Histone Deacetylase Inhibitor AR-42 Differentially Affects Cell-cycle Transit in Meningeal and Meningioma Cells, Potently Inhibiting NF2-Deficient Meningioma Growth

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Abstract

Meningiomas constitute about 34% of primary intracranial tumors and are associated with increased mortality in patients with neurofibromatosis type 2 (NF2). To evaluate potential medical therapies for these tumors, we have established a quantifiable orthotopic model for NF2-deficient meningiomas. We showed that telomerase-immortalized Ben-Men-1 benign meningioma cells harbored a single nucleotide deletion in NF2 exon 7 and did not express the NF2 protein, merlin. We also showed that AR-42, a pan-histone deacetylase inhibitor, inhibited proliferation of both Ben-Men-1 and normal meningeal cells by increasing expression of p16INK4A, p21CIP1/WAF1, and p27KIP1. In addition, AR-42 increased proapoptotic Bim expression and decreased anti-apoptotic BclXL levels. However, AR-42 predominantly arrested Ben-Men-1 cells at G2–M whereas it induced cell-cycle arrest at G1 in meningeal cells. Consistently, AR-42 substantially decreased the levels of cyclin D1, E, and A, and proliferating cell nuclear antigen in meningeal cells while significantly reducing the expression of cyclin B, important for progression through G2/M in Ben-Men-1 cells. In addition, AR-42 decreased Aurora A and B expression. To compare the in vivo efficacies of AR-42 and AR-12, a PDK1 inhibitor, we generated and used luciferase-expressing Ben-Men-1-LucB cells to establish intracranial xenografts that grew over time. While AR-12 treatment moderately slowed tumor growth, AR-42 caused regression of Ben-Men-1-LucB tumors. Importantly, AR-42–treated tumors showed minimal regrowth when xenograft-bearing mice were switched to normal diet. Together, these results suggest that AR-42 is a potential therapy for meningiomas. The differential effect of AR-42 on cell-cycle progression of normal meningeal and meningioma cells may have implications for why AR-42 is well-tolerated while it potently inhibits tumor growth. Cancer Res; 73(2); 1–12. ©2012 AACR.

Introduction

Meningiomas are tumors originating from the meningeal cells of the arachnoid layer lining the brain and can occur at the convexity, the skull base, and along the spine (1). About 80% of meningiomas are benign (WHO grade I), whereas the remaining are atypical (grade II) and anaplastic (grade III).

These tumors cause significant morbidity, including cranial nerve palsy, seizures, and brainstem compression, which may lead to paralysis, aspiration pneumonia, and death. Surgical resection and radiation are current treatment options; however, complete resection of tumors is often difficult, especially for those located along the skull base. Approximately 20% of benign meningiomas recur over 10 years, whereas grade II and grade III tumors possess greater rates of recurrence. Meningiomas can occur sporadically or in patients with neurofibromatosis type 2 (NF2), a genetic disorder characterized by the development of multiple nervous system tumors, including meningiomas and vestibular schwannomas (2). Meningiomas in patients with NF2 are associated with disease severity and increased risk of mortality. Patients with NF2 often have multiple tumors, and their treatment is challenging. Consequently, the development of novel and effective medical therapeutics to treat meningiomas is urgently needed.

NF2 is caused by mutations in the Neurofibromatosis 2 (NF2) gene, which encodes the tumor suppressor protein merlin (3, 4). Most NF2-associated meningiomas and about 50% to 60% of sporadic meningiomas contain NF2 mutations (2). The observation that NF2 mutations are present in both benign and malignant meningiomas suggests that NF2 inactivation may be an early tumorigenic event and that loss of merlin disrupts...
important signaling pathways, ultimately leading to tumorigenesis. Merlin-deficient meningioma cells exhibit specific characteristics, such as cytoskeletal and cell contact defects, altered cell morphology and growth properties, and susceptibility to senescence (5). In addition, NF2 inactivation in arachnoidal cells or meningeal precursor cells leads to meningioma formation in mice, further corroborating the role of Merlin in tumorigenesis (6, 7). While these mouse models await further characterization, additional models that closely mimic the clinical presentation of NF2-deficient benign meningiomas and facilitate efficient quantitation of intracranial tumor growth will enhance therapeutic testing.

Meningioma cell lines are valuable tools to study tumor biology and potential treatments. Several patient-derived cell lines, such as IOMM-Lee and KT21-MG1, have been established from malignant meningiomas, which exhibit complex genetic changes and aggressive features (8–10). Using IOMM-Lee cells and primary meningioma cultures, McCutcheon and colleagues (11) generated orthotopic xenografts; however, tumor growth was not monitored over time, and primary meningioma cells did not uniformly produce tumors. Baia and colleagues (12) established intracranial xenografts with luciferase-expressing IOMM-Lee cells and used bioluminescence imaging (BLI) to quantify tumor growth. However, a quantifiable NF2-deficient, benign meningioma model has not been described. While several benign meningioma cell lines have been developed using the HPV E6/E7 or SV40 T-antigen (13, 14), transformation by viral oncopgenes alters growth signaling and behavior of these cells. Püttmann and colleagues (15) generated a benign meningioma cell line, Ben-Men-1, from a grade I meningioma using telomerase. Ben-Men-1 cells exhibit characteristics of meningotheelial differentiation and lack one copy of chromosome 22, which harbors the NF2 gene. However, the status of the second NF2 allele in Ben-Men-1 cells is not known.

NF2 inactivation in meningiomas and vestibular schwannomas perturbs several signaling pathways, including the AKT pathway (16–20). Previously, we showed that a small-molecule inhibitor of the AKT pathway, AR-12 (formerly OSU-03012), effectively inhibits the growth of NF2-deficient schwannoma cells (21). We also showed that AR-42 (HDAC-42), a panhistone deacetylase inhibitor (HDACi), potently inhibits schwannoma and meningioma cell proliferation (22, 23). In addition to inhibiting the activities of histone deacetylases, which are frequently overexpressed in human cancers (24), AR-42 can also reduce AKT phosphorylation by disrupting the interaction between HDAC6 and protein phosphatase-1 (PP1), enabling free PP1 to dephosphorylate AKT (25). However, the efficacies of these compounds have not been evaluated in an NF2-deficient, benign meningioma model in vitro. Furthermore, the effect of AR-42 in normal meningeal cells has not been examined.

Here, we showed that Ben-Men-1 cells are NF2-deficient. Using luciferase-expressing Ben-Men-1 cells, we established a quantifiable intracranial meningioma model to evaluate AR-42 and AR-12 as potential therapies. Also, we found that AR-42 differentially inhibited cell-cycle progression of normal meningeal and meningioma cells.

Materials and Methods

Cell cultures and drugs

Ben-Men-1 benign meningioma cells have been described (15). Malignant meningioma KT21-MG1 and IOMM-Lee cells (8, 9) were kindly provided by Dr. Anita Lal, University of California, San Francisco (San Francisco, CA). HE1-1 is an adenovirus E1-transformed human embryonic kidney cell line (unpublished), and HMS-97 is a human malignant schwannoma cell line (26). All cell lines and primary human meningeal cells (ScienCell) were grown in Dulbecco’s Modified Eagle Medium with 10% FBS (Invitrogen). AR-42 and AR-12 were supplied by Arno Therapeutics and formulated into rodent chow (Research Diets) to deliver about 25 and 100 mg/kg/d, respectively (21–23). Also, AR-42 was dissolved in dimethyl sulfoxide (DMSO) for in vitro experiments.

Mutational analysis

Genomic DNA was extracted from Ben-Men-1 cells using the PureGene DNA Isolation Kit (Qiagen). NF2 exons were amplified by PCR using Takara ExTaq DNA polymerase and primer pairs flanking each exon (27). PCR products were purified using the Qiagen Gel Extraction kit and sequenced from both 5’ and 3’-directions via automated DNA sequencing. The results were confirmed by sequencing PCR products obtained using PhiUltra High-fidelity DNA polymerase (Stratagene).

Cell proliferation assay and flow cytometry

Cells were plated at 7,500 cells per well in 96-well plates overnight and treated with various concentrations of AR-42 for 72 hours. Cell proliferation was measured by resazurin assay (28), and the 50% inhibitory concentration (IC50) was calculated (21). For cell-cycle analysis, subconfluent cells were treated with 1 μmol/L AR-42 or DMSO as a control for 2 days. For mitotic block, nocodazole (100 ng/mL) was added to drug-treated cells for another 24 hours before harvesting. Following treatment, floating and adherent cells were collected, washed, and fixed in 75% ethanol (29). Fixed cells were incubated with 0.2 mol/L phosphate-citrate buffer, pH 7.8, to extract low-molecular-weight DNA, stained in propidium iodide (50 μg/mL) and RNase A (100 μg/mL), and analyzed using a Calibur fluorescence-activated cell sorter (Becton Dickinson; ref. 29). Data analysis was conducted using FlowJo software (TreeStar).

Western blot

Subconfluent cells were treated with the indicated concentrations of AR-42 for 1 or 2 days. Treated cells were harvested and lysed in cold radioimmunoprecipitation assay (RIPA) buffer supplemented with protease inhibitor cocktail (Sigma). Equal amount of protein (20 μg) in each lysate was run on an SDS-polyacrylamide gel, and Western blot analysis was conducted as described previously (21).

Lentiviral transduction

Ben-Men-1 cells were transduced with Lenti-CMV-Luc lentiviruses (Qiagen) in the presence of hexadimethrine bromide (8 μg/mL) at 37°C overnight. Transduced cells were passaged at 1:5 dilution and then selected for puromycin resistance. Luciferase activity was detected using the Luciferase Reporter
Assay System (Promega; ref. 30), and the clone with the highest activity, designated Ben-Men-1-lucB (data not shown), was used subsequently.

**Establishment of a skull-base meningioma model**

The Institutional Animal Care and Use Committee at Nationwide Children’s Hospital approved this animal study. Ben-Men-1-lucB cells were harvested, washed, and resuspended in PBS (0.5 × 10⁶ to 1 × 10⁶ cells/mouse in 3 μL). Six to 8-week-old SCID C.B17 mice were anesthetized with 5% isoflurane (Baxter), and their heads were stabilized in a Kopf Small-Animal Stereotaxic Instrument. A midline sagittal incision was made on the cranial skin, and a burr hole was drilled in the skull 1.5 mm anterior and 1.5 mm to the right of the bregma. A 26-gauge needle attached to a 10-μL Hamilton syringe loaded with cells was slowly inserted through the burr hole and downward about 5 mm to the skull base. The cell suspension was injected at a rate of 1.5 μL/min via an automatic micro-injection unit, and the needle was left in place for 1 minute before being withdrawn slowly. The incision was closed using 3 M VetBond Tissue Adhesive. After recovery, mice were monitored for tumor growth and any neurologic deficits.

**BLI and small-animal MRI**

To verify tumor establishment, mice stereotactically inoculated with Ben-Men-1-lucB cells were imaged using a Xenogen IVIS Spectrum (Caliper) 2 and 4 weeks after injection. Briefly, mice were injected intraperitoneally with D-luciferin (150 mg/kg body weight; Caliper) and anesthetized with isoflurane. Kinetic analysis of luciferase activity was conducted to identify the time at which the peak luminescent signal was emitted. All subsequent BLI was conducted at this peak time. Once tumors had established, mice were divided into 3 groups and fed normal diet, or AR-12 formulated diet, or AR-42—containing diet *ad libitum*. Tumor growth was monitored monthly by BLI. Photon emission was quantified by region of interest analysis using Living Image software (Caliper). Because of variation in initial tumor size, the luminescence for each mouse was normalized to the signal measured before treatment and expressed as the mean normalized luminescence ± SD for each treatment group (n = 5 per group). Also, photon emission from a representative group of mice measured together for each indicated time point was displayed as total flux. A cohort of mice treated with AR-42 for 6 months were switched to normal diet for additional 6 months and imaged monthly to assess the extent of tumor regrowth.

For MRI, mice were anesthetized with isoflurane, injected intraperitoneally with Magnevist contrast agent (0.1 mmol/L/kg), and scanned using a BioSpec 94/30 USR 9.4 T microMRI (Bruker). Tumor volumes were calculated from T1 images as described previously (22, 26).

**Immunohistochemistry**

Mice were injected intraperitoneally with bromodeoxyuridine (BrdUrd; 0.5 mg per 10 g body weight) 2 hours before euthanasia. Heads were dissected and fixed in 10% phosphate-buffered formalin. Following washing in running water for 2 hours, heads were treated with 0.1 mol/L Tris-HCl, pH 7.2 overnight and decalcified in 0.35 mol/L EDTA in 0.1 mol/L Tris-HCl, pH 6.95 for 10 to 14 days. After optimal decalcification (31), samples were cut in half, incubated in 10% sucrose in 0.1 mol/L Tris-HCl, pH 7.2 overnight, and embedded in paraffin. Sections (5 μm) were obtained, deparaffinized, and stained with hematoxylin and eosin. For immunostaining, deparaffinized sections were heated in 1 mmol/L citric acid, pH 6.0, in a steamer for 20 minutes and sequentially treated with 3% hydrogen peroxide, Super Block, and a primary antibody overnight (Supplementary Methods), followed by incubation with a horseradish peroxidase (HRP)-conjugated secondary antibody and color development with AEC chromogen (ScyTek). Hematoxylin was used as a counterstain. Stained sections were mounted and visualized under a Zeiss Axioskop microscope. Negative controls were treated with the same procedure but without the primary antibody.

**Results**

**Ben-Men-1 benign meningioma cells are NF2-deficient**

As Ben-Men-1 cells lack one copy of chromosome 22, which contains the NF2 gene (15), we determined the status of the remaining NF2 allele by scanning the 17 NF2 exons for mutations. We detected a deletion of a cytosine (nucleotide 640) relative to the major transcription initiation site designated as +1; ref. 30) in exon 7 in Ben-Men-1 cells, resulting in a premature stop codon 5 amino acids downstream of the mutation (Fig. 1A).

![Figure 1. Ben-Men-1 cells contain a mutation in the NF2 gene and do not express merlin. A, Ben-Men-1 cells carry a deletion of a cytosine residue (del640C; marked with an inverted triangle) in NF2 exon 7, resulting in premature termination. The 17 NF2 exons were obtained from Ben-Men-1 and control DNA by PCR and sequenced according to Materials and Methods. B, Western blot analysis showed that Ben-Men-1 benign meningioma cells and KT21-MG1 malignant meningioma cells did not express merlin protein, in contrast to normal meningeal cells, JOMM-Lee malignant meningioma cells, HE1-1 embryonic kidney cells, and HMS-97 malignant schwannoma cells. α-Tubulin was used as a loading control.](https://www.aacrjournals.org/cancerres/article-pdf/73/2/OF3/2969356/cancerres-12-1888.pdf)
Western blot analysis revealed that Ben-Men-1 cells did not express merlin protein, in contrast to meningeal cells, IOMM-Lee malignant meningioma cells, and HMS-97 malignant schwannoma cells (Fig. 1B). While the frameshift mutation predicts a truncated product of 218 amino acids, a protein of this size was not detected in Ben-Men-1 cells (Supplementary Fig. S1). In addition, we did not detect merlin protein in KT21-MG1 malignant meningioma cells. These results indicate that Ben-Men-1 and KT21-MG1 cells are NF2-deficient.

AR-42 differentially affects cell-cycle progression of normal meningeal and Ben-Men-1 meningioma cells

Previously, we showed that AR-42 decreased Ben-Men-1 cell growth with an IC50 of about 1 μmol/L (22). Intriguingly, AR-42 also inhibited proliferation of meningeal cells at a similar IC50 (Supplementary Fig. S2). Consistent with its action as an HDACi (32), AR-42 treatment increased global acetylation of intracellular proteins, including histone H2B, in both meningeal and Ben-Men-1 cells (Supplementary Fig. S3A and S3B). Also, AR-42 decreased expression of p-AKT and 2 downstream targets of the AKT/mTOR pathway, p-S6 ribosomal protein and p-4E-BP1, in both cell types. These results indicate that AR-42 exerts similar effects on protein acetylation and the AKT pathway in meningeal and meningioma cells.

To compare the effect of AR-42 on cell-cycle progression, we conducted flow cytometric analysis on meningeal and Ben-Men-1 cells treated with 1 μmol/L AR-42 for 2 days. Consistent with our previous observation (22), AR-42 treatment substantially increased the number of Ben-Men-1 cells in G2–M from 13.1% to 38.8% (Fig. 2). Intriguingly, AR-42 did not affect the percentage of meningeal cells in G2–M but increased the G1 population from 87.5% to 90%, suggesting G1 arrest. To enhance detection of cells arrested in G1, nocodazole, an agent that disrupts microtubule polymerization, was added to AR-42-treated cells for another day (from 48 to 72 hours) to block cells in M phase. Note that the doubling time for Ben-Men-1 cells is about 2 days (15), and meningeal cells double about every 3 days (Supplementary Fig. S4). Addition of nocodazole to AR-42-treated meningeal cells significantly increased the G1 population compared with the nocodazole/DMSO-treated control (from 83.1% to 89.1%; Fig. 2), confirming that AR-42 induced G1 arrest in meningeal cells. As expected, nocodazole substantially increased the percentage of DMSO-treated Ben-Men-1 cells in G2–M from 13.1% to 61.1% while decreasing the G1 fraction from 72.6% to 18.2%. However, addition of nocodazole to AR-42-treated Ben-Men-1 cells only slightly increased the G2–M population compared with AR-42–treated cells in the absence of nocodazole (from 38.8% to 40.2%), suggesting that AR-42 also impeded G1 progression of Ben-Men-1 cells. Collectively, these results showed that AR-42 inhibited cell-cycle progression of Ben-Men-1 meningioma cells in both G2–M and G1, whereas it arrested meningeal cells in G1.

AR-42 modulates the expression of cell-cycle regulators

To investigate the mechanism by which AR-42 differentially induces cell-cycle arrest in meningeal and Ben-Men-1 cells, we analyzed the expression of various cyclin-dependent kinase...
(CDK) inhibitors and cyclins. Both meningeal and Ben-Men-1 cells expressed low levels of p16\(^{INK4A}\), p21\(^{CIP1/WAF1}\), and p27\(^{KIP1}\). Treatment with AR-42 induced the expression of these CDK inhibitors in a dose-dependent manner in both cell types (Fig. 3A). However, AR-42 did not affect p57\(^{KIP2}\) expression. These results show that inhibition of cell-cycle progression by AR-42 in meningeal and Ben-Men-1 cells is mediated, in part, by induction of multiple CDK inhibitors. Mitogen stimulation induces the expression of cyclin D, which activates CDK4/6 at early G\(_1\), followed by increasing cyclin E and A levels during late G\(_1\), CDK2, which binds to cyclin E and A, and CDC2, which binds to cyclin E, promote the G\(_1\)-S transition. In addition, cyclin B and CDC2 are important for progression through G\(_2\) (33). While Ben-Men-1 cells expressed higher basal levels of cyclin D1 and E than meningeal cells, AR-42 treatment attenuated the expression of these cyclins and markedly decreased the cyclin A level in meningeal cells. Consistently, AR-42 notably reduced the level of proliferating cell nuclear antigen (PCNA), a protein induced in S-phase, and further decreased cyclin B and CDC2 expression in meningeal cells. Similarly, AR-42 treatment lowered the expression of cyclin D1, E, and A in Ben-Men-1 cells, albeit...
the decrease was less dramatic. Consistent with $G_2$–$M$ arrest, AR-42 only modestly decreased PCNA expression but significantly reduced the cyclin B level in Ben-Men-1 cells.

Taken together, these results suggest that AR-42 differentially affects cell-cycle progression of normal meningeal and Ben-Men-1 meningioma cells by regulating the expression of various cyclins and CDK inhibitors.

**AR-42 decreases the expression of Aurora kinases and modulates the levels of apoptotic factors**

We also analyzed the effect of AR-42 on the expression of various mitotic spindle assembly checkpoint kinases (34). Both meningeal and Ben-Men-1 cells strongly expressed Bub1 and Bub3; however, Ben-Men-1 cells exhibited higher levels of BubR1, Aurora A, and Aurora B than meningeal cells (Fig. 3C). While the Bub1, Bub3, and BubR1 levels were not affected by AR-42 treatment, Aurora A expression decreased substantially in both meningeal and Ben-Men-1 cells treated with AR-42. Also, the level of Aurora B decreased in AR-42–treated Ben-Men-1 cells. The reduced expression of Aurora kinases may further reinforce the effect of AR-42 on $G_2$–$M$ arrest in Ben-Men-1 cells.

AR-42 induces apoptosis in several types of tumor cells (22, 32, 35, 36); however, its effects on normal and tumor cells have not been compared. AR-42 treatment increased the expression of proapoptotic Bim in a dose-dependent manner but did not affect the levels of Bad and Bax in both meningeal and Ben-Men-1 cells (Fig. 3D). Similarly, AR-42 increased the Bag1 level; however, the increase was not as pronounced at higher concentrations (e.g., 2 μmol/L). Conversely, AR-42 decreased the expression of antiapoptotic BclXL and survivin in both cell types (Fig. 3E). While Ben-Men-1 cells expressed higher levels of Bcl2 and survivin than in meningeal cells, the expression of Bcl2 was not affected by AR-42 treatment. These results indicate that AR-42 affects the expression of specific pro- and anti-apoptotic regulators.

**AR-42 and AR-12 inhibited tumor growth in a quantifiable intracranial benign meningioma model**

To establish a quantifiable model for NF2-deficient benign meningiomas, we stereotactically injected luciferase-expressing Ben-Men-1-LucB cells, which exhibited a similar sensitivity to AR-42 as their parental Ben-Men-1 cells (Supplementary Fig. S5), to the skull base of SCID mice and monitored tumor growth by BLI according to Materials and Methods. BLI detected increased bioluminescent signal in Ben-Men-1-LucB xenograft–bearing mice with each month after injection. B, hematoxylin and eosin staining of the head region of a xenograft-bearing mouse 4 months after implantation showed that Ben-Men-1-LucB tumors grew from the site of injection along the skull to the top of the head region and did not invade the adjacent brain tissue. B, brain; T, tumor.

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Figure 4. Ben-Men-1-LucB cells established intracranial xenograft tumors that grew slowly along the skull over time. A, about 5 × 10^5 Ben-Men-1-LucB cells were stereotactically injected at the skull base, and tumor growth was monitored by BLI. B, hematoxylin and eosin staining of the head region of a xenograft-bearing mouse 4 months after implantation showed that Ben-Men-1-LucB tumors grew from the site of injection along the skull to the top of the head region and did not invade the adjacent brain tissue. B, brain; T, tumor.

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Figure 5. AR-42 potently suppressed the growth of Ben-Men-1-LucB tumor xenografts. Mice bearing Ben-Men-1-LucB tumors were established as described in Materials and Methods and fed either normal diet (mouse #2) or chow formulated with AR-42 (mouse #1) or AR-12 (mouse #3 and #4) for the indicated times (n = 5). Tumor growth was monitored by BLI. A, a representative image shows that while the intensity of bioluminescent signal increased over time in the mouse fed normal diet (mouse #2), the signal in the mouse fed AR-42 diet (mouse #1) decreased sharply after 1 month of treatment and remained low in subsequent months. The bioluminescent signal in mice treated with AR-12 (mouse #3 and #4) increased over time but at a slower rate than that in the mouse fed normal diet (mouse #2). Insets in the images of mice before and 1 month after treatment are displayed using a lower threshold of bioluminescence detection. B, quantitation of the bioluminescent signals emitted from tumors in mice fed AR-42–containing diet was conducted, and the relative bioluminescence signal is denoted as the percentage of total flux after each month of treatment relative to the total flux before treatment designated as a 100%. The data are shown as mean ± SD and reflect the BLI measurements from 5 animals per group imaged for 6 months. C, following BLI, tumor-bearing mice fed normal diet or diet containing AR-42 or AR-12 were imaged with gadolinium contrast using a small-animal MRI. Coronal (top) and axial (bottom) T1 MR images showed that the AR-12–treated mouse exhibited a smaller tumor than the mouse fed normal diet. Also, a tumor was not detected in the AR-42–treated mouse after 4 months of treatment. Arrowheads point to the site of injection at the skull base.
Minimal regrowth of Ben-Men-1-LucB tumors was observed after removal from AR-42 treatment

To evaluate potential tumor regrowth following AR-42 treatment, we fed an AR-42–treated mouse normal diet for an additional 6 months and monitored tumor growth monthly by BLI. While AR-42 treatment substantially decreased the tumor size as shown by the marked decrease of bioluminescence signal after six months (from $7.7 \times 10^6$ to $2.0 \times 10^5$ photons/sec), the tumor remained small with minimal regrowth (~2-fold increase in bioluminescence signal) over 6 months after removal from AR-42–containing diet (Fig. 6). Also, the tumor remained too small to be detected by MRI (Supplementary Fig. S10).

Histologic analysis corroborated that the tumors in mice treated with AR-12 for 6 months were smaller than those fed normal diet (Fig. 7A). Also, a very small tumor was found in a mouse treated with AR-42 for 3 months, consistent with the MRI result. AR-42–treated tumors exhibited increased levels of acetylated proteins compared with mice fed normal diet or diet containing AR-12 (Fig. 7B). As observed in cultured cells (Fig. 3A), a higher level of p16INK4A was detected in the tumors of AR-42–treated mice than in those of mice fed normal diet (Supplementary Fig. S8B). Consistent with the potent growth-inhibitory activity of AR-42, few or no BrdUrd- or Ki67-positive cells were seen in AR-42–treated tumors. Together with our previous observation that AR-42 induces apoptosis in vivo (22), these results indicate that AR-42 efficiently inhibits tumor growth in the Ben-Men-1-LucB benign meningioma model.

Discussion

Development of novel therapeutics for meningiomas, particularly those associated with NF2, is urgently needed and requires disease-specific models. In the present study, we generated a quantifiable orthotopic NF2-deficient benign meningioma model using luciferase-expressing Ben-Men-1-LucB cells. Using this model, we compared the in vivo efficacies of AR-42, a pan-HDACi (25), and AR-12, a PDK1 inhibitor (37), and showed that AR-42 causes tumor regression, whereas AR-12 moderately slows the growth of tumors over time.

Previously, we reported that AR-42 efficiently inhibits schwannoma and meningioma cell proliferation by arresting cells at G2–M and inducing apoptosis (22). Intriguingly, AR-42 inhibited proliferation of normal meningeal cells at about the same IC50 as that for Ben-Men-1 meningioma cells. Although AR-42 exerted similar effects on protein acetylation and AKT phosphorylation in both normal and tumor cells, it arrested meningeal cells at G1 but inhibited Ben-Men-1 cells at both G1 and G2–M. Cell-cycle progression is modulated by CDKs, which are bound and activated by one or more cyclin proteins whose
expression oscillates during specific phases of the cell cycle (33). In addition, several regulatory checkpoints exist throughout the cell cycle to maintain genomic stability. Activation of the G1 and G2 checkpoints increases the expression of CDK inhibitors and arrests cells in these phases, providing them time to repair any damage before continuing the cell cycle (38). The INK4 family of CDK inhibitors inhibits cyclin D–associated CDK4/6 at G1, whereas the CIP/KIP family regulates a wider range of cyclin–CDK complexes throughout the cell cycle. HDACi have been shown to induce G1 and/or G2–M arrest in tumor cells, and their action is mediated, in part, by altering the levels of various CDK inhibitors (39). HDACi can affect transcription of the p16INK4A and p21CIP1/WAF1 genes and alter the p27KIP1 level by a posttranslational mechanism. Consistently, AR-42 induced the expression of both the INK (p16INK4A) and CIP/KIP (p21CIP1/WAF1 and p27KIP1) members. However, the induction of these CDK inhibitors by AR-42 in both meningial and Ben-Men-1 meningioma cells implies that additional mechanisms contribute to the differential effects on cell-cycle progression in these cells.

Tumor cells frequently exhibit an abnormal G1 checkpoint as evident by alteration of the G1 cyclin-CDKs/the INK family/the retinoblastoma protein/E2F cascade (33, 38). Consistent with this notion, Ben-Men-1 cells expressed higher basal levels of the G1 cyclins, D1 and E, than meningial cells. While AR-42 treatment decreased cyclin E and A expression, significant amounts of these cyclins and PCNA were still detected even in the presence of 2 μmol/L AR-42, suggesting that a fraction of AR-42–treated meningioma cells enter S-phase. It is possible that the increased expression of multiple CDK inhibitors, together with the decreased levels of G1 cyclins, led to the growth inhibition at G1 observed in AR-42–treated Ben-Men-1 cells. However, the reduction of cyclin B expression by AR-42 may further inhibit the Ben-Men-1 cells that had progressed through S-phase and arrest them at G2. In contrast, AR-42 treatment blocked the expression of cyclin D1, E, and A in meningial cells, and this inhibition, together with the elevated levels of CDK inhibitors, could explain the G1 arrest observed in these cells. Consistently, only a small amount of PCNA and little cyclin B were detected in AR-42–treated meningial cells. HDACi can affect cyclin D, E, and B expression through a transcriptional mechanism or increase acetylation of cyclin A, which facilitates its degradation (39–42). It will be interesting to investigate why AR-42 treatment caused a more pronounced reduction of the cyclin A level in meningial cells than Ben-Men-1 cells. Nevertheless, the differential effect of AR-42 on cell-cycle progression of meningial and meningioma cells involves modulation of the expression of multiple cell-cycle regulators.
The mitotic spindle assembly checkpoint, which protects the integrity of cell division, is frequently altered in human tumors and regulated by several kinases, including Bub1, Bub3, and BubR1 (34). In addition, Aurora kinases A and B are important for spindle assembly, chromosome segregation, and cytokinesis (43). Curiously, Ben-Men-1 cells expressed higher levels of Aurora A, Aurora B, and BubR1 than meningeval cells, suggesting deregulation of the mitotic spindle checkpoint in meningioma cells. Importantly, AR-42 decreased the expression of Aurora A and B, further corroborating G2–M arrest in Ben-Men-1 cells. HDACi can decrease transcription of Aurora A and B or promote their degradation in different cell types (44–45). However, the mechanism by which AR-42 reduces the expression of Aurora kinases in meningeval and meningioma cells is not known. As Aurora A and B are frequently amplified or overexpressed in a variety of solid and hematologic malignancies (34, 43), AR-42 may also be a potential therapeutic agent for these tumors.

The members of the Bcl2 family, which consists of proapoptotic and anti-apoptotic factors, interact with each other in a delicate balance that governs whether a cell will undergo apoptosis. Our observation that AR-42 increased the expression of Bim and Bag1 and decreased the level of BclXL coincides with previous findings that AR-42 induced apoptosis in tumor cells (22, 32, 35, 36). Also, HDACi have been shown to induce the expression of Bcl2 family members, including Bim and BclXL (35, 36, 46). Together, these results suggest that AR-42–induced apoptosis is mediated, in part, through modulation of proapoptotic and anti-apoptotic factors.

Previously, we (21) showed that AR-12, a derivative of celecoxib that lacks COX-2 inhibitory activity (37), decreased AKT phosphorylation and efficiently inhibited schwannoma growth in vitro and in vivo. As in schwannoma xenografts (21), AR-12 exhibited moderate antitumor activity in Ben-Men-1-LucB meningiomas. Interestingly, AR-42 gave rise to more profound growth inhibition than AR-12 and caused tumor regression, suggesting that inhibition of the AKT pathway is not sufficient to account for the antitumor potency of AR-42. Also, the residual tumors in AR-42–treated mice showed minimal regrowth after switching to normal diet. As AR-42 also potently inhibits schwannoma growth and is well tolerated in mice (22, 23), these results suggest that it is a promising therapeutic agent for NF2-deficient tumors.

BLI is a sensitive and efficient way to noninvasively monitor tumor growth, particularly for longitudinal studies of benign tumors. Using BLI, we detected bioluminescence signal emitted from small luciferase-expressing tumors in AR–12–treated mice, whereas MRI could not identify tumors in the same mice. This observation is consistent with a previous report that MRI efficiently identifies macroscopic tumors but is less effective at detecting small tumors in mice compared with BLI (47). Also, MRI measured a less pronounced reduction in tumor size in AR–12–treated mice than BLI. It is possible that BLI may quantify the differences in cell density in benign tumors. Treatment may affect peritumoral edema of intracranial meningiomas (48), and fluid surrounding the tumors may obscure the tumor margin used in volumetric MRI measurement. Nevertheless, MRI and BLI were complementary tools to quantify the effects of AR–42 and AR–12 on tumor growth.

Overexpressed or sustained HDAC activity has been observed in many solid and hematologic malignancies, suggesting therapeutic potential of HDACi (24, 49). Several HDACi are currently in clinical trials for various types of cancer. Among them, Zolinza (vorinostat) and Romidepsin (depsipeptide) have been approved by the U.S. Food and Drug Administration (FDA) for the treatment of cutaneous T-cell lymphomas. AR-42 possesses growth-inhibitory activity that is comparable to or more potent than vorinostat in several tumor models (32, 35, 36, 50). It is orally bioavailable, penetrates the blood–brain barrier, and exhibits low toxicity. Mice treated with AR-42 showed slight weight loss, leukopenia, anemia, liver hypertrophy, and testicular degeneration, and these effects are reversible after removal from treatment (23, 50). AR-42 is currently being evaluated in a phase I/IIa clinical trial for relapsed and refractory multiple myeloma, chronic lymphocytic leukemia, and lymphoma. Our observation that AR-42 differentially affects cell-cycle progression of normal meningeal and meningioma cells may have implications for why it is well-tolerated while potently inhibiting tumor growth as prolonged G2 arrest may lead to apoptosis in proliferating tumor cells. Collectively, our results suggest that AR-42 merits a clinical trial for meningiomas and schwannomas.

Disclosure of Potential Conflicts of Interest

C.-S. Chen has ownership interest (including patents) and has royalty from licensing agreement between OSU and Arno. No potential conflicts of interest were disclosed by the other authors.

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Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): S.S. Burns, L.-S. Chang

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Acknowledgments

The authors sincerely thank Anita Lal for KT21-MG1 and 10MM-Lee cells, Kimeryl Powell and the Small-Animal Imaging Core for MRI, Allen Qian for technical assistance, and Beth Miles-Markley and Peter Houghton for critical reading of the manuscript.

Grant Support

This study was supported by grants from the Children’s Tumor Foundation, NIDCD (DC005985), US Department of Defense (NF080021), NF Midwest, and Advocate NF2 to D.B. Welling and L.-S. Chang.

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Received May 14, 2012; revised September 6, 2012; accepted October 25, 2012; published OnlineFirst November 14, 2012.
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References


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Cancer Res Published OnlineFirst November 14, 2012.