Granulocytic Differentiation of Human NB4 Promyelocytic Leukemia Cells Induced by All-trans Retinoic Acid Metabolites

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ABSTRACT

The metabolism of all-trans retinoic acid (ATRA) has been reported to be partly responsible for the in vivo resistance to ATRA seen in the treatment of human acute promyelocytic leukemia (APL). However, ATRA metabolism appears to be involved in the growth inhibition of several cancer cell lines in vitro. The purpose of this study was to evaluate the in vitro activity of the principal metabolites of ATRA [4-hydroxyretinoic acid (4-OH-RA), 18-hydroxy-retinoic acid (18-OH-RA), 4-oxo-retinoic acid (4-oxo-RA), and 5,6-epoxy-retinoic acid (5,6-epoxy-RA)] in NB4, a human promyelocytic leukemia cell line that exhibits the APL diagnostic t(15;17) chromosomal translocation and expresses the PML-RARα fusion protein. We established that the four ATRA metabolites were indeed formed by the NB4 cells in vitro. NB4 cell growth was inhibited (69–78% at 120 h) and cell cycle progression in the G1 phase (82–85% at 120 h) was blocked by ATRA and all of the metabolites at 1 μM concentration. ATRA and its metabolites could induce NB4 cells differentiation with similar activity, as evaluated by cell morphology, by the nitroblue tetrazolium reduction test (82–85% at 120 h) or by the expression of the maturation specific cell surface marker CD11c. In addition, nuclear body reorganization to macropunctated structures, as well as the degradation of PML-RARα, was found to be similar for ATRA and all of its metabolites. Comparison of the relative potency of the retinoids using the nitroblue tetrazolium reduction test showed effective concentrations required to differentiate 50% of cells in 72 h as follows: ATRA, 15.8 ± 1.7 nM; 4-oxo-RA, 38.3 ± 1.3 nM; 18-OH-RA, 55.5 ± 1.8 nM; 4-OH-RA, 79.8 ± 1.8 nM; and 5,6-epoxy-RA, 99.5 ± 1.5 nM. The ATRA metabolites were found to exert their differentiation effects via the RARα nuclear receptors, because the RARα-specific antagonist BMS614 blocked metabolite-induced CD11c expression in NB4 cells. These data demonstrate that the principal ATRA Phase 1 metabolites can elicit leukemia cell growth inhibition and differentiation in vitro through the RARα signaling pathway, and they suggest that these metabolites may play a role in ATRA antileukemic activity in vivo.

INTRODUCTION

Retinoids (vitamin A or retinol, and its derivatives) are a family of molecules involved in many physiological processes such as embryogenesis, cell growth, vertebrate development, differentiation, and homeostasis (reviewed in Ref. 1). The retinoids effects are known to be mediated by two classes of nuclear receptors, the RARs and the RXRs, each comprising three subtypes (α, β, γ), with various isoforms of each subtype (2). These receptors belong to the superfamily of nuclear hormone receptors and act as ligand-activated transcription factors of numerous genes (reviewed in Refs. 2 and 3). Retinoid receptors interact as either homo- or heterodimers on specific hormone response elements (RA responsive elements or RX responsive elements) of target gene promoters (4–6). The transcriptional activity of these receptors is further positively (homo-receptor) or negatively (apo-receptor) modulated by ligand binding (reviewed in Refs. 7 and 8). In addition, intracellular CRABPs play a regulatory function in RA signaling (9). Biological responses to ATRA may, therefore, be modulated by the type of nuclear receptors present in cells, by nuclear cofactors, by the CRABPs, and by the availability of specific retinoid ligands (reviewed in Ref. 10).

The differentiating properties of ATRA have led to the development of therapies for the prevention and treatment of various human cancers (11) including APL, in which retinoids are particularly active (12). APL is a subtype of myeloid leukemia (M3), characterized by the accumulation of cells blocked at the promyelocytic stage. This leukemia exhibits a specific chromosomal translocation t(15;17) involving the PML locus on chromosome 15 and the RARα locus on chromosome 17, thus generating a chimeric gene PML-RARα, translated into a chimeric nuclear receptor PML-RARα (13–17). PML-RARα functions as an aberrant receptor and is considered to be the cause of APL (18).

Although several clinical studies have established that ATRA can induce leukemia cell differentiation and remission in almost all patients (12, 19), resistance to this therapy develops rapidly (20). This acquired resistance appears to be attributable in part to the decline in ATRA plasma levels below therapeutic concentrations after repeated administration, presumably caused by the induction of hepatic cytochrome P450s that may increase its clearance (21–23). It has also been proposed that increased CRABPs contribute to resistance by decreasing nuclear availability of ATRA (24). More recently, mutations in the E-ligand-binding region of the RARα chimeric protein PML-RARα have been linked to ATRA resistance (25–29).

ATRA metabolism is complex and only partially understood at the present time (reviewed in Ref. 30). It can be oxidized by cytochrome P450s to various metabolites including 4-OH-RA, 4-oxo-RA, 18-OH-RA, and 5,6-epoxy-RA, which may be further metabolized to water-soluble glucuronides. Although ATRA metabolites are often considered to be catabolic products possessing low biological activity, some metabolites have been reported to be active in embryogenesis and to inhibit the growth of certain cancer cell lines (31–36). However, metabolism also seems to be involved in the response of certain cancer cells to ATRA, as shown by a study of breast cancer cell lines in which cell lines sensitive to ATRA growth inhibition (T47D and MCF7) could metabolize ATRA to polar metabolites (e.g., 4-oxo-RA and 4-OH-RA), whereas resistant cell lines (MDA-MB231 and MDA-MB418) metabolized ATRA poorly (35). Similar results involving ATRA metabolism to polar compounds by other sensitive cancer cells have also been reported (37).
As the metabolism of ATRA appears to be involved in its mechanism of action in certain cancer cell lines, the purpose of this study was to evaluate the in vitro effects of the principal oxidized ATRA metabolites using the human NB4 promyelocytic leukemia cell line that expresses the characteristic APL t(15;17) chromosomal translocation (38). Our results show that NB4 cells can metabolize ATRA to polar metabolites (4-OH-RA, 4-oxo-RA, 18-OH-RA, and 5,6-epoxy-RA), and that these metabolites are active retinoids in vitro with regard to cell growth inhibition, cell cycle arrest in G1 phase, cell differentiation, NB reorganization, and degradation of the chimeric protein PML-RARα. In addition, when using a specific RAα antagonist, ATRA metabolites are shown to act via the RARα nuclear receptor signaling pathway, as does the parent compound.

MATERIALS AND METHODS

Chemicals. ATRA, its isomers 13-cis-RA and 9-cis-RA, NBT, PMA, and propidium iodide were purchased from Sigma-Aldrich (St-Quentin-Falavier, France). 4-OH-RA, 4-oxo-RA, 18-OH-RA, and 5,6-epoxy-RA were kindly donated by Dr. Michael Klaus (Hoffmann-La Roche Ltd., Basel, Switzerland) and Dr. Louise H. Foley (Hoffmann-La Roche Inc., Nutley, NJ). The RAα antagonist BMS614 was synthesized by Bristol-Myers Squibb and kindly donated by Dr. H. Gronemeyer (Institut de Génétique et de Biologie Moléculaire et Cellulaire, Illkirch, France). Stock solutions of retinoids were prepared in ethanol at 10⁻² M and stored protected from light at −20°C.

Cell Culture. The NB4 human APL cell line, developed in our laboratory (38), was maintained in RPMI 1640 (Life Technologies, Inc.) supplemented with 10% FCS (Bayer Diagnostics, Puteaux, France), 2 mM l-glutamine, 50 units/ml penicillin G, and 50 μg/ml streptomycin (Life Technologies, Inc.). The cells were cultured at 37°C in a humidified atmosphere containing 5% CO₂. Cell density was assessed with an electronic particle counter and size analyzer (Coulter Electronics, Hialeah, FL). Stock solutions of retinoids (at 10⁻² M in ethanol) were further diluted in culture medium to the final concentration indicated in each experiment. Final concentration of ethanol in culture medium did not exceed 0.01%. Stock solutions of retinoids were regularly checked for purity using reversed-phase HPLC analysis and did not show any contamination by ATRA. Cell cultures were diluted with fresh medium every 48 h, and drug concentrations were adjusted accordingly. All of the experimental procedures were light protected.

ATRA Metabolism in NB4 Cells and HPLC. Cells (10⁶) were incubated at 37°C in 2 ml of the above medium with 1 μM ATRA for 24 h. After acidification (HCl, 1%), cells and medium were extracted with ethyl acetate (39), the organic phase recuperated by centrifugation, and evaporated under a gentle nitrogen stream. The dry residue was reconstituted in 100 μl of methanol, and 50 μl was injected onto a HPLC system composed of a Varian 5000 chromatograph, a C₁₈ reversed-phase column (Beckman, Ultrasphere 5 μm, 4.6 mm × 250 mm), protected by a precolumn, a UV detector set at 340 nm (Waters 484), and a peak integrator (Varian 4400). Elution was accomplished using a 25-min linear gradient starting at 65% methanol/35% water with 1% ammonium acetate, and ending at 90% methanol/10% water pumped at 1 ml/min.

NBT Reaction. Cells (5 × 10⁵) were added to 450 μl of 1 mg/ml NBT solution containing 3 × 10⁻⁷ M PMA in PBS buffer, and incubated at 37°C for 25 min. Cytosin preparations of 200 μl of the cell suspensions (Cytosin; Shandon) were allowed to air-dry. The NBT-positive and -negative cells were scored under phase contrast microscopy examination (Leica) at ×40. A minimum of 400 cells per slide, scored with at least two scores, were performed per experimental condition.

May-Grünewald Giemsa Staining. Cytosin preparations of 2 × 10⁴ cells were allowed to air-dry, incubated in pure May-Grünwald solution for 5 min, then in 50% May-Grünwald/water for 10 min, washed in water, and incubated in a 20% Giemsa/water solution for 20 min. The slides were then washed in water, air-dried, and examined under immersion microscopy (Leica, ×63).

Flow Cytometry Analysis of Cell Cycle Distribution. Cells (1 × 10⁶) were washed in PBS and resuspended in 200 μl of PBS. The cells were fixed in 2 ml of 75% ethanol/water for 2 min, centrifuged, and resuspended in 1 ml of PBS solution with 40 μg of propidium iodide and 100 μg of RNase A for 30 min at 37°C. Propidium iodide (red) fluorescence was measured using a FACScan flow cytometer (Becton Dickinson) with 10⁴ cells acquired per sample.

Flow Cytometry Analysis of CD11c Cell Surface Integrin Expression. Cells (1 × 10⁶) were incubated with an anti-CD11c-PE, or the isotype control IgG2a-PE (Becton Dickinson), for 20 min on ice in the dark. The cells were washed once with PBS and resuspended in 500 μl of PBS. PE (red) fluorescence was measured using a FACScan flow cytometer (Becton Dickinson) with 10⁵ cells acquired per sample.

Immunofluorescence. Cytosin preparations of 10⁴ cells were allowed to air-dry for 24 h, fixed with acetone for 10 min at 4°C, and air-dried for 20 min. The slides were rehydrated for 10 min in PBS and then incubated with a polyclonal rabbit antisemum directed against a PML recombinant protein (40) at a dilution of 1:500 in PBS for 1 h at room temperature. The slides were then incubated with fluorescein-coupled antirabbit secondary antibody (Sigma) at a dilution of 1:200 for 30 min at room temperature in the dark. All of the incubations were followed by three washes in PBS for 5 min. Preparations were examined under fluorescence microscope (Leica, ×63).

Western Blot. Crude cytoplasmic and nuclear extracts were prepared from untreated and treated NB4 cells. The cells were collected, washed once with cold PBS, centrifuged at 1300 rpm at 4°C, and resuspended in buffer A [10 mM HEPES (pH 7.9), 1.5 mM MgCl₂, 10 mM KCl, and 0.5 mM DTT] for 10 min at 4°C. After centrifugation for 1 min at 5000 rpm at 4°C, cells were lysed for 1 min on ice in buffer A containing 0.2% NP40, 1.5 μg/ml protease inhibitor cocktail, and 0.2% phenylmethylsulfonyl fluoride, and centrifuged 1 min at 5000 rpm. Supernatants corresponding to cytoplasmic proteins were collected, and the nuclear proteins contained in the pellets were extracted with buffer B [20 mM HEPES (pH 7.9), 0.2 mM EDTA, 0.5 mM DTT, 0.42 mM NaCl, 25% v/v glycerol, 1.5 μg/ml protease inhibition cocktail, and 0.2 mM phenylmethylsulfonyl fluoride] for 20 min on ice, and centrifuged 1 min at 5000 rpm at 4°C. Cytoplasmic and nuclear extracts were frozen at −80°C. Nuclear protein extracts (10 μg) were boiled in the presence of 5% β-mercaptoethanol and loaded onto 8% SDS-polyacrylamide gels, electrophoresed, and blotted onto polyvinylidene difluoride membranes (Immobilon P; Millipore). The membranes were blocked with 4% nonfat milk in PBS for 3 h at room temperature, then incubated with primary human antibody anti-RARαs [RPe(F); 1:5000; Ref. 41] in PBS-T (PBS and 0.1% Tween 20) and 0.5% milk for 18 h at 4°C. Membranes were washed five times for 5 min each with PBS-T, incubated with horseradish peroxidase-coupled antirabbit antibody (1:10000; Jackson Laboratories) for 30 min in PBS-T at room temperature, and washed five times for 5 min with PBS-T. Detection was performed as described in the ECL kit (Amersham; Ref. 42).

Determination of Relative Potency of the Retinoids. NB4 cells (2 × 10⁵ cells/ml) were exposed to ATRA or its metabolites at concentrations ranging from 7 nM to 1 μM, the NBT test was performed at 72 h, and the positive cells were scored as described above. The data from three separate experiments were normalized to determine the EC₅₀, which elicited half maximal NB4-positive cells. Nonlinear regression analysis was carried out using a sigmoidal dose-response curve and GraphPad software.

RESULTS

ATRA Metabolism in NB4 Cells. We first evaluated the ability of human NB4 promyelocytic leukemia cells to metabolize ATRA. Fig. 1 shows the ATRA metabolites formed after 24 h in the presence of 1 μM ATRA. The metabolites formed were 4-oxo-RA, 4-OH-RA, 18-OH-RA, and 5,6-epoxy-RA, which presented concentrations of 0.06, 0.03, 0.08, and 0.39 μM, respectively. The stereoisomers 13-cis-RA and 9-cis-RA presented concentrations of 0.07 and 0.16 μM, respectively, and ATRA of 0.19 μM.

NB4 Cell Growth Inhibition and Cell Cycle Arrest by ATRA Metabolites. NB4 cell growth in the presence of exogenously added ATRA metabolites was assessed at a concentration of 1 μM for 120 h (Fig. 2A). Compared with untreated cells, the growth inhibition was found to be similar for ATRA and the 4 metabolites tested, yielding 50% growth inhibition between 72 and 96 h. At 120 h, cell growth was still similar for all compounds, and ranged from 22 to 31% of...
untreated cells. Cell growth declined to 11–13% of controls for ATRA and its metabolites at 168 h (data not shown). In parallel experiments, the influence of ATRA or its metabolites on the cell cycle distribution was assessed for 5 days (Fig. 2B). A time-dependent cell cycle accumulation in the G1 phase was observed for all compounds tested, yielding 82–84% G1 accumulation at day 5, at the expense of the S and G2-M phases. These data are in agreement with the observed growth arrest.

**NB4 Cell Differentiation by ATRA Metabolites.** Because the ATRA metabolites appeared to be as effective as the parent compound with regard to cell growth inhibition and cell cycle arrest, we assessed the differentiating potential of these retinoids in NB4 cells using cell morphology, NBT reduction, and CD11c expression. Morphological differentiation using May-Grünwald Giemsa staining of NB4 cells exposed to either ATRA or its metabolites was carried out every day for 5 days. The first signs of morphological differentiation were observed at 72 h for all compounds, and the differentiation was more pronounced for 18-OH-RA and 5,6-epoxy-RA than for ATRA, 4-oxo-RA or 4-OH-RA (data not shown). At 96 h, the granulocytic maturation pattern was similar for all retinoids, with polylobular nuclei, decreased nuclear:cytoplasmic ratio, and decreased cytoplasm staining (Fig. 3A). ATRA and its metabolites induced similar kinetics of differentiation with comparable efficacy at 1 μM reaching 82–88%

**Fig. 1.** ATRA metabolism by human NB4 promyelocytic cells. A, gradient reversed-phase HPLC chromatogram of ATRA principal metabolites formed in vitro after a 24-h incubation of NB4 cells with 1 μM ATRA. The identified metabolites are 4-oxo-RA (peak 1), 4-OH-RA (peak 2), 18-OH-RA (peak 3), and 5,6-epoxy-RA (peak 4). In addition to ATRA (peak 7), its stereoisomers, 13-cis-RA (peak 5) and 9-cis-RA (peak 6) are also detected. B, standard metabolites at 1 μM: 4-oxo-RA (peak 1), 4-OH-RA (peak 2), 18-OH-RA (peak 3), 5,6-epoxy-RA (peak 4), 13-cis-RA (peak 5), 9-cis-RA (peak 6), and ATRA (peak 7).

**Fig. 2.** A, NB4 cell growth inhibition by ATRA metabolites. NB4 cells were exposed to the indicated retinoid at a final concentration of 1 μM, and cell density was assessed using an electronic particle counter. Mean of three independent experiments; error bars, SD. B, ATRA metabolite effect on NB4 cell cycle distribution. NB4 cells were exposed to 1 μM retinoids for the indicated time and then stained with propidium iodide. Cells (10⁴) were analyzed for each point using a FACScan flow cytometer.

**Fig. 3.** Differentiation induction of NB4 cells by ATRA metabolites. A, May-Grünwald Giemsa staining of NB4 cells. NB4 cells were exposed to 1 μM ATRA or its metabolites for 96 h and stained with May-Grünwald Giemsa (× 63). B, NBT assay of NB4 cells. The reduction of NBT by NB4 cells treated with 1 μM ATRA or its metabolites was determined every day for 5 days. A minimum of 400 cells per slide were scored, and at least two scores were performed per experimental condition. C, CD11c cell surface marker expression in NB4 cells. Cells were exposed to 1 μM concentration of the indicated retinoid for 24 h and incubated with an anti-CD11c-PE or with the isotype control IgG2a-PE. Cells (10⁴) were analyzed for each point using a FACScan flow cytometer.
Because differentiation of NB4 cells by ATRA is mediated through the nuclear receptor pathways involved in this response, it was of interest to investigate the nuclear receptor pathways involved in this response. NB4 promyelocytic leukemia cell differentiation, with effective concentrations to elicit 50% (EC₅₀) of NBT positive cells of 15.8 ± 1.7 nM. The metabolites yielded EC₅₀ values of 38.3 ± 1.3 nM for 4-oxo-RA, 55.5 ± 1.8 nM for 18-OH-RA, 79.8 ± 1.8 nM for 4-OH-RA, and 99.5 ± 1.5 nM for 5,6-epoxy-RA. However, at higher concentrations (from 0.25 to 1 µM), ATRA and its metabolites showed similar differentiation efficiency of about 80% NBT positive cells.

Effect of RARα Antagonist on the Induction of Differentiation by ATRA Metabolites. Because the ATRA metabolites could induce NB4 promyelocytic leukemia cell differentiation, it was of interest to investigate the nuclear receptor pathways involved in this response. Because differentiation of NB4 cells by ATRA is mediated through the RARα receptor, we therefore blocked this pathway using the RARα-specific antagonist BMS614. NB4 cells were simultaneously treated with ATRA or its metabolites at 0.1 µM, in the absence or presence of the RARα-specific antagonist BMS614 (1 µM) for 48 h (Fig. 6). As expected, BMS614 abolished ATRA-induced CD11c expression as shown by the decrease in fluorescence intensity to near control values. Likewise, induction of CD11c expression by the ATRA metabolites was blocked by BMS614, which indicated that the metabolites induced maturation through the RARα signaling pathway, as does the parent compound.

DISCUSSION

Although ATRA is considered to be the best single agent available for APL therapy, it is limited in that clinical resistance can develop

NBT positive cells in 5 days (Fig. 3B). Moreover, ATRA and its metabolites induced the expression of the maturation-specific cell surface marker CD11c in NB4 cells 24 h after retinoid exposure (Fig. 3C); at 48 or 72 h, there was little change in the percentage of CD11c positive cells compared with that at 24 h, and no difference was noted between ATRA and its metabolites with regard to the level of CD11c expression (Table 1).

NB Reorganization and PML-RARα Protein Degradation by ATRA Metabolites. The intracellular distribution of PML and PML-RARα proteins in NB4 promyelocytic leukemia cells exposed to ATRA or its four metabolites at 1 µM for 5 days was analyzed by immunocytochemistry. The nuclei from control cells presented fine and numerous labeled dots containing PML (Fig. 4A), corresponding to the micropunctated NBs typically found in APL cells. When the cells were exposed to ATRA, the morphological reorganization was characterized by an increase in NB size corresponding to macropunctated NBs, and a decrease in their number. A similar pattern of NB reorganization to that seen with ATRA was observed for all of the metabolites tested (Fig. 4A). As early as 24 h, NB reorganization could be seen, which reached a maximum at 72 h. No major difference in NB size was observed between 72 h and 120 h for ATRA or its metabolites (data not shown). Concomitant to NB reorganization, degradation of the PML-RARα chimeric protein by ATRA metabolites was also assessed. ATRA metabolites treatment induced PML-RARα degradation as did ATRA (Fig. 4B). The protein became barely detectable at 48 h, with the emergence of a lower molecular weight band corresponding to degradation of the chimeric protein (Fig. 4B).

Table 1 CD11c integrin cell surface expression of NB4 cells exposed to ATRA or its metabolites

<table>
<thead>
<tr>
<th>Treatment</th>
<th>% CD11c positive cells</th>
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<tr>
<td></td>
<td>24 h</td>
</tr>
<tr>
<td>ATRA</td>
<td>67</td>
</tr>
<tr>
<td>4-oxo-RA</td>
<td>53</td>
</tr>
<tr>
<td>4-OH-RA</td>
<td>63</td>
</tr>
<tr>
<td>18-OH-RA</td>
<td>62</td>
</tr>
<tr>
<td>5,6-epoxy-RA</td>
<td>67</td>
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The CD11c-labeled controls and the isotype (IgG2a) control cells showed 1% positive cells.

* Cells were exposed to retinoid concentrations of 1 µM for the indicated times.

Fig. 4. A, NB reorganization by ATRA and its metabolites. Intracellular distribution of PML and PML-RARα proteins in NB4 cells exposed to 1 µM ATRA or its 4 metabolites for 72 h was analyzed by immunocytochemistry and fluorescence microscopy (× 63). The slides were incubated with a polyclonal rabbit antiserum directed against recombinant PML and then were incubated with fluorescein-coupled antirabbit secondary antibody. Preparations were examined by fluorescence microscopy. B, PML-RARα chimeric protein degradation by ATRA and its metabolites. Western blot of crude nuclear extracts prepared from NB4 cells after a 48-h treatment with 1 µM concentrations of the indicated retinoids. After electrophoretic separation and membrane transfer, the membranes were incubated with primary human antibody anti-RARα.

Fig. 5. Determination of the relative potency of ATRA and its metabolites. NB4 cells were exposed to ATRA or its metabolites at concentrations ranging from 7 nM to 1 µM; the NBT reduction test was performed after 72 h, and positive cells were counted. Values are the mean of three separate experiments; error bars have not been shown for legibility.
Fig. 6. Effect of the RARα-specific antagonist BMS614 on the induction of NB4 cell differentiation by ATRA metabolites. NB4 cells were simultaneously treated with 0.1 μM ATRA or its metabolites and 1 μM of the RARα antagonist BMS614 for 48 h. CD11c expression was analyzed by flow cytometry as described in “Materials and Methods.” a, untreated control cells; b, untreated cells stained with anti-CD11c-PE; c, untreated cells stained with isotype control IgG2a-PE; d, cells treated with BMS614 and stained with CD11c-PE.

rapidly (20). One cause of ATRA resistance is attributable to its increased metabolism with rapid clearance often observed in relapsing patients (43). ATRA has, therefore, been considered to be the unique effective compound, and its metabolites have been considered as catabolic products. However, several authors have proposed that ATRA metabolism may be required for cell growth inhibition of various cancer cell lines in vitro, although no causal relationship has been shown (35, 37, 44). Because very little information is presently available concerning the biological activity of the principal Phase I metabolites, the purpose of this work was to evaluate the in vitro effects of the main oxidized metabolites of ATRA using the NB4 human promyelocytic leukemia cell line (38). The NB4 cell line is a relevant model for this study in that it exhibits the chromosomal integration of the chimeric protein PML-RARα. It can be differentiated by ATRA treatment and may be used to elucidate mechanisms of differentiation in APL, a paradigm of a disease sensitive to differentiation therapy.

Our results show that NB4 cells metabolize ATRA to the more polar metabolites 4-oxo-RA, 4-OH-RA, 18-0H-RA, and 5,6-epoxy-RA. ATRA metabolism is cytochrome P450-dependent and appears to involve several isoforms including CYP2C8 (45) and CYP26 (46, 47; reviewed in Ref. 48). More recently, Marill et al. (49) have identified several other human cytochrome P450s significantly involved in the metabolism of ATRA.

In summary, these data demonstrate new biological properties of the ATRA metabolites and indicate that they are not ineffective catabolic products. These metabolites may participate in the ATRA mechanism of action on cell growth inhibition and differentiation via the RARα receptor signaling pathway. In conclusion, the principal ATRA Phase I metabolites are active retinoids which, provided that manageable toxicity and in vivo pharmacological concentrations were achievable, could be of interest for differentiation therapy of sensitive human cancers.

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