apoptosis analysis by flow cytometry, PC-3 cells were treated with (-)-gossypol and X-ray irradiation, alone or in combination, in 12-well plates as indicated in Fig. 2 legend, then trypsinized and washed with PBS, and fixed in 70% ethanol on ice. After centrifugation, cells were stained with 50 μg/mL propidium iodide and 0.1 μg/mL RNase A and analyzed by flow cytometry using a FACStar Plus cell sorter. Each histogram was constructed with the data from at least 5,000 events. Data were analyzed to calculate the percentage of sub-G₁ population (apoptosis) using the CellQuest software (Becton Dickinson, Franklin Lakes, NJ).

Animal Model and In vivo Experiments

Male athymic NCr-nu/nu nude mice ages 5 to 6 weeks were purchased from NCI. Mice were inoculated s.c. on both sides of the lower back above the tail after alcohol preparation of the skin, using a sterile 22-gauge needle with 0.1 mL of cell suspension of 5 × 10⁶ PC-3 cells with manual restraint. When tumors reached appropriate size, as indicated in the results figures, the mice were randomized into five to eight mice per group and treated with either (-)-gossypol 10 mg/kg p.o. q.d. ×5 × 4 weeks, or X-ray irradiation 2 Gy, q.d. ×5, ×3 weeks, or the combination of (-)-gossypol and radiation. The vehicle control group and the radiation-only group received the same amount of 10% ethanol which is the solvent for (-)-gossypol. The tumor sizes and animal body weights were measured twice a week by a technician from University of Michigan Unit of Laboratory Animal Medicine without knowledge of the treatment. All animal experiments were done according to the protocol approved by University of Michigan Guideline for Use and Care of Animals.

Tumor Apoptosis and Angiogenesis Analysis

Tumors from each group were excised and stained for apoptosis by terminal deoxynucleotidyl transferase–mediated nick end labeling (TUNEL) staining using the ApopTag kit. This method is very sensitive and allows for determination of very few apoptotic cells in situ. Tumor angiogenesis was analyzed by anti-mouse CD31 immuno-histologic staining of tumor sections.

X-ray Irradiation

A 300-kV X-ray irradiator in the University of Michigan Radiation Core Facility was employed at a dose rate of ~3 Gy/min. Dosimetry was carried out using an ionization chamber connected to an electrometer system which is directly traceable to a National Institute of Standard and Technology Calibration. For in vivo irradiation, mice were restrained such that only the tumor areas were exposed to irradiation, whereas the rest of the animal body was shielded, as described previously (19–21). A fractionated dose schedule of 2 Gy q.d. ×5 for 3 weeks was employed, which is consistent with a clinical radiotherapy regime for prostate cancer. Also, we had previously used this regimen successfully for radiation in combination with p53 gene therapy and antisense therapy (19, 21–23). Control groups and (-)-gossypol only groups animals were also put in restrainers for ~2 minutes as a sham irradiation.
**Statistical Analysis**

Two-way ANOVA and two-tailed t tests were employed to analyze the animal data using Prism 3.0 software (Graphpad Prism, San Diego, CA). The synergy analysis for the combination effects of (−)-gossypol and radiation was analyzed by Chou-Talalay’s combination index-isobologram and multiple drug dose-effect analysis method (24) using CalcuSyn software (Biosoft, Inc., Cambridge, United Kingdom).

**Results**

(−)-Gossypol Sensitizes PC-3 Cells to X-ray Irradiation in an In vitro Clonogenic Assay

Treatment of PC-3 cells with (−)-gossypol significantly reduced the radiation resistance of PC-3, resulting in 10- and 20-fold reductions of colony formation from control at 6 and 8 Gy, respectively (Fig. 1). Table 1 summarizes the radiation response characteristics from Fig. 1. (−)-Gossypol-mediated radiosensitization correlated with (−)-gossypol doses \((r = 0.95, P = 0.0028)\). Similar correlations were also observed with other radiation response variables as shown in Table 1. We also analyzed the interaction between (−)-gossypol and radiation using Chou-Talalay’s synergy analysis, a widely used method to analyze and quantify the synergy in combination therapies (24–28). As shown in Fig. 1A and B, treatment of PC-3 cells with radiation plus nontoxic doses (3 and 4 μmol/L) of (−)-gossypol achieved the combination index 0.68 and 0.34, dose reduction index 1.9 and 4.3, respectively. Combination index \(<1\) and dose reduction index \(>1\) indicates synergy between the two treatments (29, 30). (−)-Gossypol (5 μmol/L) showed better synergy with radiation, but this dose of (−)-gossypol was cytotoxic alone (Table 1; Fig. 1A). The results show that the combination of (−)-gossypol with radiation resulted in significant synergy in inhibiting clonogenic cell survival of PC-3 cells. (−)-Gossypol can sensitize PC-3 cells to X-ray irradiation in a dose-dependent manner.

(−)-Gossypol Enhances Radiation-Induced Apoptosis in PC-3 Cells

As shown in Fig. 2A and B, (−)-gossypol and X-ray irradiation potently induced apoptosis in PC-3 cells in a dose- and time-dependent manner, with a plateau around 60% apoptosis. Similar results were observed with Annexin V staining for early apoptotic cells (data not shown). Based on these data, treatment conditions that induced apoptosis in the linear range (e.g., 6 Gy radiation dose and 10 μmol/L (−)-gossypol dose at 48 hours post-irradiation), were chosen in subsequent combination studies. Fig. 2C shows that (−)-gossypol significantly enhanced radiation-induced apoptosis when added to the cells 24 hours after irradiation. In this experiment, PC-3 cells were irradiated first, then

![Figure 1](https://mct.aacrjournals.org)  
**Figure 1.** Clonogenic assay of PC-3 cells exposed to X-ray irradiation with or without (−)-gossypol \((GI(−))\). PC-3 cells were plated in 6-well plates and GI(−) or DMSO vehicle control were added. Then cells were irradiated with X-ray, 300 kV, dose rate \(\sim 3\) Gy/min at room temperature with doses up to 8 Gy. The plates were cultured for 12 d, stained with crystal violet, and the colonies with over 50 cells were counted with ColCount colony counter. The survival curves were plotted with linear-quadratic model. A, plating efficiency (survival fraction) of GI(−) treatment alone. B, clonogenic survival curves of PC-3 cells in response to irradiation (normalized for the killing of GI(−)).

![Table 1](https://mct.aacrjournals.org)

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<th>CI</th>
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**Note:** Radiobiological parameters calculated from survival curves in Fig. 1 based on linear-quadratic model. The synergism analysis of (−)-gossypol with radiation at 8 Gy were performed with Chou-Talalay’s combination index-isobologram and multiple drug-dose effect analysis method as described in Materials and Methods. CI < 1, DRI >: synergy between the two treatments.

**Abbreviations:** MID, mean inactivation dose; E ratio, enhancement ratio calculated from MID in control cells divided by MID in treated cells; Gy (1%), radiation dose leading to 1% cell survival; SF (2 Gy), survival fraction at 2 Gy; CI, combination index; DRI, dose reduction index.
(-)-gossypol was added 24 hours later, cells were collected 48 hours after radiation for analysis of apoptosis. Isobologram synergism analysis (ref. 30; Fig. 2D) shows that, under this condition, 6 Gy radiation and 10 μmol/L (-)-gossypol treatment resulted in more than additive induction of apoptosis, as compared with either treatment alone, with combination index = 0.345, indicating a strong synergy in the combination therapy (30). 6 Gy radiation and 5 μmol/L (-)-gossypol treatment resulted in only an additive effect (combination index = 0.963). Interestingly, treating cells with radiation and (-)-gossypol at the same time or with (-)-gossypol 24 hours before radiation did not show any significant potentiation (Fig. 2E and F), suggesting that (-)-gossypol-mediated radiation potentiation is combination sequence specific. Our data are consistent with that of Kruit et al. (31), in which treatment with doxorubicin for 24, 48, and 72 hours after irradiation potentiated irradiation cytotoxicity of PC-3 cells. This combination sequence effect may be related to cell cycle of PC-3 cells where cells at different phases have different response to radiation and (-)-gossypol, as suggested in other cell or drug models (13, 17, 32–34).

Figure 2. (-)-Gossypol (G(-)) potentiates radiation-induced apoptosis of PC-3 cells. PC-3 cells were plated in 12-well plates overnight, and treated as indicated. At indicated time after treatment, the cells were trypsinized and fixed in 70% ethanol on ice, stained with PI, and analyzed by flow cytometry. The percentage of apoptotic cells is the percentage of cells with sub-G1 nuclei staining (n = 2). Representative results of at least three independent experiments. A, X-ray radiation-induced apoptosis is dose and time dependent. Cells were treated at indicated doses for 24, 48, and 72 h. B, G(-)-induced apoptosis of PC-3 cells. G(-) potently induced apoptosis at 10 μmol/L. C, G(-) enhanced radiation-induced apoptosis when added to the cells 24 h after irradiation. Cells were irradiated first, added G(-) 24 h later, and cells collected 48 h after radiation. D, normalized isobologram of data in C. 1, 6 Gy radiation + G(-) 10 μmol/L, combination index = 0.345, synergy. Potentiation was not observed in the cells treated with G(-) and radiation at the same time (E), nor in the cells treated with G(-) first, and radiation 24 h later (F). Cells were collected 48 h after radiation for analysis.

(-)-Gossypol Enhances Prostate Cancer Response to Radiation and Results in Tumor Regression In vivo

To investigate whether (-)-gossypol can sensitize PC-3 cells to radiation in vivo, we employed a PC-3 xenograft model in athymic nude mice. Three independent in vivo experiments with different initial tumor sizes were carried out and data are shown in Fig. 3. As shown in Fig. 3A, with an initial tumor size of ~100 mm³ at the start of irradiation, (-)-gossypol inhibited PC-3 tumor growth in vivo in the first 2 weeks of therapy (versus Vehicle control, P < 0.05, Student’s t test, n = 16), as did X-ray irradiation alone, but the tumors quickly grew back in the third week and no tumor regression was observed. However, the combination of (-)-gossypol and radiation showed significantly improved antitumor activity and was more effective than either treatment alone (P < 0.01 versus radiation and P < 0.001 versus (-)-gossypol alone, n = 16). More importantly, combination therapy resulted in tumor regression in all the xenografts in the fourth week, to 24% of their peak tumor sizes (46 ± 40 mm³ on day 30 versus 191 ± 140 mm³ on day 16). It is worth noting that only the combination therapy resulted in >50% tumor regression,
a criterion for clinical response to treatment, whereas the tumors in either \((\text{C0})-\text{gossypol~alone}\) group or radiation alone group progressed during treatment (although slower than control).

To investigate whether such improved antitumor efficacy can also be achieved with bigger tumors, we doubled the initial tumor size to \(f 200 \text{ mm}^3\) at the start of radiation treatment (Fig. 3B). Using the same dose schedule, \((\text{C0})-\text{gossypol~or~radiation~alone}\) had no obvious effect on these established large tumors, only the combination of \((\text{C0})-\text{gossypol~and~radiation}\) achieved significant antitumor activity with >50% tumor regression \((P = 0.039, \text{versus radiation alone}; \text{and } P = 0.0003, \text{versus \((\text{C0})-\text{gossypol~alone}; n = 8–10). The tumor growth delay (T/C days) was 8.5 days for radiation alone, 0 days for \((\text{C0})-\text{gossypol~alone~and~54.5 days for combination of \((\text{C0})-\text{gossypol~and~radiation. The later effect is considered significant according to NCI criteria (35).}

We further doubled the initial tumor size to \(f 400 \text{ mm}^3\) in our third in vivo experiment (Fig. 3C) in which the radiation dose was increased to 3 Gy q.d. \(\times 5\) for the first week and 2.5 Gy q.d. \(\times 5\) for the second and third weeks (total 40 Gy), with the same dose schedule of oral \((\text{C0})-\text{gossypol. As expected, a similar but profound antitumor effect was observed only in the mice treated with combination of \((\text{C0})-\text{gossypol~and~radiation, whereas neither treatment alone was active in these well-established large tumors (Fig. 3C). Importantly, the combination therapy was well tolerated by the animals; no significant animal body weight loss was observed (Fig. 3D) and no obvious organ toxicities were seen, suggesting the combination therapy did not augment toxicities.}

The tumor growth inhibition (T/C %) values for these three in vivo studies were calculated as described (35) and summarized in Table 2. According to NCI criteria, T/C < 42% is considered significant antitumor activity, T/C < 10% is considered to indicate highly significant antitumor activity and is the level used by NCI to justify a clinical trial (DN-2 level activity; ref. 35). Combination of \((\text{C0})-\text{gossypol~and~radiation can achieve T/C up to 3.4%, or 96.6% inhibition in median tumor size, without significant toxicity, which meets NCI’s DN-2 level activity (35).}
\(-\text{-Gossypol Increases Radiation-Induced Apoptosis of PC-3 Tumors and Inhibits Tumor Angiogenesis In vivo}\)

To begin to address the question of why the combination of \(-\text{-gossypol}\) and radiation had such a profound efficacy versus either treatment alone, we took the tumor tissues from each group in animal experiment B (Fig. 3B) at the end of fractionated radiation (week 3) and did TUNEL staining for apoptosis and anti-mouse CD31 immunohistochemical staining for angiogenesis. TUNEL assay results are shown in Fig. 4A, the brown nuclei staining indicates TUNEL-positive apoptotic cells. \(-\text{-Gossypol plus radiation induced significantly more apoptosis than either \(-\text{-gossypol} or radiation alone. Figure 4B}\(a\) shows the increased apoptotic cells were only seen in combination therapy treated tumor tissue but not in surrounding normal tissues.

Because the tumors in \(-\text{-gossypol} + \text{Rad group were smaller than that in other groups, to exclude the influence of tumor size on the apoptosis results, we selected extra nude mice with matching tumor size (~400 mm\(^3\)) and gave oral \(-\text{-gossypol}\) 10 mg/kg q.d. for 3 days and a single dose of 10 to 20 G\(\text{y}\) X-ray irradiation on day 3, or either treatment alone. The tumors were taken on day 4 (e.g., 24 hours after radiation and last dose of \(-\text{-gossypol}\) for TUNEL staining. As shown in Fig. 4B, significant induction of apoptosis was observed in tumors treated with \(-\text{-gossypol}\) + 10 G\(\text{y}\) radiation, whereas surrounding normal tissues were not affected by this irradiation dose (Fig. 4B(b)). On the contrary, 20 G\(\text{y}\) radiation alone induced limited apoptosis in tumor tissue but much more apoptosis in surrounding normal tissues, (Fig. 4B(c–d)), consistent with the report that PC-3 is resistant to ionizing irradiation (36). Neither 10 G\(\text{y}\) radiation alone nor \(-\text{-gossypol}\) alone induced significant apoptosis in tumor tissue (data not shown).

Moreover, anti-mouse CD31 staining indicates that the combination of \(-\text{-gossypol} and radiation almost completely inhibited tumor angiogenesis, whereas either \(-\text{-gossypol} or radiation alone had limited effect on tumor blood vessel growth (Fig. 4C). We observed no significant difference in cell proliferation marker Ki-67 staining of these tumors (data not shown). The CD31 data strongly suggest that antiangiogenesis might be one of the mechanisms involved in the in vivo antitumor activity of \(-\text{-gossypol}\) in combination with radiation.

\textbf{Discussion}

Radiation therapy is used to treat all stages of localized prostate cancer (36). However, both clinical and radiobiological evidence indicate that prostate cancer cells can be relatively resistant to radiation (37, 38). PC-3 is a hormone-refractory human prostate cancer cell line, which is resistant to current chemotherapy and radiation therapy (36). PC-3 has very high levels of Bcl-2 and Bcl-xL expression that may contribute to PC-3’s resistance to apoptosis induced by chemotherapy/radiotherapy (38). X-ray irradiation is known to be a strong inducer of apoptosis (36). Bcl-2/Bcl-xL overexpression protects cells from radiation-induced apoptosis and thus may play a role in PC-3 cell’s radiation resistance. Rosser et al. reported that patients undergoing radical prostatectomy after radiotherapy had a significantly higher rate of Bcl-2 overexpression than did patients who underwent surgery as the initial treatment (3). Bcl-2 is overexpressed in localized recurrent prostate carcinoma after radiation therapy and is reported to be important in the development of local recurrence (3). Wacheck et al. (9) showed that specific reduction of Bcl-xL protein levels by Bcl-xL antisense oligonucleotides was able to radiosensitize Caco-2 colon cancer cells which have a high level of Bcl-xL. It would thus be of clinical interest to investigate whether blocking the antiapoptosis function of Bcl-2/Bcl-xL will overcome the radiation resistance and sensitize the cancer cells to standard radiation therapy.

The natural polyphenol compound \(-\text{-gossypol has been shown to have antiproliferative and antimetastatic effects on many kinds of cancer (13, 39–42). Multiple modes of action and molecular targets have been proposed for the antitumor activity of gossypol (14, 39, 41, 43–46), including inhibition of protein kinase C activity (47), modulation of cell cycle regulatory proteins Rb and cyclin D1 (32), inhibition of cellular energy metabolism (48), direct toxicity to mitochondria (49), or antiangiogenesis (45), etc. Recently, \(-\text{-gossypol has been reported as a potent small molecule inhibitor of both Bcl-2 and Bcl-xL and potently induces apoptosis in several cancer cell lines with high levels of Bcl-2/Bcl-xL (12, 14). These studies agreed that \(-\text{-gossypol is a potent inducer of apoptosis in cancer cells and is well tolerated, clinically safe. More recently, Oliver et al. have shown that \(-\text{-gossypol acts directly on the mitochondria to overcome Bcl-2- and Bcl-xL-mediated apoptosis resistance, confirming that \(-\text{-gossypol is a potent and novel therapeutic able to overcome apoptosis resistance by specifically targeting the activity of antiapoptotic Bcl-2 family members (50). Our collaborators, Mohammad et al., have recently shown that \(-\text{-gossypol has a significant antitumor activity in vitro and in vivo as a potential novel therapy for the treatment of lymphoma (51) and Oliver et al. showed that \(-\text{-gossypol has potent antitumor activity in head and neck cancer cells in vitro, possibly by direct inhibition of Bcl-xL and Bcl-2 (50).}}

In the current study, we employed \(-\text{-gossypol to investigate whether \(-\text{-gossypol can potentiate prostate cancer’s response to radiation and whether this potentiation is accompanied with increased radiation-induced apoptosis. Our data show that \(-\text{-gossypol potently enhanced radiation-induced apoptosis and growth inhibition of human prostate cancer PC-3 cells. More importantly, \(-\text{-gossypol significantly improved antitumor activity of X-ray irradiation to PC-3 cells in vivo in an established xenograft model of PC-3 tumors in nude mice, resulting in tumor regression even in large tumors. NCI DN-2 level activity could be achieved only with the combination of \(-\text{-gossypol and radiotherapy. This enhanced response to radiation was accompanied by increased induction of apoptosis in vivo by the combination therapy. This is the first report demonstrating a potential}
small molecule inhibitor of Bcl-2/Bcl-xL improves anti-tumor efficacy of radiation therapy both in vitro and in vivo with increased induction of apoptosis. Further studies are needed to establish a formal link between the observed efficacy of (−)-gossypol and its cellular target(s), as well as the role of apoptosis in (−)-gossypol-mediated radiosensitization.

The role of Bcl-2/Bcl-xL and apoptosis in radiosensitivity of cancer cells is cell type specific and cellular context dependent (1). Using a Bcl-2-transfected PC-3 cell clone, Kyprianou et al. (52) showed that Bcl-2 overexpression afforded a 3-fold protection from radiation-induced apoptosis, without affecting the clonogenic survival of human prostate cancer cells. However, these Bcl-2-transfected PC-3 cells may not depend on exogenous Bcl-2 for survival; thus, the transfected Bcl-2 may not have a direct effect on clonogenic survival of these transfected cells. Scott et al. (10) showed that down-regulation of endogenous Bcl-2 using Bcl-2 antisense reduced prostate cancer LnCap cell survival following irradiation, suggesting a potentially important therapeutic approach for enhancing radiosensitivity in prostate tumors via antisense oligonucleotide or other drug therapies that down-regulate Bcl-2. Our results show that (−)-gossypol, a reported small molecule functional inhibitor of Bcl-2/Bcl-xL (12, 14), potently radiosensitizes PC-3 cells and enhances radiation-induced apoptosis, both in vitro and in vivo. Our data are consistent with those reported results of Bcl-2/Bcl-xL antisense therapies (9, 10, 53–57) or Bcl-2 RNA interference (58).

Table 2. Comparison of tumor growth inhibition (T/C %) versus starting tumor sizes in the three in vivo experiments

<table>
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<th>Experiment*</th>
<th>Tumor sizes at start of radiation (mm³)</th>
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<td></td>
<td>Rad [T/C(%)]</td>
<td>G(−) [T/C(%)]</td>
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<tr>
<td>A</td>
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<td>C</td>
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NOTE: When the median tumor size in control group reached 750 mm³, tumor growth inhibition (T/C %) were calculated as the % median tumor size in treatment group versus that in control group. Abbreviations: Rad, radiation; G(−), (−)-gossypol.  
*Data based on in vivo experiments shown in Fig. 3A, B, and C.

Figure 4. (−)-Gossypol [G(−)] treatment in combination with radiation significantly increased apoptosis induction in vivo in PC-3 xenograft tumors but not in surrounding normal tissues. A, TUNEL staining of PC-3 xenografts after treatment. The tumor tissues from each group in experiment B (Fig. 3B) were taken at the end of 3 wks of radiation and fixed in 10% formalin. The tumor sections were stained for TUNEL using ApopTag kit. The apoptotic cells have DNA fragmentation and are stained positive as brown nuclei. B, a, increased apoptotic cells were only seen in combination therapy treated tumors but not in surrounding normal tissues. b-d, nude mice with matching tumor size (~400 mm³) were given oral G(−) 10 mg/kg q.d. ×3 and a single dose of 10 to 20 Gy X-ray irradiation on day 3, or either treatment alone. Tumors were taken on day 4 for TUNEL staining. Surrounding normal tissues were labeled in the graph. CT, connective tissues; M, smooth muscle; BV, blood vessels. C, anti-mouse CD31 immunohistologic staining of the same tumor sections as in A for tumor angiogenesis analysis. Blood vessels were stained brown (original magnification ×400). Combination of G(−) with radiation almost completely inhibited tumor angiogenesis.
It remains to be delineated whether (-)-gossypol-mediated radiosensitization is through inhibition of Bcl-2/Bcl-xL or other molecular targets. Due to the multi-target nature of (-)-gossypol, Bcl-2/Bcl-xL may not be the only cellular target(s) inhibited by (-)-gossypol. However, our recent studies using live-cell fluorescence resonance energy transfer and a communoprecipitation pulldown assay indicate that (-)-gossypol potently blocks heterodimerization of Bcl-xL with Bax, Bad, and Bim at the (-)-gossypol doses that induce apoptosis and growth inhibition in prostate cancer cells. In FL5.12-Bcl-xL cells, (-)-gossypol seems to be able to overcome the Bcl-xL-mediated protection against apoptosis induced by IL-3 withdrawal at a nontoxic dose of (-)-gossypol. Our collaborators, Oliver et al., have recently shown an inverse correlation between Bcl-xL/Bcl-xS ratios and sensitivity to (-)-gossypol in head and neck cancer cell lines (59). Importantly, the head and neck cancer cell lines resistant to cisplatin were very sensitive to (-)-gossypol. Several recent studies showed that Bcl-2 overexpression increases angiogenic potential of cancer cells through increasing angiogenic factors such as vascular endothelial growth factor, and treatment of cancer cells with a Bcl-2/Bcl-xL-mediated apoptosis resistance in Bcl-2/Bcl-xL-transfected Jurkat T cells (50). These recent data strongly support that Bcl-2/Bcl-xL may very likely be the major molecular target(s), if not the only target, in (-)-gossypol-induced apoptosis. We are currently pursuing detailed mechanistic studies to investigate molecular mechanism(s) of action of (-)-gossypol in radiosensitization of prostate cancer cells.

In conclusion, our study shows that (-)-gossypol overexpression increases angiogenic potential of cancer cells through increasing angiogenic factors such as vascular endothelial growth factor, and treatment of cancer cells with a Bcl-2/Bcl-xL antisense oligonucleotide induces angiogenic activity via a reduction of hypoxia-induced vascular endothelial growth factor secretion (60, 61). Our CD31 staining data are consistent with these findings and strongly suggest that antiangiogenesis might be one of the mechanisms involved in the in vitro antitumor activity of (-)-gossypol in combination with radiation, possibly through inhibition of Bcl-2-mediated angiogenesis by (-)-gossypol. This observation sheds light on why only moderate radiosensitization effect was observed in vitro but a profound improvement of antitumor activity with tumor regression was seen in vivo.

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