

CEBPD Reverses RB/E2F1-Mediated Gene Repression and Participates in HMDB-Induced Apoptosis of Cancer CellsYen-Chun Pan¹, Chien-Feng Li², Chiung-Yuan Ko³, Min-Hsiung Pan⁴, Pei-Jung Chen¹, Joseph T. Tseng⁵, Wen-Chun Wu¹, Wen-Chang Chang^{1,3}, A-Mei Huang⁶, Esta Sterneck⁷, and Ju-Ming Wang^{1,3,5}**Abstract**

Purpose: Recent evidence indicates that a tumor suppressor gene *CEBPD* (CCAAT/enhancer-binding protein delta) is downregulated in many cancers including cervical cancer, which provides a therapeutic potential associated with its reactivation. However, little is known for *CEBPD* activators and the effect of reactivation of *CEBPD* transcription upon anticancer drug treatment. In this study, we identified a novel *CEBPD* activator, 1-(2-hydroxy-5-methylphenyl)-3-phenyl-1,3-propanedione (HMDB). The purpose of this study is to characterize the mechanism of HMDB-induced *CEBPD* activation and its potential effect in cancer therapy.

Experimental Design: Methylation-specific PCR assay, reporter assay, and chromatin immunoprecipitation (ChIP) assay were performed to dissect the signaling pathway of HMDB-induced *CEBPD* transcription. Furthermore, a consequence of HMDB-induced *CEBPD* expression was linked with E2F1 and retinoblastoma (RB), which discloses the scenario of *CEBPD*, E2F1, and RB bindings and transcriptional regulation on the promoters of proapoptotic genes, *PPARG2* and *GADD153*. Finally, the anticancer effect of HMDB was examined in xenograft mice.

Results: We demonstrate that *CEBPD* plays an essential role in HMDB-mediated apoptosis of cancer cells. HMDB up-regulates *CEBPD* transcription through the p38/CREB pathway, thus leading to transcriptional activation of *PPARG2* and *GADD153*. Furthermore, increased level of *CEBPD* attenuates E2F1-induced cancer cell proliferation and partially rescues RB/E2F1-mediated repression of *PPARG2* and *GADD153* transcription. Moreover, HMDB treatment attenuates the growth of A431 xenografts in severe combined immunodeficient mice.

Conclusions: These results clearly demonstrate that HMDB kills cancer cells through activation of *CEBPD* pathways and suggest that HMDB can serve as a superior chemotherapeutic agent with limited potential for adverse side effects. *Clin Cancer Res*; 16(23); 5770–80. ©2010 AACR.

The phenomenon of silencing a tumor suppressor is common in the process of tumorigenesis. Therefore, elevation of tumor suppressor expression is one mechanism for anticancer drug action (1–3). Previous studies

demonstrated that treatment with the structurally related β -diketone compounds, including 1-(2-hydroxy-5-methylphenyl)-3-phenyl-1,3-propanedione (HMDB), causes growth inhibitory effects in human cancer cells (4, 5). Moreover, HMDB was suggested to function as an anticancer drug via modulating mitochondrial functions that are regulated by reactive oxygen species, upregulating *GADD153*, *BAD*, and *p21*, and downregulating *BCL2L1* (*BCL-XL*) (4, 5). Although it has been demonstrated that HMDB causes growth inhibition and apoptosis in cancer cells, the details of how HMDB-dependent transcriptional regulation contributes to these activities remain to be elucidated.

CEBPD (CCAAT/enhancer-binding protein delta), a CCAAT/enhancer-binding protein family member, has recently been implicated in cell-cycle regulation, with its mRNA and protein levels being highly induced in mouse mammary epithelial cells upon serum and growth factor withdrawal (6). Overexpression of *CEBPD* results in a decrease in the levels of cyclin D1 and cyclin E and an increase in *p27* levels occurs, which could account for growth inhibition in prostate cancer and erythroleukemia

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Note: Supplementary article for this data are available at Clinical Cancer Research Online (<http://clincancerres.aacrjournals.org/>).

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doi: 10.1158/1078-0432.CCR-10-1025

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Translational Relevance

Reactivation of tumor suppressors is one of the most important strategies in the development of cancer chemotherapy drugs. CEBPD, a tumor suppressor, is inactivated in many cancers including cervical cancer, hepatocellular carcinoma, breast cancer, and leukemia, indicating it can serve as a drugable target. For the first time, the authors provide a new insight for the potential of HMDB serving as an anticancer drug, and they also highlight the CEBPD induction as an important therapeutic anticancer drug effect.

cells (7, 8). CEBPD is also involved in regulating proapoptotic gene expression during mammary gland involution (9). These findings suggest that CEBPD can serve as a tumor suppressor by causing growth arrest and apoptosis. However, the cell-cycle regulatory and proapoptotic genes that respond to CEBPD activation remain to be identified.

Several studies demonstrated that CEBPD gene expression is downregulated in breast cancer (10–12), leukemia (13), cervical cancer, and hepatocellular carcinoma (14). In addition, it has been suggested that CEBPD can potentially mediate differentiation because it can respond to all-trans-retinoic acid (RA) and vitamin D3 treatment (8). Thus, verifying the effects of CEBPD induction in cancer cells could be interesting because CEBPD might be an important target for the development of chemotherapeutic agents. It was reported that activation of the p38 kinase resulted in apoptosis of cancer cells (15). However, the downstream targets of p38 that participate in the p38-mediated proapoptotic effect in cancer cells are not well known. Our previous results suggest that CEBPD is a downstream target of p38 in A431 cells (16). However, whether the p38/CREB (cAMP response element-binding protein) pathway plays a crucial role in anticancer drug-induced CEBPD expression and contributes to its killing effect on cancer cells has not yet been investigated. In addition, CEBPD can interact with retinoblastoma (RB) (17), and the nature of the interplay among these proteins, especially during transcription, remains unknown.

In the current study, we demonstrate that HMDB can activate CEBPD transcription through activation of the p38/CREB pathway, but not by altering the DNA methylation status of the CEBPD promoter. Induced CEBPD can then contribute to PPARG2 and GADD153 transcription. An *in vivo* DNA-binding assay demonstrated that HMDB enhances the binding of phosphorylated CREB to the CEBPD promoter. Moreover, the effect of DNA-binding patterns, increased CEBPD levels, and loss of RB on PPARG2 and GADD153 promoter activation following HMDB treatment was determined. Finally, HMDB can attenuate xenogenic cancer formation, while an examination of metabolic indices, body weight and live tissue in treated mice indicated that this compound is nontoxic. In

conclusion, these results demonstrate that HMDB kills cancer cells through activation of CEBPD pathways and suggest that HMDB can serve as a superior chemotherapeutic agent with limited potential for adverse side effects.

Materials and Methods

Materials

Antibodies against CEBPD, CREB, Sp1, COX-1, and p38 were purchased from Santa Cruz Biotechnology. Phosphorylated CREB and p38 antibodies were purchased from Cell Signaling Technology. RB protein antibody was purchased from BD Biosciences. Assay kits for the detection of plasma levels of creatine kinase and blood urea nitrogen (BUN) were purchased from BioSystems S.A. Aspartate transaminase (AST) and alanine transaminase (ALT) assay kits were purchased from Human GmbH. HMDB was purchased from Sigma. Dominant-negative p38 and CREB expression vectors were constructed by Wang et al. (18, 19).

Cell culture and treatments

A431-, HeLa-, and E1A-immortalized wild-type and *Cebpd*^{-/-} MEFs (mouse embryonic fibroblasts) were maintained in Dulbecco's modified Eagle's medium supplemented with 10% fetal bovine serum. When cells were 80% confluent, HMDB (60 μmol/L) was added to the cells for the indicated times.

Plasmid transfection and reporter assays

Cells were transfected with plasmids using Lipofectamine 2000 according to the manufacturer's instructions. Transfectants were cultured in complete medium with or without treatment for 12 hours. Luciferase activity was measured in the lysates of transfectants.

Foci formation assays

Cells (500), including E1A-immortalized wild-type and *Cebpd*^{-/-} MEFs and transfected A431 and HeLa cells, were cultured for 10 to 14 days. Colonies were detected by methyl blue staining, and the number of colonies was counted for statistical analysis ($n = 3$, triplicate).

Reverse transcription (RT)-PCR

Total RNA was isolated after A431 cells were stimulated with HMDB. CEBPD-, PPARG2-, and GADD153-specific primers were used for analysis, and glyceraldehyde-3-phosphate dehydrogenase (GAPDH) primers were used as a control. The specific primers used were: for human CEBPD, 5'-AGCGCAACAACATCGCCGTG-3' and 5'-GTCGGGTC-TGAGGTATGGGTC-3'; for PPARG2, 5'-GCCATTCCTC-ACTGATAC-3' and 5'-GCATTATGAGACATCCCCAC-3'; for GADD153, 5'-GAAACGAAACAGAGTGGTCATTCC-CC-3' and 5'-GTGGGATTGAGGGTCACATC ATTGGCA-3'; and for GAPDH, 5'-CCATCACCATCTTCCAGGAG-3' and 5'-CCTGCTCACCACCTTCTTG-3'. Amounts of PCR product were determined using the IS-1000 digital imaging system.

Evaluation of CEBPD expression in human cervical tissue samples

Immunohistochemistry was performed on 4- μ m thick, formalin-fixed, paraffin-embedded tissue sections from representative tissue blocks of normal cervical tissue ($n = 10$), cervicitis ($n = 10$), and cervical carcinoma ($n = 10$). Sections were deparaffinized, hydrated, and immersed in a citrate buffer at pH of 6.0 in a microwave for epitope retrieval. Endogenous peroxidase activity was quenched in 3% hydrogen peroxidase for 15 minutes and sections were then incubated with 10% normal horse serum to block nonspecific immunoreactivity. Primary CEBPD antibody (1:50) was subsequently applied and detected by using the DAKO EnVision kit. Only tumor cells that demonstrated moderate-to-strong nuclear staining were regarded as having positive staining, and the expression in each sample was graded, with 0 for no staining, 1 for reactivity in less than 25% of cells, 2 for reactivity in 25% to 49% of cells, 3 for reactivity in 50% to 75% of cells and 4 for reactivity in more than 75% of cells. The difference in CEBPD expression levels in these samples was calculated using a chi-square test.

Immunoprecipitation assay

A431 cells that were transfected with the pcDNA3-HA or pcDNA3-HA/CEBPD expression vectors were lysed by a freeze-thaw method (buffer containing 20 mmol/L of HEPES [pH = 7.9], 0.2 mmol/L of EDTA, 2 mmol/L of $MgCl_2$, 1 mmol/L of DTT, 0.1 mmol/L of KCl, and 10% glycerol). α -HA antibody (1 μ g) was incubated with 200 μ g of lysate at 4°C overnight. The immune complex was washed 3 times with PBS and then separated by 10% SDS-polyacrylamide gel electrophoresis for Western blot with the indicated antibodies.

Short hairpin RNA (shRNA) assays

The lentiviral expression vectors pLKO.1-shLuciferase containing 5'-CTTCGAAATGTCCGTTCCGTT-3' and pLKO.1-shCEBPD containing 5'-GCTG TCGGCTGAGAAC-GAGAACTC-3' were obtained from the National RNAi Core Facility located at the Genomic Research Center of the Institute of Molecular Biology, Academia Sinica. The virus was produced from Phoenix cells co-transfected with the pMD2.G and psPAX2 vectors along with the pLKO.1-shLuc or pLKO.1-shCEBPD vector.

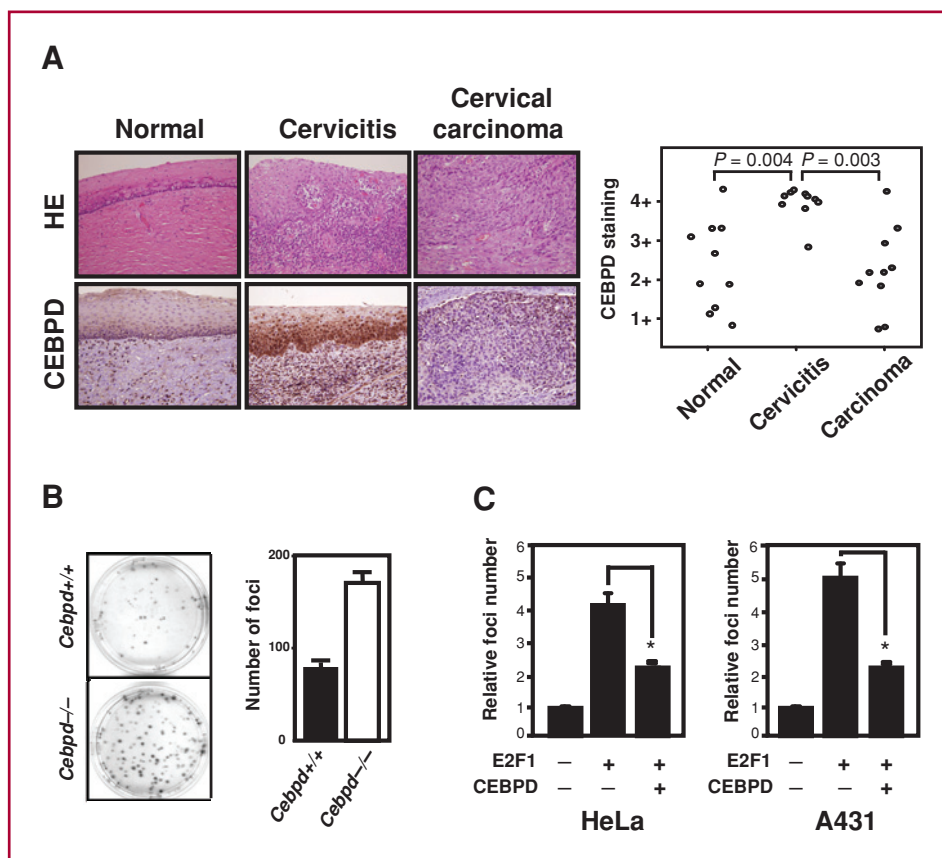


Fig. 1. CCAAT/enhancer-binding protein delta (CEBPD) functions as a tumor suppressor but is inactivated in cervical cancer specimens. **A**, CEBPD expression is low in normal cervical tissue and is significantly elevated in inflamed cervical epithelium ($P = 0.004$). CEBPD expression is diminished in cervical cancer ($P = 0.003$). **B**, Cebpd-deficient MEFs have a higher rate of proliferation. Foci assays were performed as described in the "Materials and Methods" section. **C**, increased levels of CEBPD attenuate E2F1-induced proliferation. Foci assays were performed with cells that were co-transfected with a vector encoding E2F1 and with a control vector or one encoding CEBPD. The quantifications results of colony numbers of which size were larger than 100 μ m. A very similar pattern was observed in 2 independent experiments. The total DNA concentration for each transfection was matched to equal with pcDNA3 vector. Figure is representative from 1 experiment in triplicate. Data are shown as the mean \pm S.E.M. *, $P < 0.05$ by Student's t test. HE, Hematoxylin and Eosin stain.

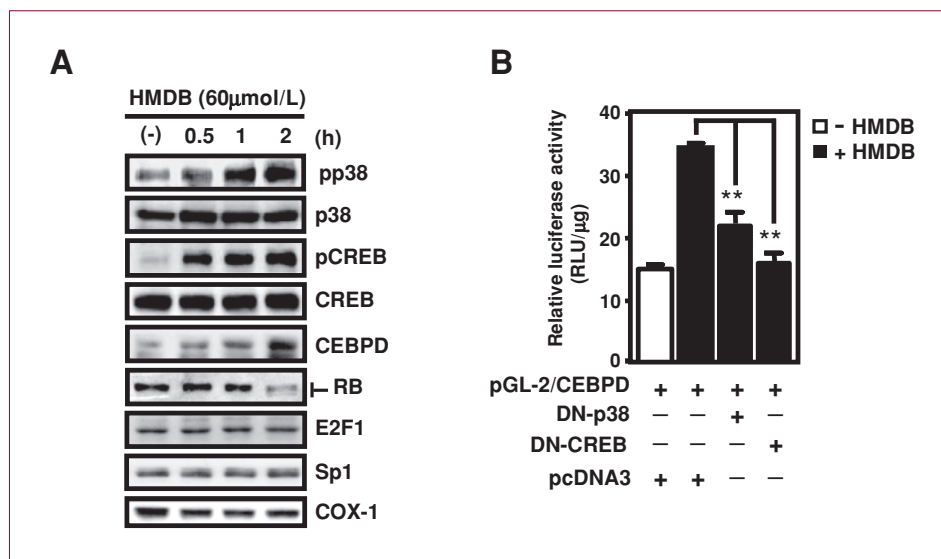


Fig. 2. The p38/CREB (cAMP response element-binding protein) pathway mediates HMDB (1-(2-hydroxy-5-methylphenyl)-3-phenyl-1,3-propanedione)-induced CCAAT/enhancer-binding protein delta (CEBPD) transcriptional activation in A431 cells. A, upregulation of CEBPD is coincident with p38/CREB activation following HMDB treatment. The lysates of HMDB-treated A431 cells were harvested at the indicated times for Western blot analysis with the indicated antibodies. B, dominant-negative p38 and CREB suppress HMDB-induced CEBPD reporter activity. A431 cells were co-transfected with a CEBPD reporter, a backbone vector and/or expression vectors encoding DN-p38 or DN-CREB. The transfectants were subsequently treated with HMDB. For this assay, 0.5 μ g of reporter and 0.5 μ g of expression vectors as indicated were co-transfected into A431 cells. The total DNA concentration for each transfection was matched to equal with pcDNA3 vector. Figure is representative from 3 experiments in duplicate. Data are shown as the mean \pm S.E.M. **, $P < 0.01$ by Student's t test.

Flow cytometry analysis

A431 cells were infected with lentiviral shCEBPD (shD) or shLuciferase (shLuc) at a multiplicity of infection of 10 for 24 hours and then incubated with or without HMDB for the indicated times. The cells were resuspended in PBS and fixed in ice-cold 100% ethanol at -20°C . Later, cell pellets were collected by centrifugation and were resuspended in propidium iodide solution (0.1% Triton X-100 in PBS, 0.2 mg/mL of RNase A, and 20 μ g/mL of propidium iodide) at room temperature for 1 hour. Fluorescence emitted from propidium iodide-DNA complexes was quantitated after excitation of the fluorescent dye by FACScan cytometry.

Chromatin immunoprecipitation assays

Chromatin immunoprecipitation (ChIP) assays were performed as described (16, 20). Briefly, A431 cells were treated with 1% formaldehyde for 15 minutes. Cross-linked chromatin was then isolated and sonicated to an average size of 500 bp. DNA fragments were immunoprecipitated with antibodies specific for CEBPD, RB, E2F1, or control rabbit immunoglobulin G (IgG) at 4°C overnight. Cross-linking was reversed and immunoprecipitated chromatin was amplified with primers corresponding to specific regions in the *PPARG2* or *GADD153* genomic loci. The ChIP primers for the *PPARG2* promoter have been described (20). The ChIP primers for the *GADD153* promoter are as follows: 5'-GGGGTACCTCGACAATCCCAGTGGATGGATAACC-3' and 5'-TGGCT TTGGGTCACGAG- GCTTCACG-3'.

Animal studies

Female, 6- to 8-week-old NOD (non-obese diabetic)/severe combined immunodeficient mice (SCID) mice were

obtained from the Laboratory Animal Center of the National Cheng Kung University, Tainan, Taiwan. A431 cells (2×10^6) in 0.2 mL of PBS were inoculated subcutaneously into the right flank of the mice. After 8 days, when macroscopic tumors (50–100 mm^3) had formed, animals ($n = 5$ per group) were placed randomly into 2 groups as follows: (1) control group, which received identical volumes of vehicle (corn oil); and (2) experimental group, treated with HMDB. HMDB, dissolved in corn oil, was given intraperitoneally at doses of 50 mg/kg/day 5 days per week for 6 weeks. Animal weight and tumor dimensions were measured every 2 days with calipers, and tumor volumes were estimated using 2-dimensional measurements of length and width and were calculated with the formula: $[l \times (w)^2] \times 0.52$, where l is length and w is width. At the end of the experiment, all animals were sacrificed and blood samples were collected in heparinized tubes. Plasma was separated from red blood cells by centrifugation (4,700 rpm for 10 minutes). The plasma levels of creatine kinase, BUN, AST, and ALT were measured, following the procedures stated in the assay protocols.

Results

Inflammation-induced CEBPD is inactivated in cervical cancer specimens

CEBPD is responsive to proinflammatory stimuli, such as IL-1 β and TNF α (21, 22). In addition, the CEBPD gene was observed to be inactivated in cervical cancer through increased hypermethylation of its promoter (14). However, these phenomena have not yet been linked with clinical specimens. In the current study, we quantified CEBPD

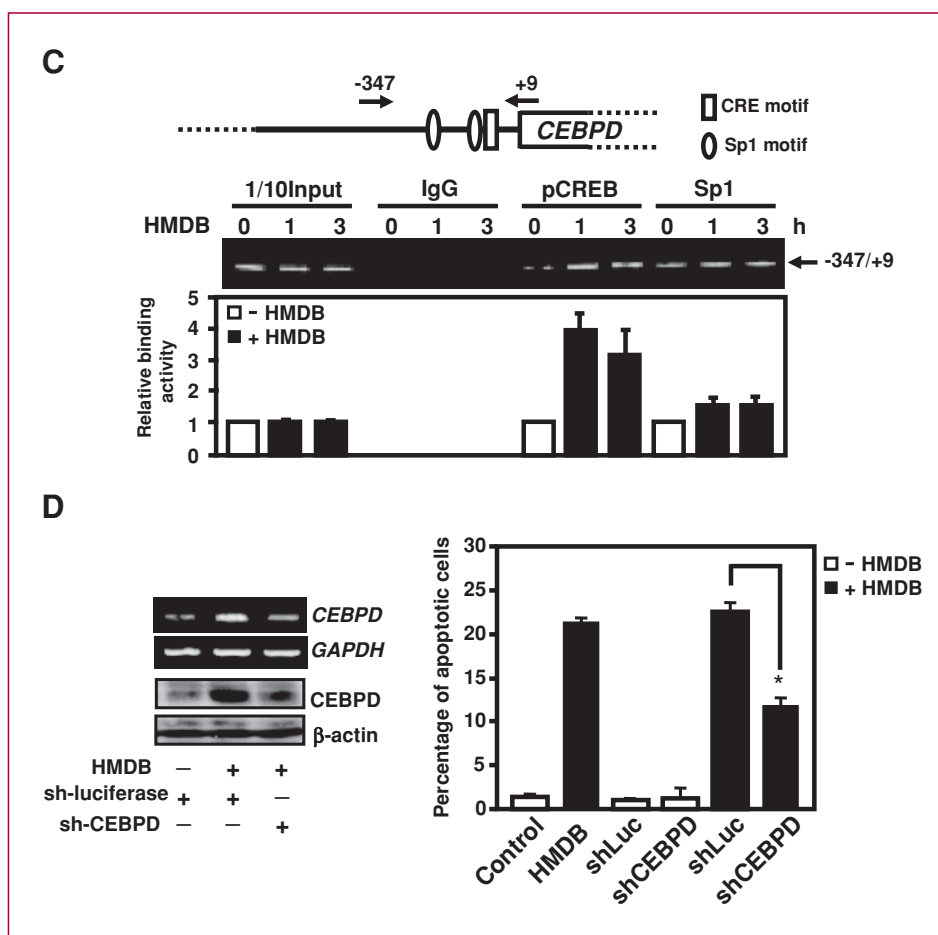


Fig. 2. (cont'd). C, HMDB enhances the binding of phosphorylated CREB to the CEBPD promoter *in vivo*. As a positive control, PCR amplification was also carried out with 1/10 of input DNA from chromatin before the immunoprecipitation (IP) step. Chromatin was isolated from cells with or without HMDB treatment as indicated time courses (untreated [0], 1, and 3 hours), and the IP step performed with various antibodies as indicated. "-347/+9" denotes the PCR product following specific primer amplification with purified template from the IP step. Bottom plot represents data that show means \pm standard deviation (SD) of 2 independent experiments. Setting the image intensity of 0 time course in each group to be standard as 1, the rest of intensity values were normalized with their individual standard. D, Loss of CEBPD attenuates HMDB-induced death of A431 cells. A431 cells were transfected with vectors expressing shLuciferase or shCEBPD for 24 hours. After 6 hours of HMDB treatment, the lysates and total RNA were harvested and used for Western blot analysis with the indicated antibodies and RT-PCR with specific primers (left), respectively. Flow cytometry analysis was also performed on HMDB-treated cells (right). A similar pattern was observed in 2 independent experiments. Figure is representative from 1 experiment in triplicate. Data are shown as the mean \pm S.E.M. *, $P < 0.05$ by Student's *t* test. The total DNA concentration for each transfection was matched to equal with related backbone vector.

expression in normal, inflamed, and cancerous cervixes. As shown in Figure 1A, the expression level of CEBPD was low in the normal cervix but significantly elevated in inflamed cervical epithelium ($P = 0.004$). Moreover, inactivation of CEBPD was observed in a majority of cervical cancers relative to inflamed cervical epithelium ($P = 0.003$). Our previous study demonstrated that the hypermethylation of CpG islands within the CEBPD promoter plays an important role in CEBPD silencing in cervical cancer (14). To address whether the inactivation of CEBPD can enhance proliferation, a foci assay was performed with wild-type and *Cebpd*-deficient MEFs (23). Our results suggest that the loss of *Cebpd* expression leads to enhanced proliferation (Fig. 1B). In addition, E2F1 demonstrates oncogenic activity in the induction of cancer cell proliferation (24, 25). To address whether CEBPD can serve as a negative regulator of

E2F1-induced proliferation in A431 and HeLa cells, these cells were co-transfected with vectors encoding CEBPD and with empty vector or vector encoding E2F1, and foci assays were performed. As shown in Figure 1C, the overexpression of CEBPD attenuates E2F1-induced proliferation. Taken together, these results suggest that the incremental insensitivity of CEBPD to external stimuli, such as EGF (16) or TNF α (22), could benefit the E2F1-mediated tumorigenesis.

The preceding experiments demonstrated that CEBPD expression inhibits tumor formation. Therefore, we wanted to investigate whether CEBPD levels are changed in A431 cells following treatment with clinical anticancer drugs. Interestingly, CEBPD transcription is induced in response to stimulation from multiple anticancer drugs, including dexamethasone (Dex), RA, and 5'-azacytidine (5'-Aza)

(Supplementary Fig. 1). In addition, we found that treatment with a potential anticancer chemical, HMDB, results in transcriptional activation of the CEBPD gene. We previously demonstrated that CEBPD transcription is upregulated through activation of the p38/CREB MAPK pathway (16) and/or epigenetic regulation (14). Therefore, to clarify which mechanism underlies HMDB-induced CEBPD transcriptional activation, we first performed a methylation-specific PCR assay. Treatment with HMDB resulted in the consistent methylation of the CpG islands within the CEBPD promoter (Supplementary Fig. 2), suggesting that HMDB has no effect on the epigenetic regulation of the CEBPD promoter. Importantly, HMDB can activate p38/CREB signaling and decrease RB protein levels, but has no effect on the levels of E2F1 and Sp1 (Fig. 2A and Supplementary Fig. 3A). To determine whether the p38/CREB pathway participates in HMDB-induced CEBPD activation, a reporter assay was performed in which cells were co-transfected with the CEBPD reporter and vectors expressing dominant-negative forms of p38 or CREB. Dominant-negative p38 and CREB effectively attenuated HMDB-induced CEBPD reporter activity (Fig. 2B and Supplementary Fig. 3B). Furthermore, an *in vivo* DNA-binding assay was performed to examine whether the binding of phosphorylated CREB (pCREB) on the CEBPD promoter is sensitive to

HMDB treatment. Results from the ChIP assay indicated that HMDB strongly enhances binding of pCREB and slightly increases Sp1 binding to the CEBPD promoter (Fig. 2C). Taken together, these results suggest that the p38/CREB pathway plays a critical role in HMDB-induced CEBPD transcription, but not by changing the methylation status of the CEBPD promoter. To further examine the contribution of CEBPD to HMDB-induced apoptosis in cancer cells, A431 cells were transfected with expression vector encoding shRNA against CEBPD and were subsequently treated with HMDB. Loss of CEBPD attenuated HMDB-induced cancer cell death (Fig. 2D and Supplementary Fig. 3C), suggesting that CEBPD activation is important for the proapoptotic activity of HMDB.

PPARG2 and GADD153 are downstream targets of HMDB-induced CEBPD expression

GADD153, an oxidative stress-inducible and proapoptotic gene (26), is responsive to HMDB treatment (5). Our previous study demonstrated that the transcription of PPARG2, an inducer of adipogenesis and apoptosis, is regulated by CEBPD (20). However, it was unclear whether the activation of the GADD153 and PPARG2 genes was regulated by HMDB-induced CEBPD expression. As shown in Figure 3A and Supplementary Figure 1, expression of

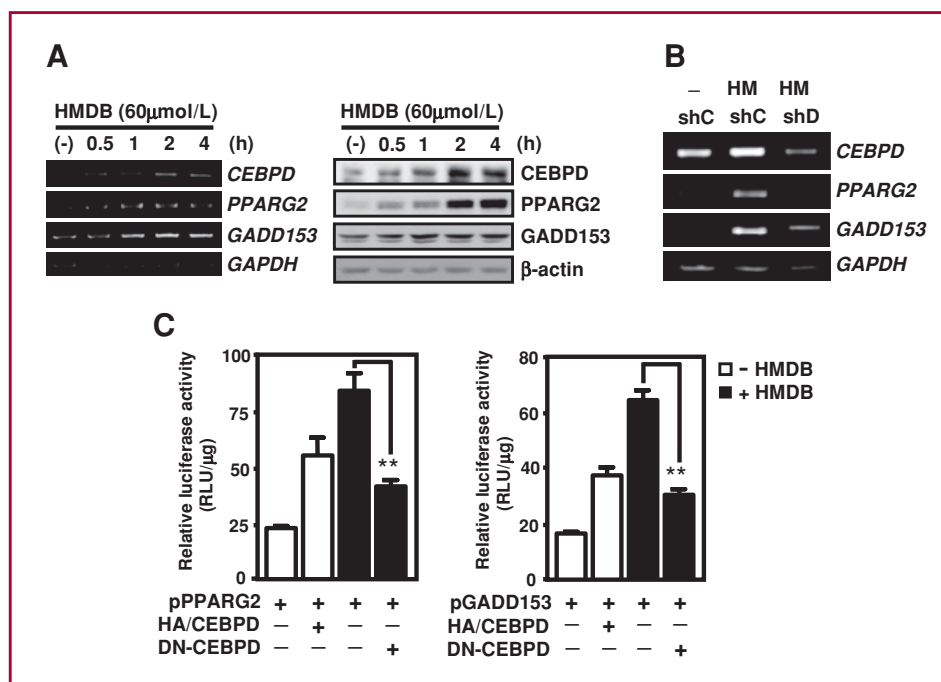


Fig. 3. CCAAT/enhancer-binding protein delta (CEBPD) mediates the induction of PPARG2 and GADD153 transcription following HMDB (1-(2-hydroxy-5-methylphenyl)-3-phenyl-1,3-propanedione) treatment. A, PPARG2 and GADD153 gene expression is coincident with the increase in CEBPD levels after HMDB treatment. Total RNA and lysates from HMDB-treated A431 cells were harvested at the indicated times for RT-PCR with gene-specific primers (left) and Western blot analysis with the indicated antibodies (right), respectively. B, CEBPD is an upstream activator of HMDB-induced PPARG2 and GADD153 transcription. A431 cells were transfected with vectors encoding shControl (shC) or shCEBPD (shD) for 24 hours. After 6 hours of HMDB treatment, the amounts of CEBPD, PPARG2, and GADD153 transcripts were determined by RT-PCR with gene-specific primers. C, dominant-negative CEBPD represses HMDB-induced PPARG2 and GADD153 reporter activity. A431 cells were co-transfected with PPARG2 or GADD153 reporters and with a control vector or 1 encoding DN-CEBPD, and cells were treated with HMDB. Figure is representative from 3 experiments in duplicate. Data are shown as the mean \pm S.E.M. **, $P < 0.01$ by Student's *t* test. For this assay, 0.5 μ g of reporter and 0.5 μ g of expression vectors as indicated were co-transfected into A431 cells. The total DNA concentration for transfection was matched to equal with pcDNA3 or related backbone vectors.

GADD153 and PPARG2 is upregulated by HMDB and coincident with CEBPD expression. Experiments were performed to clarify whether CEBPD participates in HMDB-induced activation of GADD153 and PPARG2 transcription. An RT-PCR analysis demonstrated that shRNA-mediated knockdown of CEBPD blocked HMDB-induced PPARG2 and GADD153 transcription, suggesting that CEBPD is an upstream regulator of the expression of these genes (Fig. 3B). In a complementary approach, reporter assays were performed in which exogenous CEBPD was introduced into cells. Wild-type CEBPD transactivated the PPARG2 and GADD153 reporters, whereas the dominant-negative CEBPD attenuated the HMDB-induced reporter activity of both constructs (Fig. 3C and Supplementary Fig. 4).

RB negatively regulates CEBPD-mediated activation of PPARG2 and GADD153 transcription

RB can act as a transcriptional repressor and controls cell-cycle progression, differentiation/survival, and geno-

mic integrity through its interaction with E2F1 (27, 28). CEBPD was demonstrated to bind to RB in an *in vitro* protein-protein interaction assay (17). However, the details of how RB and CEBPD interact during transcriptional regulation were unknown. An immunoprecipitation (IP) assay was performed with the initial aim of verifying that CEBPD can interact with RB in A431 cells. RB was, in fact, detected in the CEBPD-IP complex (Fig. 4A). Subsequently, we wanted to characterize the function of RB in CEBPD-mediated promoter regulation. Overexpression of RB-attenuated CEBPD-induced GADD153 and PPARG2 promoter activity (Fig. 4B). As shown in Figure 2A, HMDB treatment resulted in decreased RB in A431 cells, while attenuating the levels of the hyperphosphorylated form of RB. These interesting observations led us to subsequently investigate the interplay between RB, E2F1, and CEBPD in the regulation of GADD153 and PPARG2 reporter activity. In these experiments, CEBPD functioned in opposition to E2F1 and RB to activate PPARG2 and GADD153 reporter activity

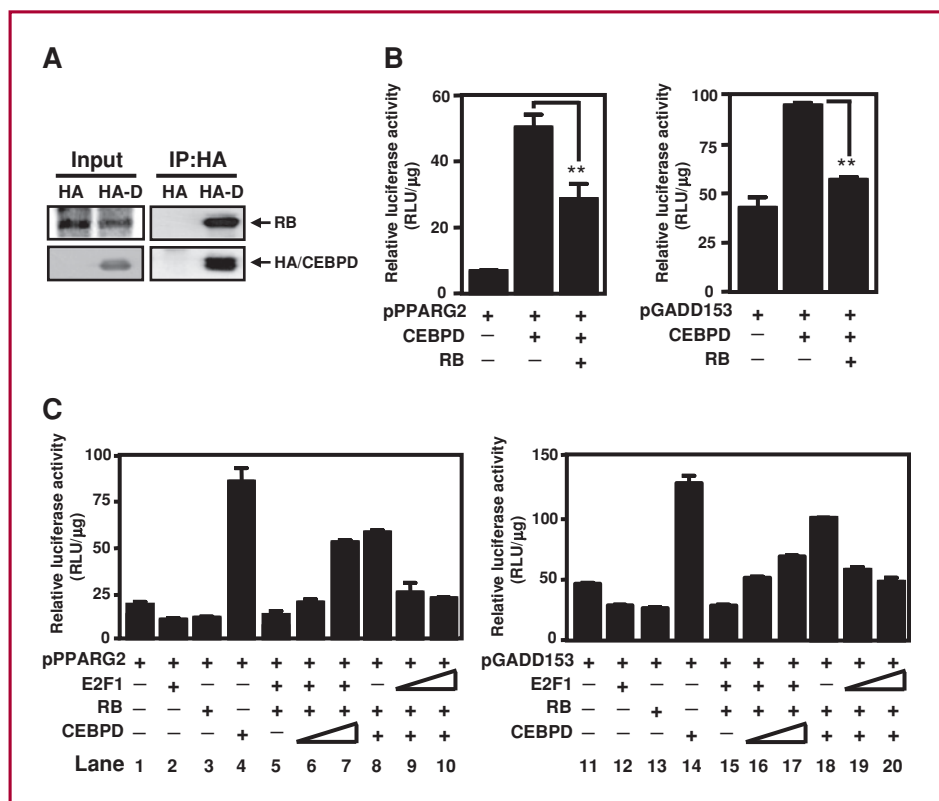


Fig. 4. Retinoblastoma (RB) functions as a repressor of CCAAT/enhancer-binding protein delta (CEBPD)-mediated activation of PPARG2 and GADD153 transcription. A, CEBPD interacts with RB. A431 cells were transfected with HA/CEBPD or empty expression vector for 24 hours. The lysates of the transfectants were harvested and IPs were performed with HA antibody. The IP products were further examined with RB or HA antibody. B, RB attenuates CEBPD-induced PPARG2 and GADD153 reporter activity. Indicated reporters were co-transfected into cells with a vector encoding CEBPD and with a control vector or with one encoding RB for 24 hours. The lysates of these transfectants were harvested for a luciferase assay. Figure is representative from 2 experiments in triplicate. Data are shown as the mean \pm S.E.M. **, $P < 0.01$ by Student's *t* test. C, CEBPD reverses RB/E2F1-mediated suppression of PPARG2 and GADD153 reporter activity. Indicated reporters were co-transfected into cells with various expression vectors as indicated. The total DNA amount for each transfection was equalized with empty pcDNA3 or related vectors. The lysates of the transfectants were harvested for luciferase assays. Figure is representative from 2 experiments in triplicate. Data are shown as the mean \pm S.E.M. For this assay, 0.5 μ g of reporter and 0.5 μ g of expression vectors as indicated were co-transfected into A431 cells. The total DNA concentration for transfection in A, B, and C was matched to equal with pcDNA3 vector.

(Fig. 4C, compare lanes 2, 3, and 4 with lane 1; and lanes 12, 13, and 14 with lane 11). E2F1 is an efficient repressor of PPARG2 expression in the presence of RB, potentially by replacing CEBPD within the transcriptional complex (Fig. 4C, compare lanes 9 and 10 with lane 8; and lanes 19 and 20 with lane 18). Moreover, increased levels of CEBPD reverse RB/E2F1-mediated repression of PPARG2 and GADD153 reporter activity (Fig. 4C, compare lanes 6 and 7 with lane 5; and lanes 16 and 17 with lane 15), implying that the loss of RB is crucial for CEBPD to function as a tumor suppressor in HMDB-mediated cancer cell death. ChIP assays were then performed to determine the nature of RB, E2F1, and CEBPD binding to the PPARG2 and GADD153 promoters following HMDB treatment. HMDB enhanced CEBPD binding to the PPARG2 and GADD153 promoters, while attenuating the binding of RB and having no significant effect on E2F1 binding (Fig. 5). In summary, we have demonstrated that HMDB treatment not only results in the degradation of RB and in decreased levels of hyperphosphorylated RB, but this treatment also restores CEBPD expression, thus overcoming the repression of proapoptotic genes by the RB/E2F1 transcriptional complex.

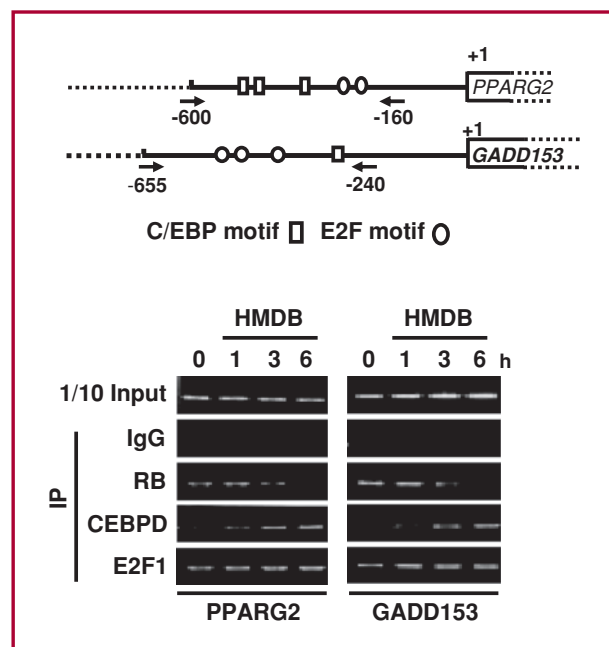


Fig. 5. *In vivo* binding of retinoblastoma (RB), CCAAT/enhancer-binding protein delta (CEBPD), and E2F1 to the PPARG2 and GADD153 promoters after HMDB (1-(2-hydroxy-5-methylphenyl)-3-phenyl-1,3-propanedione) treatment. The scheme of the 5'-flanking regions of the PPARG2 and GADD153 genes and the location of primers designed for PCR (top). CEBPD, RB, and E2F1 bound to the PPARG2 and GADD153 promoters *in vivo*. Chromatin was separately immunoprecipitated with specific antibodies including those against CEBPD, RB, and E2F1 or with control IgG and was then amplified by PCR with primers as indicated in the top. PCR cycles: 32 for 1/10 Input, IgG-IP, CEBPD-IP, and E2F1-IP; 34 (PPARG2) and 35 (GADD153) for RB-IP. Consistent results were observed from at least 2 independent experiments.

An antitumor effect of HMDB in A431-bearing SCID mice

Previous studies demonstrated that HMDB induced cancer cell apoptosis (4, 5). To assess the potential use of HMDB as an antineoplastic drug, we evaluated its effect on the growth of A431 xenografts in mice. We examined the mice that were administered a single dose of HMDB per day (50 mg/kg, intraperitoneal) (Fig. 6A). Compared with the control, HMDB treatment resulted in a 67% reduction in tumor growth after 6 weeks of treatment. Furthermore, the levels of CEBPD, PPARG2, GADD153, and RB were verified in these experimental mice. As shown in Figure 6C, coincident with reduced tumor size, the higher levels of CEBPD, PPARG2, and GADD153 and decrease of RB were observed in HMDB-administrated A431 xenografts SCID mice. In addition, to determine the toxicity of HMDB in animals, the plasma levels of liver-specific enzymes such as ALT and AST were measured and renal function tests such as BUN and creatinine level detection were performed. The intraperitoneal administration of HMDB at a dose of 50 mg/kg/day for 42 consecutive days was well tolerated, as no toxic deaths or body weight loss were observed during or after treatment (Fig. 6B).

Discussion

It is known that p38 signaling participates in the regulation of apoptotic cell death by upregulating the expression of proapoptotic genes, such as Fas ligand, PPARG2, and GADD153 (29–32). Moreover, p38 is also involved in the negative regulation of cell growth, as it represses cyclin D1 expression and activates p27 (33, 34). The p38 signaling pathway also induces the differentiation or apoptosis of malignant cells and can be activated by chemicals that are used for clinical cancer therapy, such as RA, Dex, and Vitamin D3 (35–37). Previously, our studies suggested that transcriptional activation of CEBPD occurs downstream of the p38/CREB signaling pathway in A431 cells (16), a cervical cell line that is responsive to EGF-induced apoptosis (38). Moreover, upregulation of CEBPD was also observed following treatment with RA, Dex, D3, and HMDB (Supplementary Fig. 1). The overexpression of CEBPD can also downregulate the expression of cyclin D1 and E (8) while upregulating p27 (7). These studies suggest a close relationship between p38 signaling and the activation of CEBPD gene expression.

PPARG2 and GADD153 have been reported to function in tumor suppression (39–42). CDK4 was suggested to derepress RB/E2F1-mediated PPARG2 gene inactivation in adipogenesis (43). In the current study, the promoter activities of the proapoptotic genes, PPARG2 and GADD153, were found to be modulated by RB (Fig. 4). Furthermore, HMDB treatment induced CEBPD expression and decreased RB levels, which were coincident with the induction of PPARG2 and GADD153 transcription (Fig. 2A, Fig. 3A and B). Our molecular evidence links CEBPD and RB in transcriptional regulation following HMDB treatment and suggests that CEBPD enhancement

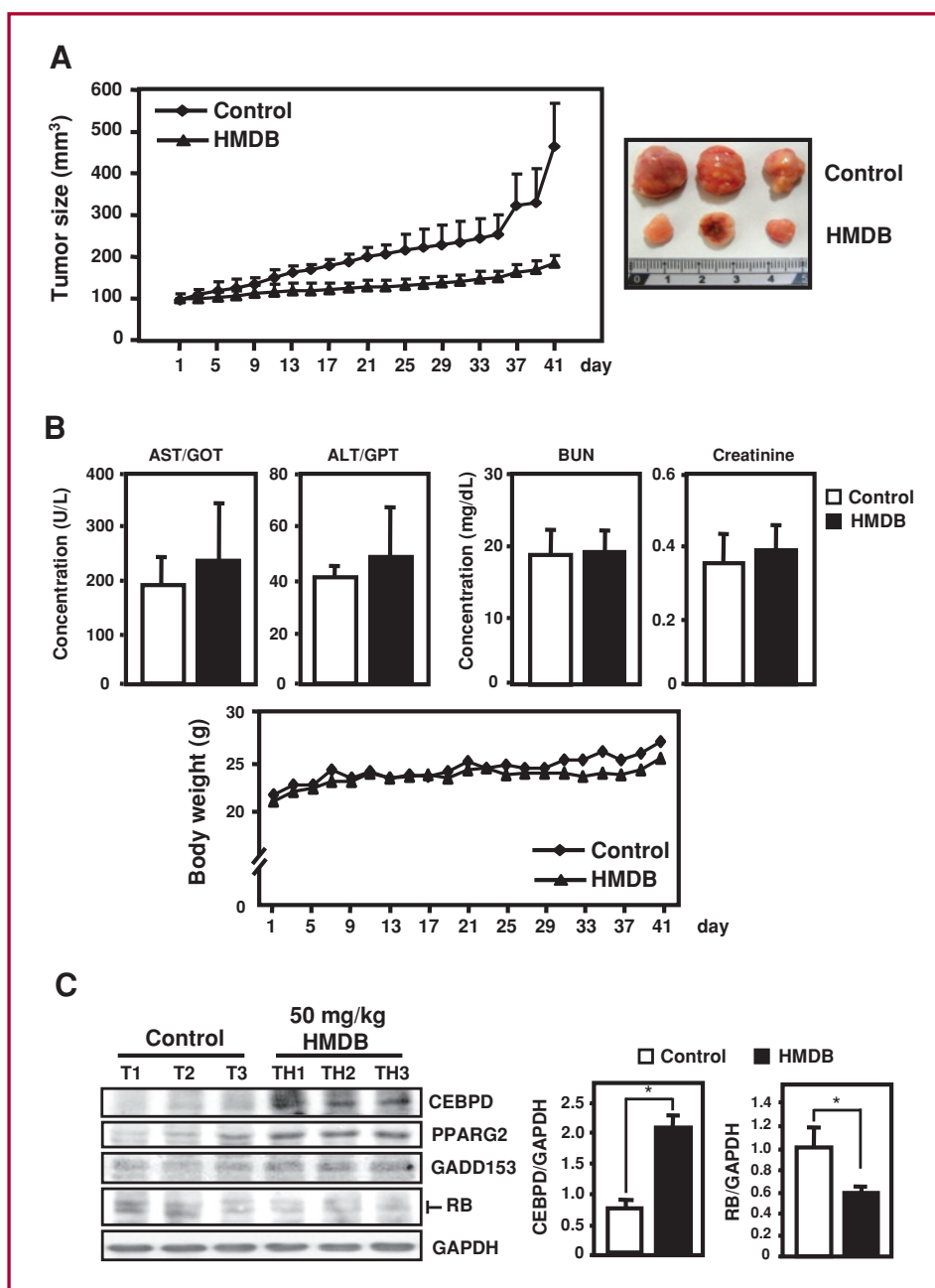


Fig. 6. *In vivo* anti-tumor effect of HMDB (1-(2-hydroxy-5-methylphenyl)-3-phenyl-1,3-propanedione) in A431-bearing severe combined immunodeficient (SCID) mice. Effect of 6 weeks of intraperitoneal administration of HMDB on the size of tumors in A431-bearing SCID mice. A, NOD/SCID mice in 2 groups of 5 were subcutaneously inoculated with A431 cells (2×10^6). Following solid tumor formation, animals were injected intraperitoneally with 0.1 mL of vehicle or HMDB at doses of 50 mg/kg/day. B, evaluation of the toxicity of HMDB in the liver and kidney tissues of the hosts. Following a 6-week drug treatment, all animals were sacrificed and their plasma collected. Plasma levels of the liver-specific enzymes alanine transaminase (ALT), aspartate transaminase (AST) and renal function tests, such as blood urea nitrogen (BUN) and creatinine levels, were measured. Notably, organ function was comparable between the HMDB-treated and vehicle-treated groups. Data from 5 mice in each group are presented as the mean \pm SD. Tumor dimensions and animal weight were measured every 2 days. C, increase of CCAAT/enhancer-binding protein delta (CEBPD) and loss of retinoblastoma (RB) are observed in A431-bearing SCID mice. Following a 6-week drug treatment, all animals were sacrificed and the tumors were collected for extractions of protein. The protein samples were performed with Western blot by using specific antibodies. Data in the bottom show the changes of CEBPD and RB levels of with or without HMDB treatment A431 xenografts SCID mice.

of GADD153 and PPARG2 transcription can account for the tumor inhibitory effect of HMDB in A431 cells. Furthermore, both gain-of-function and loss-of-function assays demonstrated that RB is important for the E2F1-mediated inactivation of proapoptotic genes (Fig. 4). CEBPD, RB, and E2F1 were demonstrated to interact with each other following treatment with HMDB (Fig. 5), suggesting that the induction of CEBPD by HMDB can reverse RB/E2F1-mediated repression of the PPARG2 and GADD153 genes.

The inactivation of CEBPD has been observed in several cancers, including breast cancer (10–12), acute leukemia (13), hepatocellular carcinoma, and cervical cancer (14). One therapeutic approach induces cancerous cells to behave like normal cells in what is known as "differentiation therapy" (44). Several studies have demonstrated that CEBPD plays a functional role in differentiation and causes growth arrest (6, 7). In addition, CEBPD is an inducible gene that can be upregulated by several external stimuli, including Dex, RA, and 5'-Aza (7, 14, 45) (Supplementary Fig. 1). However, these clinical anticancer drugs are not ideal because of their induction of hepatotoxicity in cancer patients (46–48). Herein, we demonstrate that the cytotoxicity of HMDB is quite low in cancer cell xenograft mice, as determined by the examination of metabolic indices, body weight, and liver tissue in these mice (Fig. 6B). Moreover, our preliminary results indicate that the cytotoxicity of HMDB is lower than that of 5'-Aza in xenograft mice, suggesting that HMDB could be a nontoxic alternative to anticancer drugs or could be used in combination with current drugs for effective cancer therapy.

Comparison of HMDB with other anticancer drugs in terms of cytotoxicity and efficacy remain to be performed to evaluate whether HMDB is a suitable candidate to replace other marketed drugs. Interestingly, this study has identified the need to determine CEBPD levels when treating patients with current clinical anticancer drugs. Our recent results demonstrate activation of COX-2, which has been suggested to serve as an oncogene, in response to CEBPD induction (49). Additionally, increased levels of MMP1, 3, and 10, which have been suggested to act as inducers of metastasis, are coincident with CEBPD levels (Wang et al., unpublished results). Moreover, overexpression of CEBPD not only induces

apoptosis and growth arrest, but also activates inflammation-like responses, such as an increase in genomic instability and cell migration. These intriguing observations reveal another side of CEBPD activity that opposes the side associated with its suspected role as a tumor suppressor. Hence, further investigation is necessary to modulate the inflammation-like responses resulting from CEBPD-inducing anticancer drug treatment to achieve better therapeutic effects in clinical settings. Furthermore, it is well known that anticancer drug resistance may result from a wide variety of mechanisms. One possible mechanism is that some cancer cells can escape the initial cytotoxicity of anticancer drugs and may continuously increase their drug resistance by long-term cellular adaptations. Therefore, treatment with anticancer drugs that potentially cause CEBPD induction, such as p38 activators or DNA methylation inhibitors, may be a double-edged sword, in that they may also lead to the development of drug resistance. This may result from CEBPD not only acting as a proapoptotic activator, but also inducing inflammation-like responses that could be involved in drug resistance. Accordingly, the activation status of CEBPD should be considered before the use of certain anticancer drugs. Another possible strategy could be a combination treatment of CEBPD-inducing anticancer drugs with COX-2, MMP, and/or genomic instability inhibitors to block drug resistance or other adverse effects.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

The authors thank Dr. Tsung-Lin Liu and Christine Chin-Jung Hsieh for critical review of this manuscript.

Grant Support

This work was supported in part by NSC grant 96-2320-B-006-044-MY2 and by NCKU landmark grant C007 (Taiwan). Fund for Open Access publication was provided by the NCKU landmark grant C007.

Received 04/20/2010; revised 09/03/2010; accepted 09/08/2010; published OnlineFirst 10/22/2010.

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CEBPD Reverses RB/E2F1-Mediated Gene Repression and Participates in HMDB-Induced Apoptosis of Cancer Cells

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Clin Cancer Res 2010;16:5770-5780. Published OnlineFirst October 22, 2010.

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