Nonsteroidal anti-inflammatory drugs (NSAIDs) are used to reduce inflammation and as analgesics by inhibition of cyclooxygenase-2. At higher concentrations, some NSAIDs inhibit proliferation and induce apoptosis of cancer cells. Although several molecular mechanisms have been postulated to explain the anticancer effects of NSAIDs, they do not involve merely the inhibition of cyclooxygenase-2, and a more proximate initiator molecule may be regulated by NSAIDs to inhibit growth. The p75 neurotrophin receptor (p75NTR) is a proximate cell membrane receptor glycoprotein that has been identified as a tumor and metastasis suppressor. We observed that NSAID treatment of cell lines from bladder and other organs induced expression of the p75NTR protein. Of the different types of NSAIDs examined, ibuprofen was more efficacious than aspirin and acetaminophen and comparable with (R)-flurbiprofen and indomethacin in induction of p75NTR protein expression. This rank order NSAID induction of the p75NTR protein correlated with the ability of these NSAIDs to reduce cancer cell survival. To examine a mechanistic relationship between ibuprofen induction of p75NTR protein and inhibition of survival, bladder cancer cells were transfected with ponasterone A-inducible vectors that expressed a death domain-deleted (ΔDD) or intracellular domain-deleted (ΔICD) p75NTR product that acts as a dominant negative antagonist of the intact p75NTR protein. Expression of ΔDD and ΔICD rescued cells from ibuprofen inhibition of growth. These observations suggest that p75NTR is an important upstream modulator of the anticancer effects of NSAIDs and that ibuprofen induction of the p75NTR protein establishes an alternate mechanism by which ibuprofen may exert an anticancer effect.

INTRODUCTION

Nonsteroidal anti-inflammatory drugs (NSAIDs) are one of the most commonly consumed types of medicines, used primarily as analgesics for the relief of pain and to control inflammation (1). An increasing number of epidemiological, clinical, and laboratory studies have also suggested that NSAIDs may be able to inhibit the initiation and proliferation of some tumors (2–6). However, the specific mechanism(s) of NSAID action to limit neoplasia remains elusive. It is generally assumed that the analgesic and anti-inflammatory efficacy of NSAIDs arises primarily from their inhibition of cyclooxygenases (COXs) that convert arachidonic acid to prostaglandins (7). Prostaglandins are thought to contribute to tumor growth by inhibiting apoptosis (8) and by inducing the formation of new blood vessels needed to sustain tumor growth (9). Hence, COX inhibition of prostaglandin synthesis could explain part of the antitumor activity of certain NSAIDs. However, NSAIDs can also inhibit tumor formation and growth of COX-null cell lines (10). In addition, certain NSAIDs that lack COX-inhibitory activity can still have significant anticancer effects both in vivo (11) and in vitro (12). Pharmacologically, NSAIDs generally inhibit COX activity and thus prostaglandin synthesis at concentrations 100- to 1,000-fold less than the concentrations that are associated with antitumor activity (1), suggesting the existence of additional cellular targets (9, 10, 13). Hence, COX-independent mechanisms may account for some of the anticancer effects of certain NSAIDs in which high concentrations of NSAIDs appear to be required (1). At these higher concentrations, the possible mechanisms for the antitumor activity of NSAIDs include inhibition of cell cycle progression (14) and induction of apoptosis (15). At the molecular level, the anticancer effects of NSAIDs have been associated with the down-regulation of both the antiapoptotic Bcl-2 protein (16) and the prosurvival kinase Akt (17). Other molecular mechanisms proposed to mediate the anticancer action of NSAIDs involve activation of protein kinase G (14); up-regulation of proapoptotic proteins Bax and Bcl-xl (18); inhibition of peroxisome proliferator-activated receptors β and δ (19); increasing arachidonic acid levels, leading to the production of ceramide (20); or inhibition of the transcription factor nuclear factor (NF)-κB by blocking the phosphorylation and degradation of IκBα (21, 22). For these pathways to be activated, there is a strong indication of the presence of a proximate initiator molecule that promotes transmission of a signal from the plasma membrane and the accompanying changes regulated by NSAIDs (18).

The p75NTR is a M, 75,000 cell surface glycoprotein that shares both structural and sequence homology with the tumor necrosis factor receptor superfamily of proteins (20, 23). Some of these proteins, including p75NTR, have similar sequence motifs of defined elongated structure (20) designated “death domains” based on their apoptosis-inducing function (23). Recently, p75NTR was identified as a tumor and metastasis suppressor of cancer cells derived from the urogenital system (24, 25). Interestingly, even though the gene encoding p75NTR was intact in these cancer cells, expression of the p75NTR protein was suppressed at the posttranscriptional level (26). Ectopic reexpression of p75NTR in these cells increased their rate of apoptosis (24) via a mitochondria-mediated caspase cascade (27). Additionally, ectopic p75NTR expression in these same cancer cells selectively altered progression through the G1 phase with a corresponding reduction of cells in the S phase of the cell cycle (28). These observations showed that the p75NTR tumor suppressor inhibits growth by both retarding cell proliferation and promoting apoptosis. Considering that p75NTR is a proximate initiator molecule that promotes inhibition of growth, comparable with that proposed as a possible target of some NSAIDs (18), we investigated whether NSAIDs could induce expression of the p75NTR gene product that was causal of the inhibition of tumor cell survival.

MATERIALS AND METHODS

Cell Lines and Culture Conditions. The bladder epithelial cell line T24, previously designated TSU-prl (29), containing the neomycin (neo) resistance gene as well as transgenic clones expressing low, intermediate, and high levels of the p75NTR have been described previously (25, 26). The RT-4 transitional cell papilloma bladder cell line and 5637 primary carcinoma bladder cell line were obtained from the American Type Culture Collection (Manassas, VA). Additional cell lines (HCT-116, MDAMB231, MCF7, HEK293, A549,
SKOV3, and DU145) were obtained from the tissue culture core facility (Lombardi Cancer Center, Georgetown University, Washington, D.C.). All cell lines were maintained in Dulbecco’s modified Eagle’s medium (Mediatech Inc., Herndon, VA) containing 4.5 g/L glucose and l-glutamine supplemented with antibiotic/antimycotic (100 units/ml penicillin G, 100 µg/ml streptomycin, and 0.25 µg/ml amphotericin B; Mediatech), 5% fetal bovine serum (Sigma Chemical Co., St. Louis, MO), and McCoy’s 5A medium (modified). Cell cultures were incubated in the presence of 10% CO2 at 37°C. The A875 human melanoma cell line was used as a positive control in all p75NTR Western blots as described previously (30).

Cell Treatment and Cell Lysis. Each cell line was seeded (5 × 105) overnight before treatment. All NSAIDs [ibuprofen, acetaminophen, aspirin, (R)-flurbiprofen, and indomethacin (Sigma Chemical Co.)] were dissolved in dimethyl sulfoxide (Sigma Chemical Co.) at a concentration of 200 mmol/L stock solution. Each cell line was incubated with different NSAIDs of various concentrations for 48 hours. Subsequently, the cells were placed in lysis buffer [10 mmol/L Tris-Cl (pH 7.4), 10 mmol/L NaCl, 3 mmol/L MgCl2, and 0.5% Nonidet P-40] containing protease inhibitors. The supernatant of the lysate was retained for estimation of protein concentration according to the manufacturer’s instruction (Bio-Rad Laboratories, Hercules, CA).

Immunoblot Analysis. Immunoblot analyses of the cell lysates were performed as described previously (31). Briefly, 50 µg of protein were loaded onto 10% SDS-polyacrylamide gels for electrophoresis, transferred to a nitrocellulose membrane, blocked in 5% nonfat milk, and incubated in a primary murine monoclonal p75NTR antibody (Upstate Cell Signaling Solutions, Lake Placid, NY) and murine monoclonal β-actin antibody (Sigma Chemical Co.). Membranes were incubated in a horseradish peroxidase-conjugated goat anti-mouse secondary antibody (1:2,000; Bio-Rad Laboratories). Immunoreactivity was detected using the enhanced chemiluminescence detection reagent (Amersham Pharmacia Biotech, Piscataway, NJ). Densitometric analysis of protein levels was performed using a ChemilImager apparatus (Alpha Innotech Corp., San Leandro, CA).

Transfection Assays. T24 cells were transiently transfected with edcsyne-one-inducible p75NTR dominant negative vectors, as described previously (32), that expressed a death domain-deleted p75NTR gene product (ΔDD) or an intracellular domain-deleted p75NTR gene product (ΔICD). Transient transfection was performed with LipofectAMINE reagent (Invitrogen, Carlsbad, CA). The cells were cotransfected for 6 hours in serum-free medium with the edcsyne receptor plasmid pVgRxR and either ΔDDp75NTR or ΔICDp75NTR, followed by the addition of serum-containing medium for 18 hours. Subsequently, incubation of cells in ponasterone A (1 µmol/L; Invitrogen) for 24 hours was used to drive expression of the dominant negative gene products. A control transforming growth factor β receptor II (TGFβRII) expression vector was transiently transfected into T24 cells as described above. The TGFβRII-transfected cells were used as a positive control for immunoblot of 48-hour ibuprofen treatment of cells probed with TGFβRII antibody (1:200 dilution, Santa Cruz Biotechnology, Santa Cruz, CA).

Cell Survival Assay. The number of cells in each well after treatment (48 hours) with NSAIDs was estimated using the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay. MTT labeling reagent (final concentration, 0.5 mg/ml; Roche Diagnostics Corp., Indianapolis, IN) was added to each of the NSAID-treated T24 cells, ponasterone A alone-treated cells,

Fig. 1. A, expression of the p75NTR protein in T24 bladder cells after 48-hour treatment with 0 to 2.0 mmol/L ibuprofen (Ibu), aspirin (Asp), acetaminophen (Ace), (R)-flurbiprofen (Flu), and indomethacin (Ind), respectively. Cell lysates containing 50 µg of T24 protein or 5 µg of protein from the A875 melanoma cell line (positive control) were subjected to SDS-PAGE and immunoblot analysis with a monoclonal antibody to the human p75NTR protein. B. MTT analysis of T24 cell survival after 48-hour treatment with 0 to 2.0 mmol/L acetaminophen, aspirin, ibuprofen, (R)-flurbiprofen, and indomethacin, respectively. Results are expressed as the mean ± SE. **, P < 0.01; ***, P < 0.001, relative to the control (0 mmol/L) for each type of NSAID. C. Hoechst staining of T24 bladder cells exhibiting apoptotic nuclear fragmentation (arrows) after 48-hour treatment with 0 to 2.0 mmol/L ibuprofen. Cells were fixed in 10% formalin, rinsed, resuspended in PBS, and stained in a 1:1,000 dilution of aqueous Hoechst stain solution (Hoechst 33258). Cells were visualized under a fluorescence microscope. Scale bar = 8 µm.
DDp75NTR-transfected cells plus ponasterone A, and ΔICDp75NTR-transfected cells plus ponasterone A (2 × 10^5 cells/well) in 96-well culture plates (final volume, 100 μl culture medium/well) and incubated for 4 hours at 37°C in a humidified atmosphere of 10% CO₂. Subsequently, cells were incubated overnight with 100 μl of solubilization solution per well, and the samples were quantified at 570 nm using a microtiter plate reader (Bio-Rad Laboratories, Richmond, CA).

Hoechst Dye Nuclear (DNA) Staining. Hoechst staining (33) with modifications was used to distinguish between intact cell nuclei and fragmented nuclei undergoing cell death. Briefly, T24 cells treated for 48 hours with varying concentrations of ibuprofen were fixed in 10% formalin (Fischer Scientific, Pittsburgh, PA), rinsed with PBS (pH 7.4), and centrifuged, after which the cell pellet was resuspended in PBS. The cells were dried to a slide, rehydrated with PBS, covered with a 1:1,000 dilution of aqueous Hoechst stain solution (Hoechst 33258; bis-benzamide, 10 mg/ml; Molecular Probes, Eugene, OR), rinsed, dried, and mounted under a coverslip with aqueous-based Shur/Mount (Electron Microscopy Sciences, Washington, PA). The stained cells were visualized using an Axioplan 2 imaging fluorescence microscope (Zeiss, Jena, Germany).

Statistical Analysis. The statistical differences between data sets and/or means were analyzed by analysis of variance, Student’s t test, or correlation analysis using the Prizm program (Graph Pad Software), and the data are expressed as the mean ± SE. Data were deemed statistically significant when P < 0.05.

RESULTS

NSAID-Induced Expression of the p75NTR Gene Product Is Associated with Inhibition of Cell Survival. Pharmacokinetic studies of ibuprofen have indicated that clinically tolerable high doses (i.e., up to 3,200 mg/d) can produce levels (i.e., 0.5–1 mmol/L) in the blood (34–36) that fall within the range used for these studies. In comparison, at clinically tolerable high doses of aspirin, peak serum concentrations are usually not much more than 0.5 mmol/L (37). Clinically tolerable high doses of acetaminophen can achieve peak serum concentrations of not much more than 0.1 mmol/L (38, 39), whereas blood levels in excess of 14 μmol/L indomethacin are considered toxic (40). Hence, to provide comparisons, we examined the effect of various NSAIDs that span those concentrations achievable for ibuprofen. In this context, treatment (48 hours) of T24 bladder cancer cells with five common NSAIDs [ibuprofen, aspirin, acetaminophen, (R)-flurbiprofen, and indomethacin] induced expression of the p75NTR gene product in a dose-dependent manner (Fig. 1A). The A875 melanoma cell line that has been characterized to constitutively express abundant levels of the p75NTR gene product was included as a positive control. In rank order, ibuprofen, its analog (R)-flurbiprofen, and indomethacin were most efficacious in promoting the highest levels of ibuprofen-induced p75NTR gene product among the three cell lines, ibuprofen did not induce expression of another cell surface receptor protein, the TGFRII gene product (Fig. 3A). As a positive control, T24 cells transfected with a TGFRII gene product (Fig. 3A). As a positive control, T24 cells transfected with a TGFRII gene product (Fig. 3A).

Because the ibuprofen class of NSAIDs appeared highly efficacious in the induction of the p75NTR gene product (Fig. 1A) and inhibition of survival (Fig. 1B and C), we examined whether this relationship may be associated with inhibition of COXs (Fig. 2A and B). In the COX-deficient HCT-116 cell line (41, 42), ibuprofen and (R)-flurbiprofen, the latter of which lacks COX-inhibitory activity (43), both induced expression of the p75NTR gene product (Fig. 2A), which was associated with the inhibition of survival (Fig. 2B) in a dose-dependent manner. Hence, the dose-dependent induction of expression of the p75NTR gene product and associated inhibition of survival by ibuprofen and (R)-flurbiprofen appeared independent of COX-inhibitory activity.

Specificity of Ibuprofen-Induced Expression of the p75NTR Gene Product. Treatment of additional bladder cancer cell lines with ibuprofen also induced expression of the p75NTR gene product in a dose-dependent manner (Fig. 3A). Ibuprofen treatment significantly induced the dose-dependent expression of the p75NTR gene product of the well-differentiated (RT-4) bladder cell line (Fig. 3B; P < 0.05), moderately differentiated (5637) bladder cell line (Fig. 3C; P < 0.05), and poorly differentiated (T24) bladder cell line (Fig. 3D; P < 0.05). Although the T24 cell line expressed the highest levels of ibuprofen-induced p75NTR gene product among the three cell lines, ibuprofen did not induce expression of another cell surface receptor protein, the TGFBRII gene product (Fig. 3A). As a positive control, T24 cells transfected with a TGFBRII expression vector were shown to express the TGFBRII gene product (Fig. 3A).

Cell lines derived from a number of different organs were also examined for their response to ibuprofen induction of the p75NTR gene product (Fig. 4A). Cell lines derived from the human bladder (RT-4, 5637, and T24), kidney (HEK293), ovary (SKOV3), and prostate (DU145) exhibited substantial induction of the p75NTR gene...
product (Figs. 3B and 4B and C), with associated inhibition of survival (Table 1), in response to treatment with 2 mmol/L ibuprofen. Conversely, cell lines derived from human lung (A549), estrogen-refractory breast (MDAMB231), and estrogen-responsive breast (MCF7) exhibited either a minimal or more modest induction of the p75NTR gene product (Fig. 4B and C) and inhibition of survival (Table 1) in response to treatment with 2 mmol/L ibuprofen (Fig. 4A—C). The relative survival of each cell line incubated in 2 mmol/L ibuprofen was inversely correlated with the levels of the p75NTR relative to T24 cells ($r = -0.786; P < 0.001$).

**Fig. 3.** Expression of the p75NTR protein in three bladder cell lines (RT-4, 5637, and T24) after 48-hour treatment with 0 to 2.0 mmol/L ibuprofen. Cell lysates containing 50 µg of protein or 5 µg of protein from the A875 melanoma cell line (positive control) were subjected to SDS-PAGE and immunoblot analysis with a monoclonal antibody to the human p75NTR protein (A). The same cell lysates were similarly subjected to immunoblot analysis with a monoclonal antibody to the human β-actin protein as a loading control. Expression of the TGFβRII protein was not observed in T24 cells treated with 0 to 2 mmol/L ibuprofen (A). Immunoblot of TGFβRII transiently transfected T24 cells was used as positive control. Densitometry of p75NTR protein normalized to β-actin levels is shown for RT-4 cells (B), 5637 cells (C), and T24 cells (D).

**DISCUSSION**

A recent population-based case-control study with individuals matched by sex, age, and race showed that intake of many classes of NSAIDs was associated with reduced bladder cancer risk (44). Taking into consideration the diversity of chemical structures with the associated differences in pharmacological properties encompassed within the broad classification of NSAIDs, it was also shown that the strength of the protective effect of NSAIDs against developing bladder cancer varied by category of formulation (44). When the categories of NSAIDs were ranked according to their association with reduced bladder cancer risk, the propionic acids (e.g., ibuprofen) and acetic acids (e.g., indomethacin) were more effective than acetylsalicylic acids (e.g., aspirin), and acetaminophen (i.e., Tylenol) was the least effective agent (44). Significantly, the rank order of NSAID induction of p75NTR expression and inhibition of bladder cancer cell survival observed in vitro was similar to the rank order of these compounds shown to have reduced bladder cancer risk in the population-based study (44).

The p75NTR was recently identified as a tumor suppressor and metastasis suppressor of both bladder and prostate cancer cells (24, 25). Although the gene encoding p75NTR was intact in these cells, expression of p75NTR protein was suppressed at the posttranscriptional level (26). Significantly, treatment of bladder cancer cells with several common NSAIDs restored p75NTR expression and concurrently inhibited cell survival in a dose-dependent manner. Ibuprofen;
IBUPROFEN INHIBITS SURVIVAL OF BLADDER CANCER CELLS

its analog, (R)-flurbiprofen, which lacks COX-inhibitory activity (43); and indomethacin were more efficacious in their induction of the p75NTR protein compared with both aspirin and acetaminophen. Ibuprofen-induced expression of the p75NTR protein appeared relatively receptor specific because ibuprofen did not induce expression of another cell surface tumor suppressor protein, the TGFβRII protein. Tissue specificity was variable, with tumor cells derived from the urogenital system (i.e., bladder, prostate, kidney, and ovary) and colon exhibiting greater ibuprofen induction of p75NTR expression than cell lines from the lung or breast. This correlation between ibuprofen induction of p75NTR expression and loss of survival of cancer cells derived from a variety of organs suggests a more general antitumor effect that may share a common mechanism mediated through induction of the p75NTR tumor suppressor.

Evidence to support a mechanism of ibuprofen induction of p75NTR expression causing the inhibition of bladder cancer cell growth is derived from three observations. The first observation is that the rank order of NSAID induction of p75NTR protein levels correlated with the same rank order of NSAID inhibition of cell survival in vitro and in population-based studies of analgesic users (44). In rank order, the

Table 1 Relative survival and levels of p75NTR of various cell lines after incubation in 2 mmol/L ibuprofen for 48 hours

<table>
<thead>
<tr>
<th>Cell line</th>
<th>Organ of origin</th>
<th>Survival (%) after 48-h treatment with 2 mmol/L ibuprofen</th>
<th>Levels of p75NTR relative to T24 cells</th>
</tr>
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<tbody>
<tr>
<td>T24</td>
<td>Bladder</td>
<td>9 ± 3*</td>
<td>1.0</td>
</tr>
<tr>
<td>5637</td>
<td>Bladder</td>
<td>22 ± 10*</td>
<td>0.65</td>
</tr>
<tr>
<td>RT-4</td>
<td>Bladder</td>
<td>35 ± 4*</td>
<td>0.61</td>
</tr>
<tr>
<td>SKOV3</td>
<td>Ovary</td>
<td>58 ± 1*</td>
<td>1.64</td>
</tr>
<tr>
<td>HEK293</td>
<td>Kidney</td>
<td>45 ± 2*</td>
<td>2.27</td>
</tr>
<tr>
<td>DU145</td>
<td>Prostate</td>
<td>21 ± 4*</td>
<td>1.22</td>
</tr>
<tr>
<td>MDAMB231</td>
<td>Breast</td>
<td>86 ± 3</td>
<td>0.16</td>
</tr>
<tr>
<td>MCF-7</td>
<td>Breast</td>
<td>108 ± 4</td>
<td>0.15</td>
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<tr>
<td>A549</td>
<td>Lung</td>
<td>93 ± 6</td>
<td>0.27</td>
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NOTE. Relative survival is shown as the mean ± SE. Correlation between cell survival and levels of p75NTR, r = −0.786; P < 0.001.

A

Fig. 4. Expression of the p75NTR protein in tumor cells derived from the (A) bladder (T24), kidney (HEK293), lung (A549), ovary (SKOV3), estrogen-refractory breast (MDAMB), estrogen-responsive breast (MCF7), and prostate (DU145) after 48-hour treatment with 2 mmol/L ibuprofen (+) or vehicle (−). Cell lysates containing 50 µg of protein were subjected to SDS-PAGE and immunoblot analysis with a monoclonal antibody to the human p75NTR protein. The same cell lysates were similarly subjected to immunoblot analysis with a monoclonal antibody to the human β-actin protein as a loading control. Densitometry of p75NTR protein normalized to β-actin levels in T24 cells is shown in comparison with cell lines of the (B) kidney (HEK293), lung (A549), and ovary (SKOV3) and (C) estrogen-refractory breast (MDAMB231), estrogen-responsive breast (MCF7), and androgen-refractory prostate (DU145).

B

Fig. 5. A, immunoblot of the p75NTR protein in either the A875 melanoma cell line (positive control) or T24 bladder cells transfected with two types of vector that can express truncated forms of the p75NTR protein (Δp75NTR). The cells were cotransfected for 6 hours in serum-free medium with the ecdysone receptor plasmid pVgRxR and either ΔDDp75NTR or ΔICDp75NTR, followed by addition of serum containing medium for 18 hours. The cells were then incubated in 1 µmol/L ponasterone A for 24 hours was used to drive expression of the dominant negative gene products. The vectors expressed a truncated p75NTR protein that lacked the death domain (ΔDD) or lacked an intracellular domain (ΔICD) after induction with ponasterone A (+), but not in the presence of vehicle alone (−). B, MTT analysis of T24 cell survival after 48-hour treatment with 0, 0.5, and 1.0 µmol/L ibuprofen (IBU), respectively. The cells were cotransfected with ponasterone A-inducible ecdysone receptor plasmid pVgRxR and either ΔDDp75NTR or ΔICDp75NTR, which can express truncated p75NTR protein that lacks the death domain (ΔDD), or ΔICDp75NTR, which can express truncated p75NTR protein that lacks an intracellular domain (ΔICD). Subsequently, incubation of cells in 1 µmol/L ponasterone A (P) was used to drive expression of the dominant negative gene products. Results are expressed as percentage of the vehicle-treated cells (0 µmol/L ibuprofen) showing the mean ± SE. *, P < 0.001 relative to the control.
propionic acids [e.g., ibuprofen and (R)-flurbiprofen] and acetic acids (e.g., indomethacin) induced the expression of the p75<sup>ΔNTR</sup> gene product with associated inhibition of cell survival to a greater degree than aspirin, whereas acetaminophen was the least effective compound to induce p75<sup>ΔNTR</sup> protein levels and the least effective inhibitor of bladder cancer cell survival. Hence, it appears that ibuprofen induction of the p75<sup>ΔNTR</sup> gene product may have caused, at least in part, the inhibition of bladder cancer cell survival. Because (R)-flurbiprofen has been shown to lack COX-inhibitory activity (43), the inhibition of survival would appear to be independent of COX. This is consistent with studies showing that specific NSAIDs can also inhibit tumor formation and growth of COX-null cell lines (45). In addition, other NSAIDs that lack COX-inhibitory activity have also been shown to have significant anticancer effects both in <i>vivo</i> (7) and in <i>vitro</i> (46). Indeed, the results from the COX-deficient HCT-116 cell line (41, 42) demonstrating that ibuprofen and (R)-flurbiprofen both induced expression of the p75<sup>ΔNTR</sup> gene product with associated inhibition of survival are clearly consistent with a mechanism of action independent of COX-inhibitory activity. Moreover, NSAIDs generally inhibit COX at concentrations 100- to 1,000-fold less than the concentrations that are associated with antitumor activity (47), consistent with the existence of additional cellular targets (9, 10, 13) such as the p75<sup>ΔNTR</sup> tumor suppressor. In this context, because the p75<sup>ΔNTR</sup> is a proximate receptor, it could have wide-ranging downstream effects to inhibit growth. Although the details of the p75<sup>ΔNTR</sup> signal transduction pathway have largely been extrapolated from other tumor necrosis factor receptor family members (48), inhibition of NF-κB has been linked to p75<sup>ΔNTR</sup> (49), which is consistent with studies showing that NSAIDs can also inhibit NF-κB (21, 22). The second observation to support a mechanism of ibuprofen induction of p75<sup>ΔNTR</sup> expression causing inhibition of bladder cancer cell growth is the dose-dependent relationship between the induction of p75<sup>ΔNTR</sup> protein levels and inhibition of survival. In addition to ibuprofen, the other two most efficacious NSAIDs examined [(R)-flurbiprofen and indomethacin] induced expression of p75<sup>ΔNTR</sup> and inhibition of cell survival at a much lower concentration when compared with either aspirin or acetaminophen. The reduction in the levels of p75<sup>ΔNTR</sup> in T24 cells treated with the higher concentrations of indomethacin appeared to result from protein degradation resulting from the rapid onset of p75<sup>ΔNTR</sup>-associated cell death. The third observation to support a mechanism of ibuprofen induction of p75<sup>ΔNTR</sup> expression causing the inhibition of bladder cancer cell growth is that dominant negative antagonism of the p75<sup>ΔNTR</sup> protein rescued ibuprofen inhibition of cell survival. The two truncated p75<sup>ΔNTR</sup> expression vectors (32) that rescued ibuprofen inhibition of survival exhibit intracellular deletions of either the death domain (ΔDDp75<sup>ΔNTR</sup>) or a larger deletion of the intracellular domain (ΔICDp75<sup>ΔNTR</sup>) of the gene products. The intracellular moieties deleted from these two truncated p75<sup>ΔNTR</sup> expression vectors contain sequence motifs of defined elongated structure (20) designated death domains based on their apoptosis-inducing function (23). Hence, these truncated gene products (ΔDDp75<sup>ΔNTR</sup> and ΔICDp75<sup>ΔNTR</sup>) have been shown to function as dominant negative antagonists of the full-length p75<sup>ΔNTR</sup> gene product (32). Thus, taken together, the rank order of NSAID induction of p75<sup>ΔNTR</sup> expression and inhibition of cell survival, the correlation between the dose-dependent induction of p75<sup>ΔNTR</sup> expression and inhibition of cell survival for individual NSAIDs, and the rescue of ibuprofen inhibition of cell survival by dominant negative antagonism of ibuprofen-induced p75<sup>ΔNTR</sup> protein expression all support a novel mechanism of ibuprofen inhibition of bladder cancer cell growth by induction of p75<sup>ΔNTR</sup> expression. Considering the pharmacological actions of ibuprofen, it seems possible that additional mechanisms of action may also contribute to inhibition of growth. Nevertheless, our observations provide strong support for a novel mechanism for ibuprofen induction of p75<sup>ΔNTR</sup> expression causing inhibition of bladder cancer cell growth.

From a clinically relevant perspective, among the different types of NSAIDs, ibuprofen is one of the least damaging to the gastric mucosa (49). Patients have been maintained on high doses of ibuprofen for years without serious adverse effects (34), with advanced age having very little effect on the pharmacokinetics of ibuprofen (50). Hence, the chronic use of ibuprofen as an analgesic for many conditions, such as arthritis, could inadvertently provide a chemopreventive benefit to individuals at risk of developing bladder cancer. Because serum ibuprofen readily distributes throughout the body, a possible benefit may also extend beyond organ-confirmed bladder cancers to target distant locations throughout the body, thereby further facilitating the potential utility of ibuprofen as a potential agent for chemoprevention and possible treatment of NSAID-sensitive neoplasias. However, this activity of ibuprofen against bladder cancer and NSAID-sensitive neoplasias should first be confirmed in animal models for safety and efficacy. In addition, considering the broad spectrum of biological activities exhibited by NSAIDs in <i>vivo</i> and in <i>vitro</i> (44), it may be useful to screen combinatorial chemistry derivatives of the propionic and acetic acid NSAIDs for efficacy of p75<sup>ΔNTR</sup>-induced expression as it relates to chemoprevention and anticancer efficacy in similar animal models.

**ACKNOWLEDGMENTS**

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Ibuprofen Inhibits Survival of Bladder Cancer Cells by Induced Expression of the p75 NTR Tumor Suppressor Protein


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