

Activation and Potentiation of Interferon- γ Signaling by 3,3'-Diindolylmethane in MCF-7 Breast Cancer Cells

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ABSTRACT

3,3'-Diindolylmethane (DIM), a natural autolytic product in plants of the *Brassica* genus, including broccoli, cauliflower, and Brussels sprouts, exhibits promising cancer protective activities, especially against mammary neoplasia in animal models. We observed previously that DIM induced a G₁ cell-cycle arrest and strong induction of cell-cycle inhibitor p21 expression and promoter activity in both estrogen-responsive and -independent breast cancer cell lines. We showed recently that DIM up-regulates the expression of interferon γ (IFN γ) in human MCF-7 breast cancer cells. This novel effect may contribute to the anticancer effects of DIM because IFN γ plays an important role in preventing the development of primary and transplanted tumors. In this study, we observed that DIM activated the IFN γ signaling pathway in human breast cancer cells. DIM activated the expression of the

IFN γ receptor (IFNGR1) and IFN γ -responsive genes p56- and p69-oligoadenylate synthase (OAS). In cotreatments with IFN γ , DIM produced an additive activation of endogenous p69-OAS and of an OAS-Luc reporter and a synergistic activation of a GAS-Luc reporter. DIM synergistically augmented the IFN γ induced phosphorylation of signal transducer and activator of transcription factor 1, further evidence of DIM activation of the IFN γ pathway. DIM and IFN γ produced an additive inhibition of cell proliferation and a synergistic increase in levels of major histocompatibility complex class-1 (MHC-1) expression, accompanied by increased levels of mRNAs of MHC-1-associated proteins and transporters. These results reveal novel immune activating and potentiating activities of DIM in human tumor cells that may contribute to the established effectiveness of this dietary indole against various tumors types.

3,3'-Diindolylmethane (DIM) is a natural product formed during the autolytic breakdown of glucobrassicin present in food plants of the *Brassica* genus, including the common vegetables cabbage, Brussels sprouts, cauliflower, and broccoli. DIM also is produced after ingestion of indole-3-carbinol (I3C), the immediate precursor of DIM in the plants (Grose and Bjeldanes, 1992). In addition, DIM is slowly produced from I3C under near neutral pH cell culture conditions during extended incubation periods. Results of several studies indicate that DIM exhibits promising cancer-protective activities, especially against mammary neoplasia (Wattenberg and Loub, 1978; Shertzer, 1983, 1984). Oral intubation of I3C in a single dose

before carcinogen treatment reduced the incidence and multiplicity of dimethylbenz(α)anthracene-induced mammary tumors in rats by 70 to 80% (Wattenberg and Loub, 1978; Grubbs et al., 1995). Repeated oral administrations of DIM during the promotion stage of dimethylbenz(α)anthracene-induced mammary tumorigenesis inhibited tumor growth in rodents by as much as 95% (Chen et al., 1998). We observed that under conventional cell culture conditions, DIM could inhibit the proliferation of breast tumor cell lines, regardless of estrogen receptor status (Riby et al., 2000). DIM induced a G₁ cell-cycle arrest and produced a strong induction of p21 cell-cycle inhibitor gene expression and promoter activity in both estrogen responsive and estrogen independent breast cancer cells. The antiproliferative effects of DIM involved Sp1/Sp3 transcription factor activation of p21 as a target for cell cycle control in human breast cancer cells (Hong et al., 2002).

Interferons (IFNs) are a group of immune cytokines with

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ABBREVIATIONS: DIM, 3,3'-diindolylmethane; I3C, indole-3-carbinol; IFN, interferon; bp, base pair(s); ATF, activating transcription factor; AP-1, activator protein 1; IFNGR1, interferon- γ receptor-1; STAT, signal transducer and activator of transcription; RT, reverse transcription; PCR, polymerase chain reaction; GAS, interferon- γ -activated sequence; DTT, dithiothreitol; PBS, phosphate-buffered saline; FITC, fluorescein isothiocyanate; HLA, human leukocyte antigen; %PC, percentage of positive cells; MFV, mean fluorescence value; OAS, oligoadenylate synthase; JAK, Janus-activated kinase; DMSO, dimethyl sulfoxide; RA, retinoic acid; RRP, recurrent respiratory papillomatosis; GAPDH, glyceraldehyde-3-phosphate dehydrogenase.

antiviral and cytostatic functions. Type I IFNs, including IFN α and IFN β , are produced by virus-infected cells. Type II IFN, usually called interferon- γ (IFN γ) or the "immune interferon", promotes B cell differentiation into immunoglobulin-producing cells (Boehm et al., 1997). The recently recognized antitumor activity of IFN γ includes the priming of macrophages for nonspecific tumoricidal activity; the activation of monocytes, natural killer cells, and T cells to increase cytotoxicity against tumor cells; and the inhibition of tumor-induced angiogenesis (Ikeda et al., 2002). The possible therapeutic use of IFN γ in cancer patients, however, has been limited because of serious side effects (Wimer, 1998).

In a recent report (Xue et al., 2005), we showed that DIM can up-regulate the expression of IFN γ in the human MCF-7 breast cancer cell line. Using promoter deletions, we showed that the region between -108 and -36 bp in the IFN γ promoter, which contains two conserved and essential regulatory elements, is required for DIM-induced IFN γ expression. DIM activates both c-Jun NH $_2$ -terminal kinase and p38 pathways, induces the phosphorylation of c-Jun and ATF-2, and increases the binding of the homodimer or heterodimer of c-Jun/ATF-2 to the proximal AP-1-cAMP response element-binding protein-ATF-binding element. Moreover, studies with specific enzyme inhibitors showed that upstream Ca $^{2+}$ -dependent kinase(s) is required for the inducing effects of DIM in MCF-7 cells. These results established that DIM-induced IFN γ expression in human breast tumor cells is mediated by activation of both c-Jun NH $_2$ -terminal kinase and p38 pathways, which is ultimately dependent on intracellular calcium signaling.

In the present study, we report that DIM activated the IFN γ signal transduction pathway in human breast cancer cells. DIM treatment increased the expression of IFN γ receptor-1 (IFNGR1) and the IFN γ -responsive genes p56 and p69-oligoadenylate synthase (OAS). In addition, DIM produced a synergistic increase in IFN γ -induced activation of phosphorylation of signal transducer and activator of transcription 1 (STAT-1) and reporter gene expression. Finally, DIM and IFN γ exhibited additive antiproliferative activities in cultured cells but produced synergistic increases in expression of major histocompatibility complex class I (MHC-I). This latter result is consistent with a strong immune potentiation activity of DIM.

Materials and Methods

Materials. Dulbecco's modified Eagle's medium, Opti-MEM, and Lipofectamine were supplied by Invitrogen (Carlsbad, CA). Fetal bovine serum (FBS) and human recombinant IFN γ , were supplied by Sigma Chemical Co. (St. Louis, MO). [γ - 32 P]ATP was supplied by New England Nuclear (Boston, MA). DIM was prepared from I3C as described previously (Grose and Bjeldanes, 1992) and recrystallized in toluene. All other reagents were of the highest grade available.

Cell Culture. The human breast adenocarcinoma MCF-7 cell line, obtained from the American Type Culture Collection (Manassas, VA), was grown as adherent monolayers in Dulbecco's modified Eagle's medium, supplemented to 4.0 g/l glucose, 3.7 g/l sodium bicarbonate, and 10% heat-inactivated FBS, in a humidified incubator at 37°C and 5% CO $_2$, and passaged at approximately 80% confluence. Cultures used in subsequent experiments were at less than 25 passages.

Cell Counting. Cells were harvested by trypsinization and resuspended in complete medium. Aliquots were diluted 50-fold in Isoton II (Beckman Coulter, Fullerton, CA), and 500- μ l duplicates were counted in a model Z1 Coulter particle counter and averaged.

Microarray Analysis of Differential Expression. MCF-7 cells were treated with 50 μ M DIM for 24 h or with the DMSO vehicle for

controls. Poly-A-RNA was isolated by two cycles of purification on oligo-dT cellulose. Labeled cDNA probes were prepared using the fluorescent dyes cyanine 3 and cyanine 5 for the treated and the control samples, respectively, and were hybridized simultaneously to microarrays (Incyte Genomics, Fremont, CA) of 960 selected cDNAs representing human genes involved in cell cycling, apoptosis, signal transduction, motility, adhesion, and angiogenesis. Differential expression was measured by the ratio of the fluorescence intensity at the wavelengths corresponding to the two probes. The samples were spiked with known concentrations of various nonhuman cDNA to serve as positive controls and to correct for variations in hybridization efficiency.

Determination of mRNA by RT-PCR. Cells were lysed by addition of Tri-reagent (Molecular Research Center, Inc., Cincinnati, OH) and chloroform was used for phase separation. After centrifugation, the aqueous upper phase was collected and total RNA was precipitated by isopropanol, washed with 75% ethanol, and dissolved in diethyl pyrocarbonate-treated water. Levels of specific mRNAs were determined by reverse transcription-polymerase chain reaction (RT-PCR) using Invitrogen enzymes and reagents. Reverse transcription was done using a 15-mer oligo-dT primer to generate cDNAs from mRNAs only. The sequences of the PCR primer pairs for specific mRNA are given in Table 1. After the appropriate number of cycles, the PCR products were dyed with ethidium bromide, separated on a 1.5% agarose gel, and photographed under UV light to verify the size of the amplicons and relative abundance of the specific mRNA templates.

Reporter Assays. The interferon-inducible luciferase reporter pGL2-25AS (-972) (OAS-Luc) was a gift from Dr. Georgia Floyd-Smith (Arizona State University, Tempe, AZ) (Floyd-Smith et al., 1999). OAS-Luc contains the promoter and 5'-flanking region (-972) of p69-OAS. The consensus GAS reporter, GAS-Luc, containing four repeats of the GAS element (5'-GATCAGTGATTTCTCGGAAA-GAGAG-3') from the IFN γ consensus sequence binding protein (consensus motif underlined) was a gift from Dr. Keiko Ozato (National Institute of Child Health and Human Development, Bethesda, MD) (Kanno et al., 1993). Reporter plasmids were transiently transfected

TABLE 1
Primer sequences and expected amplicon sizes

Primer	Sequence	Expected Amplicon Size
		bp
p69-OAS		330
Upper	CGAGCGGCACAAAATCGTCA	
Lower	GGCCGGGAGCGAATGAAGTT	
p56		404
Upper	CGCTGGGTATGCGATCTCTGC	
Lower	GCCCTCTAGGCTGCCCTTTTG	
IFNGR-1		185
Upper	CCAGGCATGCATACCGAAGACA	
Lower	GCGATGCTGCCAGGTTTCTAGA	
IFN γ		288
Upper	TGCAGGTCAATTCAGATGTAGCGGATA	
Lower	TCATGTATTGCTTTGCGTTGGACA	
HLA-A		331
Upper	GACGACACGCAGTTCGTGC	
Lower	CATGTCCGCGCGGTCCAA	
HLA-B		156
Upper	ACCAGAGCGAGGCGCGG	
Lower	GTGTCCGCGCGGTCCAG	
HLA-C		301
Upper	CGCGCGGAGTCCRAGAGG	
Lower	GTGTCCGCGCGGTCCAG	
β_2 -Microglobulin		335
Upper	CTCGCGCTACTCTCTCTTTCTGG	
Lower	GCTTACATGTCTCGATCCCACTTAA	
TAP-1		280
Upper	TCTCTCTCTTTGGGAGATG	
Lower	GAGACATGATGTACCTGTCTG	
TAP-2		300
Upper	CTCCTCGTTGCCGCTTCT	
Lower	TCAGCTCCCCTGTCTTAGTC	

in MCF-7 cells by lipofection (Lipofectamine; Invitrogen), and after treatments as indicated under *Results*, luciferase activity in cell lysates was measured as described previously (Riby et al., 2000).

Gel Mobility Shift Assay. Nuclear extracts of cells were prepared as described previously (Riley et al., 2000) at the end of the treatment periods indicated under *Results*. The complementary 25-mer oligonucleotides 5'-GATCAGTGATTTCTCGGAAAGAGAG-3' and 5'-GATCCTCTCTTCCGAGAAATCACT-3', containing the palindromic γ -activated sequence (GAS) consensus motif (underlined), were annealed and 5'-end-labeled with [γ - 32 P]ATP using T4 nucleotide kinase. The resulting labeled, double-stranded DNA probe was purified on a Sephadex G50 spin-column, precipitated in ethanol, dissolved in Tris-EDTA buffer, and diluted in 25 mM HEPES, 1 mM dithiothreitol (DTT), 10% glycerol, and 1 mM EDTA to contain approximately 25,000 cpm/ μ l 32 P. Nuclear extracts (7 μ g of proteins), were mixed with 90 ng of poly(dI-dC), 25 mM HEPES, 1 mM DTT, 10% glycerol, 1 mM EDTA, and 160 mM KCl in a total volume of 21 μ l. For antibody supershift experiments, 0.5 μ g of monoclonal mouse-IgG anti-human-IFN γ (Santa Cruz Biotechnology, Santa Cruz, CA) was added to the incubation mixture. After incubation for 15 to 20 min at room temperature, 4 μ l (100,000 cpm) of end-labeled 32 P-ERE probe was added and incubated for another 15 min at room temperature. After addition of 2.8 μ l of 10 \times Ficoll loading buffer (0.25% bromophenol blue, and 25% Ficoll type 400), 22- μ l aliquots were loaded onto a prerun, nondenaturing 4.0% polyacrylamide gel in 67 mM Tris, 33 mM sodium acetate, and 10 mM EDTA, pH 8.0, at 120 V for 2 h. The gel was then dried and autoradiographed using BioMax MR film (Eastman Kodak, Rochester, NY).

Flow Cytometry Analysis of Cell Cycle Measurements. MCF-7 cells were plated at 10,000 cells/well of a six-well tissue culture dish and treated for 6, 24, 48, 72, 96, 120, and 144 h in complete medium. DIM was added to a final concentration of 10 and 30 μ M and IFN γ to 10 ng/ml. Medium was changed every 24 h. After treatment, cells were washed with phosphate-buffered saline and hypotonically lysed in 1 ml of DNA staining solution (0.5 mg/ml propidium iodide, 0.1% sodium citrate, and 0.05% Triton X-100). Cell debris was removed by filtration through 60- μ m nylon mesh (Sefar America Inc., Kansas City, MO). Nuclear-emitted fluorescence with wavelengths of >585 nm was measured with a Coulter Elite instrument. Ten thousand nuclei were analyzed from each sample at a rate of 300 to 500 nuclei/second. The percentages of cells within the G₁, S, and G₂/M phases of the cell cycle were determined by analysis with the Multicycle software MPLUS (Phoenix Flow Systems) in the Cancer Research Laboratory Microchemical Facility of the University of California, Berkeley.

Flow Cytometry Analysis of MHC-I Expression. Flow cytometric analysis of membrane immunofluorescence was performed as follows: MCF-7 cells were pretreated with 30 μ M DIM separately for 6, 24, or 48 h and then treated with different concentrations of IFN γ for another 16 h. Cells were harvested, washed with phosphate-buffered saline (PBS), and then 10⁶ cells in 90 μ l of PBS were incubated with 10 μ l of FITC-conjugated HLA-ABC mouse monoclonal antibody or negative control FITC-conjugated IgG2b antibody (Chemicon International, Temecula, CA) on ice for 30 min. After washing twice with PBS, the fluorescence density was measured using a Coulter Elite instrument and analyzed with WinMDI 2.8 software provided by Duke University (Durham, NC). The expression of HLA-I complex was calculated as the percentage of antibody-positive cells (%PC) and mean fluorescence value (MFV).

Western Blot Analysis. After the indicated treatments, cells were harvested in radioimmunoprecipitation assay buffer (150 mM NaCl, 0.5% deoxycholate, 0.1% Nonidet P-40, 0.1% SDS, and 50 mM Tris) containing protease and phosphatase inhibitors (50 μ g/ml phenylmethylsulfonyl fluoride, 10 μ g/ml aprotinin, 5 μ g/ml leupeptin, 0.1 μ g/ml NaF, 1 mM dithiothreitol, 0.1 mM sodium orthovanadate, and 0.1 mM glycerophosphate). Equal amounts of total cellular protein were mixed with loading buffer (25% glycerol, 0.075% SDS, 1.25 ml of 14.4 M 2-mercaptoethanol, 10% bromophenol blue, and 3.13%

stacking gel buffer) and fractionated by electrophoresis on 10% polyacrylamide/0.1% SDS resolving gels. Rainbow marker (GE Healthcare, Little Chalfont, Buckinghamshire, UK) was used as the molecular weight standard. Proteins were electrically transferred to nitrocellulose membranes (Micron Separations, Inc., Westborough, MA) and blocked overnight at 4°C with 5% non-fat dry milk in 1 \times Western wash buffer (10 mM Tris-HCl, pH 8.0, 150 mM NaCl, and 0.05% Tween 20). Blots were subsequently incubated with antibodies against IFNGR1, phosphorylated STAT1 (P-STAT1), or STAT1 protein purchased from Santa Cruz Biotechnology, Inc. (Santa Cruz, CA). The antibody concentration was 2 μ g/ml in Western wash buffer. Immunoreactive proteins were detected after 1 h of incubation at room temperature with horseradish peroxidase-conjugated secondary antibodies. Goat anti-rabbit antibodies were used as secondary antibodies (Bio-Rad) after being diluted 1:3000 in wash buffer. Blots were treated with enhanced chemiluminescence reagents (PerkinElmer Life and Analytical Sciences, Boston, MA), and fluorescence was detected using BioMax MR film (Eastman Kodak). Equal protein loading was ascertained by Ponceau S staining of blotted membranes and by reprobing the membranes with anti-tubulin antibody.

Statistical Analyses. Statistically significant differences were determined by two-way analysis of variance using the SigmaStat software (Systat Software, Inc., Point Richmond, CA).

Results

DIM Activates Transcription of IFN γ and Related Genes in MCF-7 Human Breast Tumor Cells

An initial cDNA gene expression microarray screen of human breast cancer MCF-7 cells treated with DIM, followed by confirmation of results using semiquantitative RT-PCR, established the transcriptional activation of IFN γ -IFNGR1-OAS family member protein 69 (p69-OAS) and interferon-inducible protein 56 (p56) (Fig. 1). The expressions of IFN γ , p69-OAS, and p56 were fully induced after 6 h of treatment, whereas maximum IFNGR1 induction was reached after 48 h of treatment. As shown previously (Xue et al., 2005), the level of mRNA for IFN γ returned to near control level after 48 h of DIM treatment. The mRNA levels for p56, IFNGR1 and p69-OAS remained elevated after 48 h of treatment. Maximum induction for IFN γ , IFNGR1, p69-OAS, and p56 were 4.6-, 3.8-, 3.2-, and 4.0-fold, respectively. The mRNAs for IFN α and IFN β were not detectable by RT-PCR analysis in DIM-treated or -untreated MCF-7 cells (data not shown).

DIM Induces Expression of IFNGR1 Protein in MCF-7 Cells

Western blot analysis (Fig. 2) showed that levels of IFNGR1 protein were strongly up-regulated by DIM treatments. IFNGR1 protein levels increased by approximately 7-fold after 24 h and persisted to 48 h compared with DMSO-treated control cells. These results are consistent with the increase in mRNA levels shown in Fig. 1 and suggest that the effect of DIM on the regulation of IFNGR1 expression is exerted primarily through transcriptional control.

DIM Augments IFN γ -Induced Expression of the Endogenous p69-OAS Gene and Associated Reporter Gene Constructs

Endogenous Genes. We next examined in more detail the effects of DIM alone and in combination with IFN γ on expression of endogenous p69-OAS. The results of RT-PCR analyses of p69-OAS transcripts (Fig. 3A) showed that sepa-

rate treatments with DIM (50 μ M) and IFN γ (10 ng/ml) produced inductions of approximately 3.5- and 5.0-fold, respectively, over the control, whereas treatment with a combination of the two produced an increase of nearly 12-fold. These results suggest a roughly additive interaction of DIM and IFN γ on induced expression of endogenous p69-OAS.

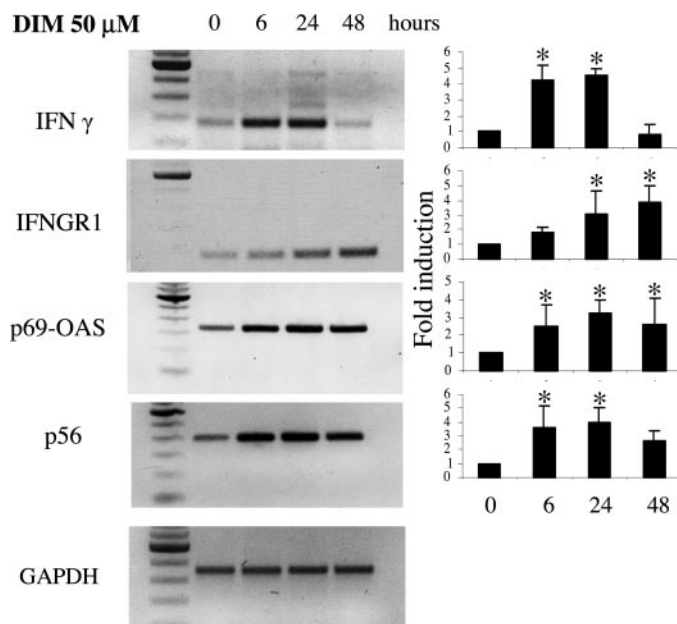


Fig. 1. Transcriptional activation of IFN γ and related genes by DIM. Cells were treated with 50 μ M DIM for the indicated times. The mRNA levels were measured by RT-PCR. Quantitative detection of amplicons required 40 PCR cycles for IFN γ and 17 cycles for the other genes. Images of the ethidium bromide-stained gels were inverted (negative black/white) for presentation. Molecular weights are compared with a 100-bp ladder (darker band is 600 bp) to confirm identity of the amplicons. GAPDH was used as the control. Densitometry results are presented as -fold induction over the 0-h treatment after correction for GAPDH. Results are presented as the mean \pm S.D. of three separate experiments. *, statistically significant difference with time 0 control ($p < 0.05$).

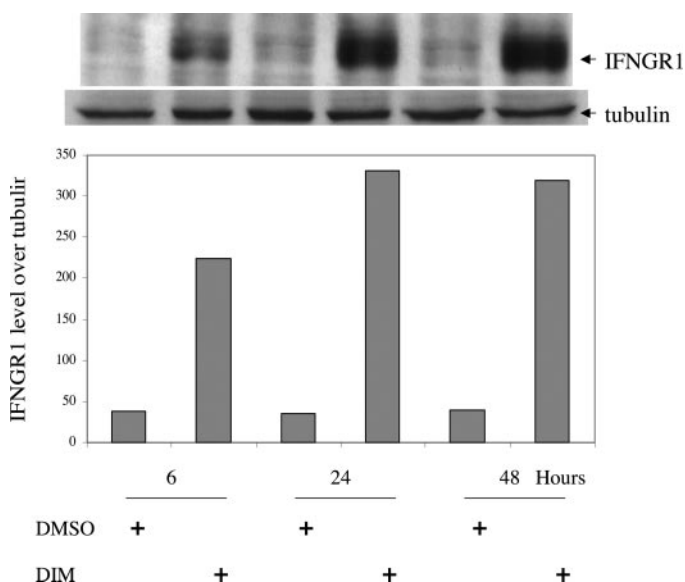


Fig. 2. Western blot analysis of INFGR1. Cells were treated with DMSO (control) or 50 μ M DIM for 6, 24, or 48 h. The relative abundance of INFGR1 was corrected for variations in tubulin, as a loading control between samples. A representative Western blot from three separate experiments is shown.

We determined next whether the inducing effects of DIM on endogenous p69-OAS gene expression required concurrent protein synthesis. Results presented in Fig. 3B indicate that cotreatments with the translation inhibitor cycloheximide blocked the inducing effects of DIM treatments as well as the enhancing effects of DIM on IFN γ -induced expression of endogenous p69-OAS.

Transfected Reporter Gene Constructs. To examine whether the inducing effects of DIM operate at the transcriptional level, the activities of two luciferase reporter constructs, OAS-Luc and 4GAS-Luc were measured after treatment with DIM. OAS-Luc contains the promoter and 5'-flanking region (-972) of p69-OAS and GAS-Luc contains four repeats of the consensus GAS element. MCF-7 cells transiently transfected with these reporter constructs were treated with IFN γ , DIM, or a combination of both for 24 h. As shown in Fig. 3C, DIM treatment induced expression of the OAS-Luc reporter to a maximum of approximately 2.3-fold, a level of induction that was somewhat less than the level we observed for induction of the corresponding endogenous gene of over 3-fold. IFN γ induced transcriptional activity of this reporter in a concentration-dependent manner to a maximum of only approximately 1.8-fold, which is considerably less than the response of the endogenous gene of approximately 5.0-fold. In marked contrast to the maximum effects of combined treatments of the inducers on endogenous gene expression (an increase of nearly 12-fold compared with vehicle-treated cells), the reporter gene construct responded with less than a 3-fold increase over control cells. These results show that whereas the reporter and endogenous gene responded similarly to treatment with DIM by itself, the reporter was considerably less responsive than the endogenous gene to IFN γ .

Finally, studies with cells transfected with the 4GAS-Luc reporter (Fig. 3D) showed an inducing effect of DIM that was similar to the responses of the p69-OAS gene but a more robust response to IFN γ that was accompanied by a consistent synergistic response to cotreatments with the two inducers. Thus, treatment with DIM (50 μ M) by itself again produced a 2- to 3-fold increase in activity of this reporter. IFN γ treatments, however, produced a robust concentration-dependent increase in reporter activity to approximately 40-fold induction compared with vehicle-treated controls. Cotreatments with DIM and IFN γ produced a roughly 2-fold synergistic activation of the 4GAS-Luc reporter at all IFN γ concentrations examined, reaching a maximum induction of approximately 75-fold.

Taken together, these results show that DIM by itself produced similar levels of activation of endogenous and transfected reporter genes that are differentially responsive to IFN γ . The results show further that the inducing effects of DIM are mediated by a short-lived transcription factor or require de novo synthesis of an intermediate regulatory protein.

Synergistic Effects of DIM on IFN γ -Mediated Signal Transduction

To probe further the role of GAS element activation in transcriptional activation by DIM, we examined the effect of this indole on downstream events in the GAS signaling pathway. For this purpose, the effects of DIM on phosphorylation of STAT-1 were determined, and the binding of the activated

STAT-1 dimer to the cognate GAS responsive element were examined. Phosphorylation of STAT-1 by Janus-activated kinase (JAK) is the first step in IFN γ signaling after binding to IFNGR1. For these studies, cells were pretreated with DIM for 6 or 24 h followed by a 15-min exposure to IFN γ . STAT-1 phosphorylation levels in lysates of DIM-treated cells were compared with levels in control cells that received IFN γ but had not been treated with DIM. Phosphorylation was measured by Western blot analysis using an antibody specific to STAT-1 phosphorylated on Tyr-701 residue. Results presented in Fig. 4 show that whereas DIM treatment by itself for 6 or 24 h did not induce STAT-1 phosphorylation, pretreatment with DIM augmented IFN γ -induced STAT-1 phosphorylation by more than 4-fold after 24-h DIM pretreatment. These treatments did not significantly affect the levels of inactive (total) STAT-1.

An electrophoretic gel-mobility-shift assay was used to verify that the phosphorylated STAT-1 was effectively activated to a dimer that could bind to the GAS element. The 32 P-labeled DNA probe containing a GAS sequence was incu-

bated with nuclear extracts from cells pretreated with DIM for various times as indicated and with IFN γ for 30 min. As shown in Fig. 5, IFN γ treatment produced a band-shift (band 1) that increased in intensity with the duration of the DIM pretreatment. DIM treatments in the absence of IFN γ did not produce a shifted band at any time (data not shown). When samples were incubated with an antibody specific to STAT-1, the band was supershifted (band 2), confirming the identity of the protein binding to the labeled GAS probe.

Taken together, these results show that DIM can augment IFN γ -induced STAT-1 activation, dimerization, and binding to the GAS element in DNA. We obtained no evidence for STAT-1 activation by DIM by itself, however, under these assay conditions.

Effects of DIM and IFN γ on Proliferation and Cell Cycling

Possible functional consequences of the synergistic effects of DIM and IFN γ on gene expression were examined at the level of proliferation rates in MCF-7 cells. Cell proliferation was measured over a 4-day treatment period with treatments

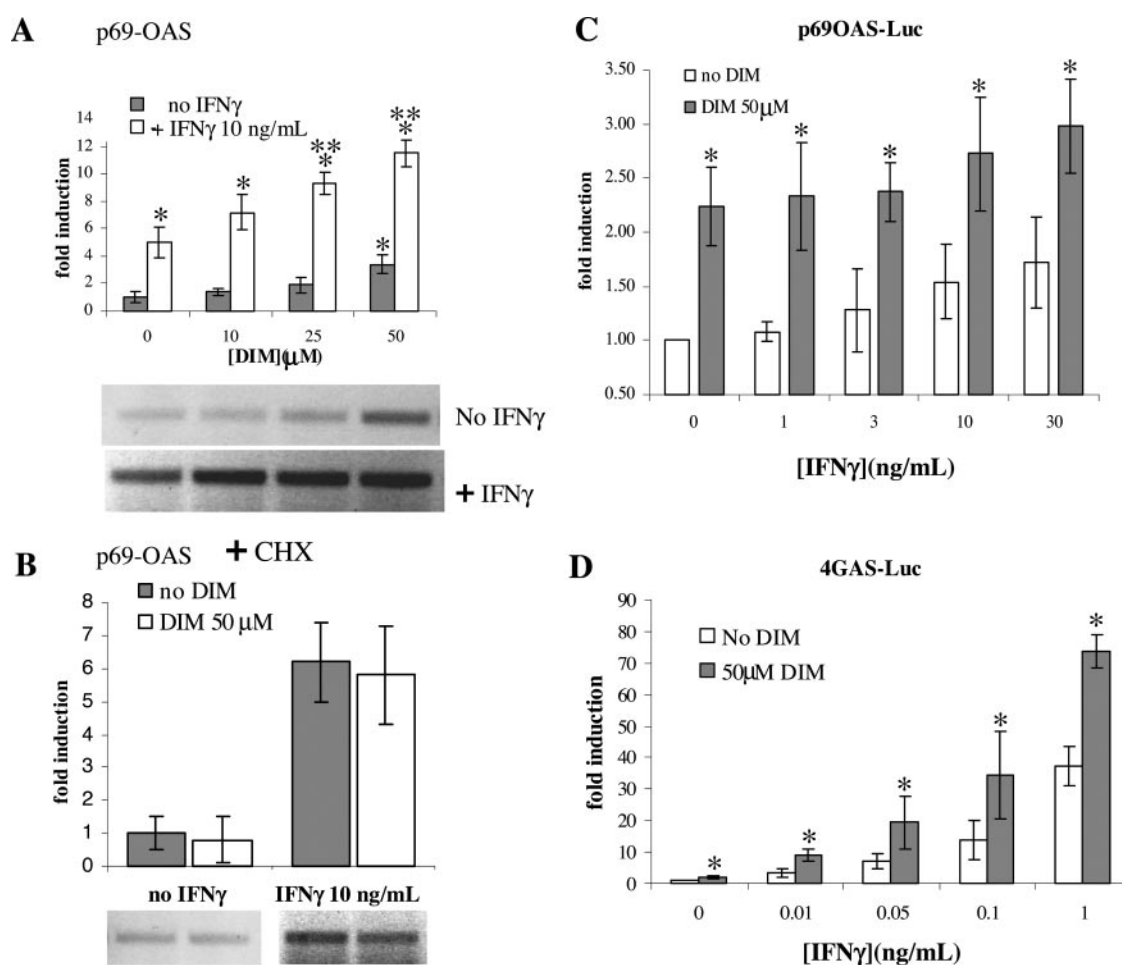


Fig. 3. DIM activates transcription of IFN γ -responsive genes. A and B, transcriptional activation of endogenous p69-OAS was measured by RT-PCR. Cells were treated with 10, 25, or 50 μ M DIM alone or in combination with 10 ng/ml IFN γ for 24 h. In addition (B), some plates received 50 μ M cycloheximide (CHX) 1 h before the beginning of the treatments to inhibit protein synthesis. Results are presented as the mean \pm S.D. of three separate experiments. *, statistically significant difference with the corresponding DMSO control for each concentration of DIM ($p < 0.05$); **, significant difference with IFN γ alone ($p < 0.05$). C, cells transfected with the p69OAS-Luc reporter were treated with IFN γ (1.0–30 ng/ml) alone or in combination with DIM 50 μ M, for 24 h. Transcriptional activity is expressed as -fold induction over the DMSO treated control. Results are presented as the mean \pm S.D. of three separate experiments. *, statistically significant difference with the DMSO control ($p < 0.05$). D, cells transfected with the 4xGAS-Luc reporter were treated with IFN γ (10 pg/ml–1 ng/ml) alone or in combination with 50 μ M DIM, for 24 h. Transcriptional activity is expressed as -fold induction over the DMSO-treated control. Results are presented as the mean \pm S.D. of three separate experiments. *, statistically significant difference with the DMSO control ($p < 0.05$).

with DIM, IFN γ , or both substances and compared with a DMSO control. As shown in Fig. 6, with heat-treated serum, IFN γ alone reduced cell proliferation by as much as 70% compared with controls. DIM treatments reduced proliferation by as much as 60%. With the exception of the highest concentration of IFN γ , combined treatments with DIM and IFN γ resulted in roughly additive increases in the cytostatic activity compared with treatment with DIM by itself. These effects were accompanied by morphological changes characteristic of apoptosis (data not shown). We observed no significant effect of IFN γ on proliferation of cells grown in unheated serum (data not shown).

Flow cytometry was used to determine the effects of DIM and IFN γ on cell cycling. Data presented in Fig. 7 show the proportion of the cell population in the G₁ phase of the cell

cycle at different intervals up to 3 days. In control groups, approximately 50% of the cells were in G₁. Treatment with IFN γ alone caused a small progressive increase in G₁ blocked cells of up to 10% above the DMSO control, after 3 days. DIM had a more immediate effect that increased over time up to 30% above the DMSO control. The combination of DIM and IFN γ had an additive effect leading to the presence of more than 90% of the cells in G₁ arrest after 3 days, correlating with the absence of proliferation shown in Fig. 6. Taken together, these results indicate that the effects of DIM and IFN γ on cell proliferation are additive and are consistent with separate cytostatic mechanisms for DIM and IFN γ .

DIM Potentiates IFN γ -Induced Expression of MHC-I Complex in MCF-7 Cells

Induced expression of the MHC-I complex is well established as an important downstream target of IFN γ -mediated signal transduction. To examine the possible synergistic effects of DIM on this highly significant metabolic product of IFN γ signaling, we tested the effects of cotreatment with

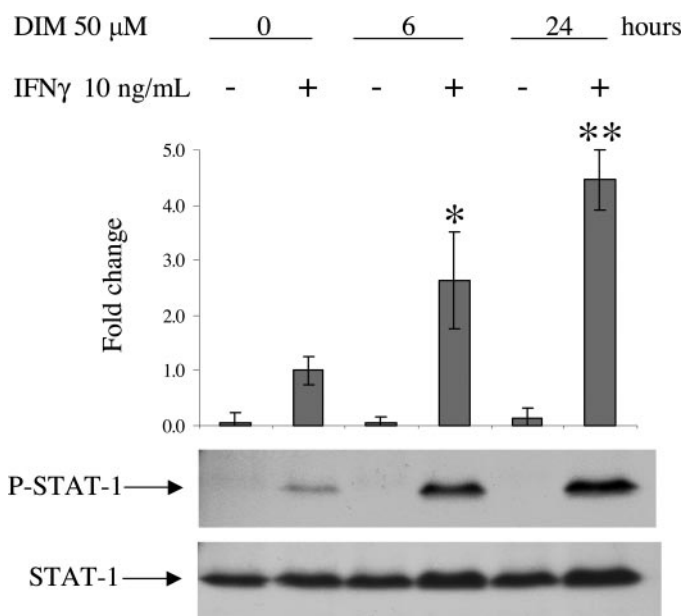


Fig. 4. Effects of DIM on STAT-1 activation. Cells were pretreated with 50 μ M DIM for 0, 6, or 24 h. After treatments, some plates were also treated with 10 ng/ml IFN γ for 15 min. Phosphorylated STAT-1 and total STAT-1 were measured by Western analysis. Three replicate blots were analyzed by densitometry. Results are presented as the mean \pm S.D. of three separate experiments. A representative Western blot from three separate experiments is shown. *, statistically significant difference with the IFN γ alone without pretreatment with DIM ($p < 0.05$); **, significant difference between 6 and 24 h of DIM pretreatments ($p < 0.05$).

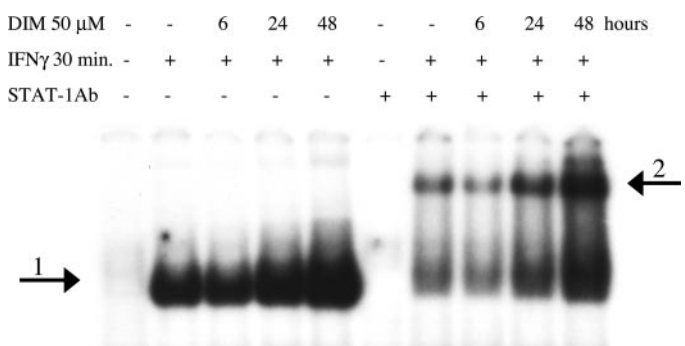


Fig. 5. Gel mobility shift analysis of STAT-1 binding to GAS. Cells were pretreated with 50 μ M DIM for the indicated periods and then with 10 ng/ml IFN γ for 30 min. Nuclear extracts were incubated with a ³²P-labeled DNA probe containing a GAS consensus sequence. The identity of the DNA binding protein was confirmed by supershifting with a STAT-1 antibody. Results are representative of three separate experiments.

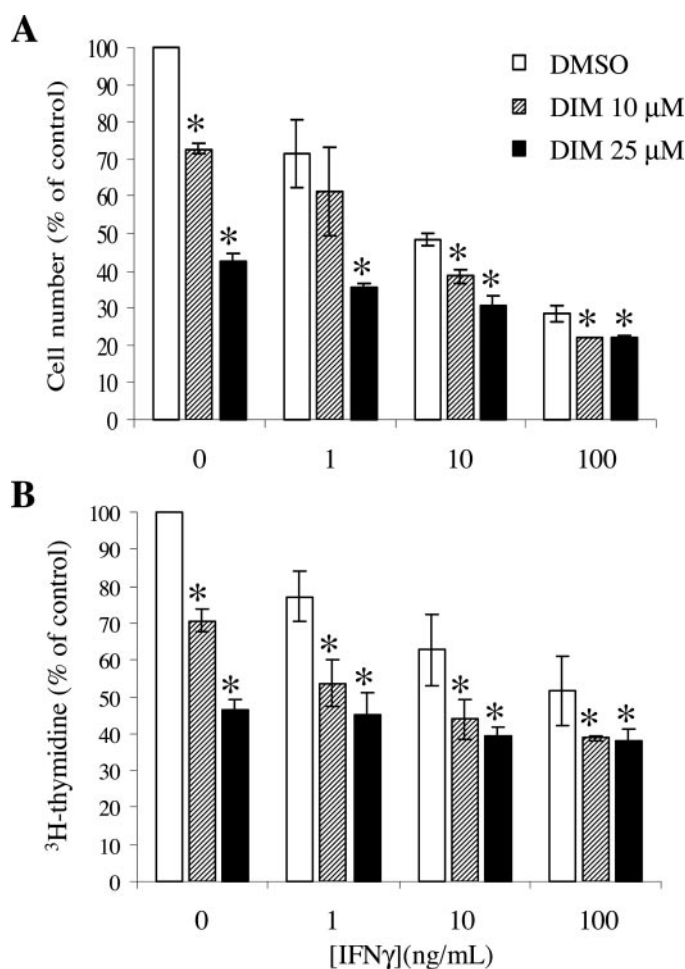


Fig. 6. Cell proliferation. Plates were seeded with 4×10^4 cells and incubated overnight to allow attachment before starting the treatments. Treatments were DMSO as a control, 10 or 25 μ M DIM, and 1, 10, or 100 ng/ml IFN γ alone or a combination of DIM in triplicate wells. A, cells were counted 4 days after the beginning of treatments. B, thymidine incorporation was measured after 24 h from the beginning of treatments. Results are presented as the mean \pm S.D. of three separate experiments. *, statistically significant difference with the corresponding DMSO control for each concentration of IFN γ ($p < 0.05$).

DIM on IFN γ -induced expression of MHC-I complex in MCF-7 cells.

Flow cytometry analysis of cell surface MHC-I expression was conducted using FITC-conjugated HLA-ABC antibody. In an initial control experiment, cultured MCF-7 cells were pretreated with 30 μ M DIM for 48 h and then with or without 10 ng/ml IFN γ for another 16 h. Analyses using a negative control antibody, FITC-conjugated mouse IgG2b, indicated no significantly induced signal (data not shown). In a subsequent experiment in which cells were treated with a range of IFN γ concentrations and analyzed with the anti-MHC-ABC antibody, a strong signal indicative of IFN γ -induced MHC-I expression (Fig. 8) was detectable at 0.1 ng/ml treatment, and the level seemed to plateau at 10 ng/ml. In cells treated with vehicle control only, MHC-I expression was not detected in greater than 99% of cells. In another control experiment, treatment of cells with 30 μ M DIM induced MFV of approximately 60 after 48 h in only 2% of the cells. Pretreatment with 30 μ M DIM for 48 h followed by treatment with 0.1 ng/ml IFN γ produced a further strong increase in %PC from 12.97% to 40.98%, but had no significant effect on MFV (Fig. 8D). Exposure to DIM of cells treated with 10 ng/ml of IFN γ , approximately 95% of which expressed MHC-I produced a strong increase in MFV from 72 to 131. As expected, addition of an IFN γ blocking antibody into the medium before the treatments abrogated the inducing effects of cotreatments of IFN γ and DIM on MHC-I expression (data not shown), confirming the requirement of the cytokine for the observed effects. In an analogous experiment, we observed no effect of DIM or IFN γ on MHC-II expression in the MCF-7 cells (data not shown). These results show that whereas DIM by itself produces little or no effect on expression of MHC-I, this indole strongly augments the proportion of cells that express this protein complex, as well as the maximum level of MHC-I per cell, in response to IFN γ .

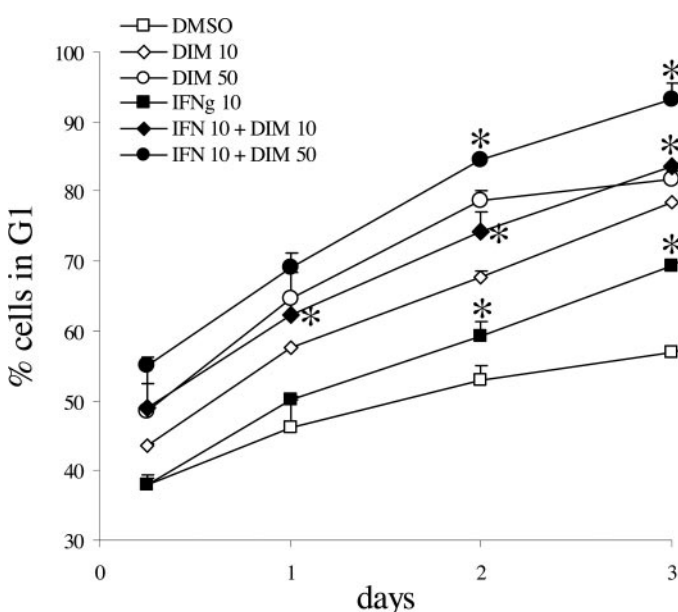


Fig. 7. Flow cytometry. The percentage of cells in the G₁ phase of the cell cycle was measured in cells treated with DIM, IFN γ , or combinations of the two for 6 h or 1, 2, or 3 days. Results are presented as the mean \pm S.D. of three separate experiments. *, statistically significant difference with the corresponding DIM treatment without IFN γ at the same time point is noted ($p < 0.05$).

DIM Enhances IFN γ -Induced Transcription of MHC-I Components and Transporters in MCF-7 Cells

Because the level of the IFN γ -induced MHC-I protein complex on the surface of MCF-7 cells could be enhanced by pretreatment with DIM, we examined whether expressions of the corresponding genes for the complex and its transporters were also increased. Results of RT-PCR analyses of human MHC-I, including HLA-A, HLA-B, HLA-C, and β -microtubulin, and of two important associated transporters, TAP1 and TAP2, are presented in Fig. 9. The expression levels of all six genes were not significantly enhanced by DIM compared with vehicle-treated MCF-7 cells. As expected, the expressions of these genes were increased 2- to 8-fold by treatment with IFN γ . The results show that pretreatment of cells with DIM further increased the mRNA levels of these genes by at least 2-fold above the levels induced by IFN γ by itself, which equates to increases in mRNA levels of 4- to 16-fold above background levels.

These results show that DIM synergistically enhances the level of IFN γ -induced expression of the MHC-I protein complex and associated mRNAs. The roughly 2-fold augmentation by DIM in levels of both MHC-I protein/cell and in the associated mRNAs suggests that MHC-I expression induced by DIM is regulated at the level of gene transcription.

Discussion

The results of these studies indicate that DIM is an immunomodulator that not only can induce expression of IFN γ in breast tumor cells as shown in our previous report (Xue et al., 2005) but also can modify the response of the cells to exogenous exposure to this cytokine. We measured the levels of secreted IFN γ protein in conditioned medium, using a very sensitive ELISA assay, and found that after 3 days of DIM treatment, IFN γ had accumulated to a concentration of less than 100 pg/ml, whereas it was undetectable in DMSO controls (data not shown). Therefore, the inducing effects on the IFN γ -responsive genes and reporters do not seem to result from DIM-induced secretion of IFN γ , because this concentration is below the effective concentration of IFN γ treatments. Furthermore, it is unknown whether the immunoreactive material found in the conditioned medium had retained biological activity. The results of the present study show that in MCF-7 cells DIM can 1) induce the expression of IFN γ , the IFN γ receptor, and two IFN γ -inducible genes, 2) induce the expression of IFN γ -inducible reporter gene constructs, 3) synergistically augment IFN γ -mediated activation of the STAT-1 signal transduction pathway, 4) additively augment the cytostatic effects of IFN γ in cultured cells, and 5) synergistically augment the expression of IFN γ -induced MHC-I protein complex and associated mRNAs.

The signaling cascade regulated by IFN γ has been examined in considerable detail in many laboratories. Binding of IFN γ to the highly specific IFNGR1 on the membrane of target cells activates a phosphorylation cascade involving JAK1, JAK2, and STAT-1. Phosphorylated STAT-1 homodimerizes, translocates to the nucleus, and binds to the IFN γ -activated sequence in the promoter of IFN γ -inducible genes, and activates transcription. Activation of one such gene, p69-OAS, plays an important role in the prevention of replication of viral RNA in infected cells. In addition, p69-OAS has been identified recently as an inhibitor of cell

growth and a pro-apoptotic protein related to Bcl-2 (Ghosh et al., 2001). Our results confirm that IFN γ can activate the JAK/STAT pathway in breast tumor cells and show that each of the steps in IFN γ -induced gene activation is synergistically augmented by treatments with DIM.

The effects of DIM are clearly distinguishable from the effects of other cytostatic agents that induce IFN γ expression. In one series of studies, the synergistic effects of retinoic acid (RA) and IFN γ in breast cancer cells were described. At first, a synergistic antiproliferative effect was observed after sequential treatment of cells with IFN γ and RA. The effect seemed to result from an IFN γ -mediated augmentation of RA cytostatic activity. IFN γ was shown to increase RA cytostatic potency by increasing levels of expression of retinoic acid receptor- γ and decreasing expression of cellular RA-binding proteins (Widschwendter et al., 1995). Thereafter, the effects of RA on IFN γ signaling were also examined in breast tumor cells. The results showed that RA could synergistically augment the effects of IFN γ on gene transcription in MCF-7 cells by a mechanism that involved RA-mediated augmentation of STAT1 expression (Kolla et al., 1996). In another series of

studies, the effects of combined treatments of breast cancer cells with IFNs and the estrogen antagonist tamoxifen were examined. Cotreatments with these substances caused an augmentation of the expression of certain IFN-stimulated genes, including the transcription factors ISGF-3 and GAF (Lindner et al., 1997). Tamoxifen by itself, however, produced no effect on the expression of these transcription factors. Thus, our results with DIM show significant differences from the reported effects of RA and tamoxifen on IFN γ action. We observed only an additive inhibitory effect of DIM and IFN γ on MCF-7 cell proliferation, whereas the effect with RA was synergistic. Also, in contrast to RA, although DIM synergistically augmented IFN γ signal transduction, this indole did not increase STAT1 expression in the absence of IFN γ treatment. Finally, DIM treatment by itself clearly induced expression of IFNGR1, IFN γ , and OAS-related genes, effects that were not reported for RA or tamoxifen.

Our observation of a synergistic effect of DIM on IFN γ -induced expression of MHC-I is potentially of considerable importance because this complex plays a central role in tumor immunosurveillance. MHC-I molecules are required for

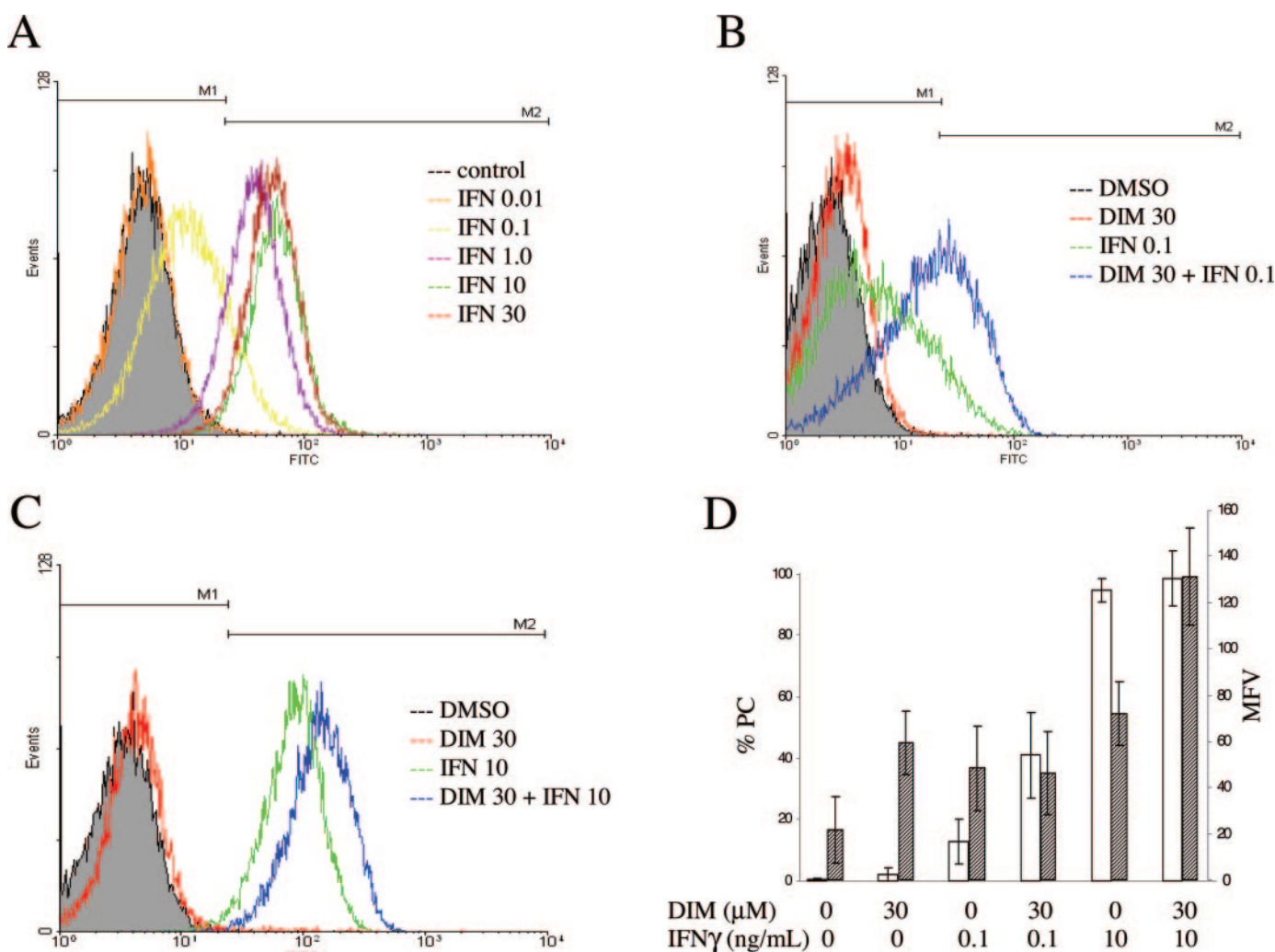


Fig. 8. The expression level of MHC-I complex on the MCF-7 cell surface. A, cells were treated with different concentrations of IFN γ for 16 h. B and C, cells were pretreated with DMSO (control) or 30 μ M DIM for 48 h, followed by 0.1 ng/ml of IFN γ (B) or 10 ng/ml of IFN γ (C) for another 16 h. One million cells were incubated in 90 μ l of PBS with 10 μ l of FITC-conjugated anti-HLA-ABC mouse monoclonal antibody. The fluorescence intensity was measured by flow cytometry using a Coulter Elite instrument and analyzed by WinMDI 2.8 software provided by Duke University. D, the expression of HLA class I complex was calculated as %PC (open bars) and MFV (cross-hatched bars).

the presentation of tumor-associated antigen to cytotoxic T lymphocytes. Decreased expression of MHC antigen is thought to protect tumor cells from immunosurveillance (Goodenow et al., 1985; Marincola et al., 2000). Therefore, loss or down-regulation of MHC-I has been shown to be a frequent event in breast tumorigenesis. Indeed, several studies with murine models of induced carcinogenesis have confirmed the role of down-regulation of MHC-I antigens in increasing the tumorigenic and metastatic potential of tumors (Tanaka et al., 1988). Conversely, induced MHC-I expression is thought to be important in antitumorigenic properties of IFN γ (David-Watine et al., 1990) and certain small molecule cancer therapeutic agents, including the nucleotide analog 5-azacytidine, cytosine, arabinoside, 5-fluorouracil, retinoids, vitamin D3, as well as the plant alkaloid vincristine (Geissmann et al., 2003; Ohtsukasa et al., 2003). In contrast to the activities of these other MHC-I inducers, we observed little or no effect of DIM by itself, whereas we observed a clear synergistic augmentation by DIM of IFN γ -induced MHC-I expression. Significant also was our observation that after treatments with the higher concentrations of DIM, the level of MHC-I expressed/cell was increased to levels that were unattainable by treatments with IFN γ by itself. The roles in these synergies of DIM-induced increases

in expression of IFN γ or possibly of modified MHC-I protein processing and trafficking are under investigation in our laboratories.

A comparison between our current results with DIM and our recently published studies with I3C (Chatterji et al., 2004) shows some distinct differences in the activity of DIM and its *in vivo* precursor in their effects on IFN γ signaling. Similar to our current results with DIM, we showed in the previous work that I3C also can affect IFN γ signaling in MCF-7 cells by a mechanism that involves a strong and rapid increase in expression of IFN γ and synergistic activation of STAT1 signaling. Similar effects of DIM and I3C were also observed on cell proliferation and cell cycling. In contrast to the present results with DIM, however, we did not observe in the previous studies increased expression by I3C of the IFN γ -stimulated genes (p56 and p69-OAS). These results are consistent with the hypothesis that the effects of I3C on IFN γ expression are mediated by its slow conversion to DIM during incubation with the cells. Indeed, we have shown previously that DIM accumulates in the nucleus of cultured MCF-7 cells treated with I3C (Staub et al., 2002). We speculate that our failure to detect I3C-induced expression of p56 and p69-OAS in the previous studies may be due to insufficient intracellular concentrations of DIM or, more interest-

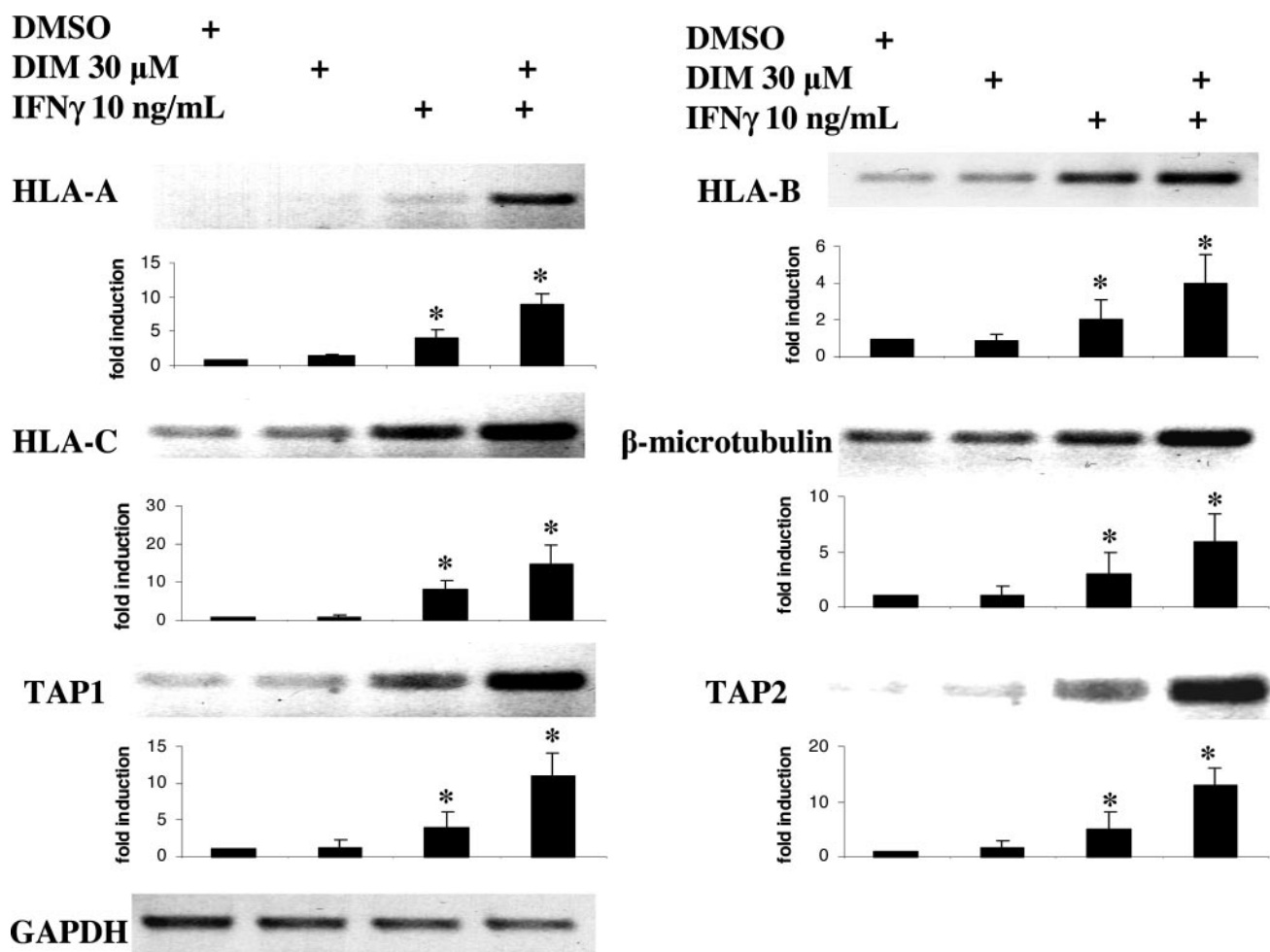


Fig. 9. DIM further increases IFN γ -induced transcription of MHC-I components and two associated transporter proteins. Cells were pretreated with 30 μ M DIM for 48 h, and 10 ng/ml of IFN γ was added into the medium for another 16 h. The mRNA levels were measured by RT-PCR. GAPDH was used as the control. Densitometry results are presented as -fold induction over the DMSO treatment after correction for GAPDH. Results are presented as the mean \pm S.E. of three separate experiments. *, statistically significant difference from DMSO control ($p < 0.05$).

ingly, to a requirement for extracellular exposure to DIM for induced expression of these genes. Further studies are in progress to test these possibilities.

Our results may provide a rationale for explaining the clinical effectiveness of indole treatments in the control of recurrent respiratory papillomatosis (RRP). I3C and DIM are said to be the most popular adjunct therapies for this disorder because of their effectiveness and low level of toxicity (Auborn, 2002; Wiatrak, 2003). RRP is caused by certain types of human papilloma viruses (Coll et al., 1997; Rosen et al., 1998), and a hallmark of this disease is the tendency of the papillomas to recur after surgical removal (Gissmann et al., 1982; Kashima et al., 1996). One report indicated that most patients (55.4%) responded to the treatment of I3C/DIM by slowing down the recurrence rate, and recurrence of the disease was completely inhibited in 19% of patients (Yuan et al., 1999). Previously suggested modes of action of I3C/DIM in the control of RRP include induction of a better estrogen metabolite balance (Yuan et al., 1999), inhibition of cell proliferation (Cover et al., 1998), and induction of apoptosis (Hong et al., 2002). Our results suggest that I3C/DIM may function by yet another mechanism, that of immune potentiation. If confirmed by on going studies in our laboratories, this activity might be useful not only in the prevention of recurrent papillomas but also in treatment of papillomatosis and prevention of malignant conversion of a broad range of tumor types.

In summary, our studies have shown that DIM can induce the expression of IFN γ , IFNGR1, and two IFN γ -responsive genes in cultured human breast tumor cells. The inducing effects on the IFN γ responsive genes do not seem to result from DIM-induced secretion of IFN γ , but they are dependent on de novo protein synthesis. DIM synergistically augments IFN γ -induced STAT-1 signaling, which, in combination with the increased expression of IFNGR1, may be responsible for an increase in MHC-I expression per cell that is not attainable by treatment with IFN γ by itself. However, the antiproliferative effects of DIM and IFN γ in MCF-7 cells are only additive, suggesting that these substances may affect cell cycling by unrelated mechanisms. Thus, these studies provide evidence that DIM is a novel immune potentiator that can induce IFN γ expression and potentiate IFN γ activities in breast tumor cells. Further studies of the immune function of DIM are in progress.

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