Transducible Peptide Therapy for Uveal Melanoma and Retinoblastoma

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Objective: To determine whether transducible peptides that inhibit the oncoproteins HDM2 and Bcl-2 may selectively kill uveal melanoma and retinoblastoma cells.

Methods: Peptides were tested by viability assay, flow cytometry, TUNEL (terminal deoxynucleotidyl transferase-mediated fluorescein-dUTP nick-end labeling) assay, Western blot analysis, and reverse transcription–polymerase chain reaction in cultured eye tumor cells and normal cells. Preclinical studies were performed in a rabbit xenograft model of retinoblastoma.

Main Outcome Measures: Cell survival, apoptosis, gene expression, and tumor regression.

Results: The anti–Bcl-2 peptide induced apoptosis in tumor cells, but it also caused apoptosis in normal cells in culture and induced retinal damage after intravitreal injection. In contrast, the anti-HDM2 peptide induced rapid accumulation of p53, activation of apoptotic genes, preferential killing of tumor cells, and minimal retinal damage after intravitreal injection. The anti-HDM2 peptide also induced regression of human retinoblastoma cells in rabbit eyes.

Conclusions: Peptide transduction is a promising new approach to molecular eye cancer therapy. Inhibition of HDM2 can selectively activate p53 in transformed cells and may be an effective strategy for inducing apoptosis in eye cancer cells with minimal damage to normal ocular tissues.

Clinical Relevance: Molecular characteristics of uveal melanoma and retinoblastoma may be used to design novel therapeutic agents that have greater specificity and fewer adverse effects than current therapies.

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Uveal melanoma and retinoblastoma are the most common primary intraocular cancers in adults and children, respectively. Current treatments for eye cancer, such as radiation and chemotherapy, are effective in many patients. However, the mechanisms of action of these modalities are nonspecific, leading to substantial injury to normal tissues and consequent dose-limiting complications. Molecular therapy may reduce the complications of conventional therapies by antagonizing specific molecules in cancer cells and selectively killing tumor cells with less damage to normal cells.

Several oncoproteins have been identified as potential targets for therapeutic inhibition, including HDM2 and Bcl-2. HDM2 inhibits p53 and maintains it at very low levels in normal cells. However, some cancers, such as uveal melanoma, seem to functionally inhibit p53 by overexpressing HDM2. Because p53 is rarely mutated in uveal melanoma, inhibition of HDM2 may trigger apoptosis in uveal melanoma cells by releasing the endogenous, wild-type p53 from its negative interaction with HDM2. Bcl-2 blocks apoptosis by inhibiting pro-apoptotic proteins such as Bax. Bcl-2 is overexpressed in most uveal melanomas and is the most consistently observed molecular abnormality in this eye cancer. Thus, inhibition of Bcl-2 may liberate pro-apoptotic proteins and allow them to trigger apoptosis in uveal melanoma cells.

Although HDM2 and Bcl-2 have not been adequately studied in retinoblastoma, inhibition of these proteins may also be effective in this pediatric eye cancer, which usually expresses wild-type p53 and is susceptible to apoptosis.

Transducible peptides represent a promising new technology for efficiently delivering designer therapeutic molecules into cells. Transducible peptides contain a therapeutic domain linked to a transduction domain that allows the...
chimeric peptide directly to traverse, or “transduce,” cell membranes independent of cell surface receptors or other transport molecules.13 Eye cancers provide an attractive model for testing transducible peptides because therapeutic agents can be delivered locally to the tumor using standard ophthalmic techniques. In this article, we present preliminary studies to examine transducible peptide inhibitors of HDM2 and Bcl-2 in cultured eye tumor cells and in a rabbit model of retinoblastoma.

METHODS

CULTURED CELLS

Primary uveal melanoma cells (MM-23, MM-24, and MM-26) were obtained from 3 patients and established in short-term culture (cells used after ≤3 passages). Cultures of normal choroidal fibroblasts and melanocytes (MM-23N and MM-26N) were obtained from 2 of these patients. Y79 and WER1-RB1 retinoblastoma cells, U2OS osteosarcoma cells, and C33A cervical carcinoma cells were obtained from American Type Culture Collection (Manassas, Va). Adult human diploid fibroblasts and mouse embryonic fibroblasts were obtained from BioWhittaker Inc (Walkersville, Md). Cells were maintained in Dulbecco Modified Eagle Medium with 0.1% or 10% fetal calf serum (as indicated) at 37°C in 5% CO₂.

IMMUNOHISTOCHEMICAL ANALYSIS

Immunohistochemical analysis was performed as previously described.3 Briefly, we used the streptavidin-biotin method with the Vector ABC Elite kit (Vector Laboratories Inc, Burlington, Calif) and nuclear fast red for counterstain. Four-micron sections of paraffin-embedded primary tumor tissue (MM-23, MM-24, and MM-26) or cytopsin of 105 cultured cells (U2OS, Y79, and WERI) were deparaffinized, rehydrated with alcohol, and treated with 0.3% hydrogen peroxide. Heat-induced antigen retrieval was performed. Antibodies against HDM2 (NCI-MDM2; Novocastra Laboratories Ltd, Newcastle, England), 1:30 dilution; p53 (clone 1801; Biogenics, Napa, Calif), 1:80 dilution; and Bcl-2 (Dako, Glostrup, Denmark), 1:500 dilution, were applied at 4°C overnight. The percentage of positive cells for each antibody was estimated by counting at least 200 cells in at least 8 fields with magnification ×40 for each specimen.

PEPTIDES

Transducible peptides were generated by linking the Tat transduction sequence YGRKKRRQRRRGG to the amino-terminus of the following peptides: Tat-tHDM2 (a 12-amino acid peptide derived from the p53 sequence that mediates binding to HDM2), Tat-tHDM2-ala (a 12-amino acid control mutant of the HDM2 binding peptide in which the residues required for binding to HDM2, corresponding to Phe-19 and Trp-23 in p53, are converted to alanine), Tat-tBcl2 (a 19-amino acid peptide derived from the BH3 domain of the protein Bad, which binds and inhibits the anti-apoptotic proteins Bcl-2 and Bcl-xL), Tat-scrambled (an 8-amino acid control peptide with a randomly scrambled sequence), and tBcl2 (the Bcl-2 binding peptide without Tat), and Tat alone. Peptides were synthesized (John Gorka, PhD, Biomolecules Midwest, Inc, St Louis, Mo) using an ABI 431 synthesizer and eluted with 0.1N acetic acid. Amino acid content and purity greater than 90% were confirmed by mass spectrometry. Peptides were solubilized in sterile water and analyzed at a range of 50 to 300µM. The optimal ratio of tumor cell–normal cell killing was observed at 200µM, so most subsequent studies were performed at this concentration.

CELL STUDIES

Cell survival was measured by MTS assay (Promega Inc, Madison, Wis). Cells were seeded onto 96-well plates at 10⁴ cells/well in Dulbecco Modified Eagle Medium with 10% fetal calf serum. Peptides were added to the media the next day, and spectrophotometric assay was performed 24 hours later. TUNEL (terminal deoxynucleotidyl transferase–mediated fluorescein-dUTP nick-end labeling) assay was performed 8 hours after addition of the indicated peptides using the Apoptag kit (Intergen Inc, Purchase, NY). The broad-spectrum caspase inhibitor Z-Va-Ala-Asp(OCH3)-fluoromethylketone (BIOMOL Research Laboratories Inc, Plymouth Meeting, Pa) was added to MTS plates as indicated. For Western blot analysis and reverse transcription–polymerase chain reaction (RT-PCR), cells were obtained at various points after the addition of 200µM Tat-tHDM2, lysates were obtained, and protein concentration was normalized. Western blot analyses were performed using a polyclonal p53 antibody (sc-6243; Santa Cruz Biotechnology Inc, Santa Cruz, Calif), dilution 1:500, and a polyclonal p73 antibody (sc-7957; Santa Cruz Biotechnology), 1:500 dilution. For semiquantitative RT-PCR, total RNA was obtained using the RNaseasy kit (Qiagen, Valencia, Calif). Reverse transcription was performed in 20 µL of RNase-free water containing 5mM magnesium chloride, 10mM Tris-hydrochloride (pH 8.8), 50mM potassium chloride, 0.1% Triton X-100, 1mM dNTP, 20 U of rRNA inhibitor, 15 U of AMV reverse transcriptase (Promega Inc), and 0.5 µg oligo(dT)15 nucleotide primers at 42°C for 60 minutes, 99°C for 5 minutes, and then 5°C for 5 minutes. For PCR, 5 µL of the reverse transcription product was added to a 25-µL mixture containing primers for p21, Bax, P23, or GAPDH, and 2.5 µL of Taq polymerase in standard PCR buffer (GIBCO BRL, Grand Island, NY). Reaction cycles (n=20-25) and temperatures varied for each gene (details and primer sequences are available from the authors on request).

ANIMAL EXPERIMENTS

New Zealand White rabbits (2-4 kg) were used. For toxicity studies, peptides were injected into the vitreous cavity, and eyes were obtained 48 hours later for histopathologic examination. To create intraocular tumors, 10⁴ WERI cells were injected into the right anterior chambers of animals immunosuppressed with cyclosporine (15 mg/kg per day). Tumors were observed daily by visual inspection of the anterior chamber, and they were observed to implant and begin growing within 1 to 2 weeks. Peptides were dissolved in sterile water and injected into the anterior chambers at an estimated intraocular concentration of 200µM. Two injections were administered over 3 days, and animals were humanely killed 48 hours later. Eyes were embedded in paraffin, stained with hematoxylin-eosin, or analyzed for apoptosis using the Apoptag TUNEL kit. Tumor destruction was quantified by projecting histopathologic sections and scoring areas of viable and apoptotic tumor. Studies conformed to the animal studies committee protocol of Washington University.

RESULTS

Amino acid sequences for peptides used in this study are listed in Table 1. The immunohistochemical expression of p53, HDM2, and Bcl-2 for each tumor sample is...
summarized in Table 2. Transducible peptides tagged with fluorescein were shown to enter approximately 100% of cells and cell nuclei within 1 to 2 minutes of addition to culture media (data not shown), as previously described.\textsuperscript{15}

**INHIBITION OF Bcl-2**

Tat-αBcl2 efficiently induced cell death in MM-23, MM-24, MM-26, Y79, WERI, and U2OS cells (Figure 1 and Figure 2A). However, Tat-αBcl2 also induced variable levels of cell death in normal primary choroidal cells (MM-23N and MM-26N), mouse embryonic fibroblasts, and normal human diploid fibroblasts (Figure 2A). Intravitreal injection of Tat-αBcl2 in normal rabbit eyes (approximate intraocular concentration, 100µM) caused mild to moderate disruption of retinal cells, especially in the inner nuclear layer (Figure 2B). Approximately 75% of the apoptosis induced by Tat-αBcl2 was blocked by the caspase inhibitor Z-Val-Ala-Asp(OCH\textsubscript{3})-fluoromethylketone (Figure 3A).

**INHIBITION OF HDM2**

Tat-αHDM2 efficiently killed MM-23, MM-24, MM-26, Y79, WERI, U2OS, and C33A cells (Figures 1 and 2A). Tat-αHDM2 induced positive TUNEL staining in tumor cells consistent with apoptosis (Figure 3B). At concentrations that induced apoptosis in tumor cells, Tat-αHDM2 had little effect on normal cells (Figure 2A and Figure 4). Intravitreal injection of Tat-αHDM2 in normal rabbit eyes (approximate intraocular concentration, 200µM) induced minimal histologic damage to the

**Table 1. Peptides Used in This Study**

<table>
<thead>
<tr>
<th>Peptide Name</th>
<th>Peptide Sequence</th>
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<tbody>
<tr>
<td>Tat</td>
<td>YGRKKRRQRRRG</td>
</tr>
<tr>
<td>Tat-αHDM2</td>
<td>YGRKKRRQRRRG-QETFSDLWKLLP</td>
</tr>
<tr>
<td>Tat-αHDM2-ala</td>
<td>YGRKKRRQRRRG-QETSDLAKLLP</td>
</tr>
<tr>
<td>Tat-αBcl2</td>
<td>YGRKKRRQRRRG-MGQVGRQLAIIGDDINRRY</td>
</tr>
<tr>
<td>αBcl2</td>
<td>MGQVGRQLAIIGDDINRRY</td>
</tr>
<tr>
<td>Tat-scrambled</td>
<td>YGRKKRRQRRRG-KRLALDPV</td>
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</tbody>
</table>

**Table 2. Immunohistochemical Expression Profile of Tumors in This Study**

<table>
<thead>
<tr>
<th>Tumor</th>
<th>p53\textsuperscript{*}</th>
<th>HDM2</th>
<th>Bcl-2</th>
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<tr>
<td>MM-23</td>
<td>0.2</td>
<td>79</td>
<td>99</td>
</tr>
<tr>
<td>MM-23</td>
<td>0.3</td>
<td>81</td>
<td>99</td>
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<tr>
<td>MM-26</td>
<td>0.3</td>
<td>85</td>
<td>99</td>
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<tr>
<td>U2OS</td>
<td>3.0</td>
<td>93</td>
<td>2</td>
</tr>
<tr>
<td>Y79</td>
<td>6.0</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>WERI</td>
<td>4.0</td>
<td>2</td>
<td>18</td>
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\textsuperscript{*}Low p53 expression (<20%) suggests absence of mutation.

**Figure 1.** Representative 24-hour survival curves measured by MTS assay (Promega Inc, Madison, Wis) (in triplicate) in MM-23 uveal melanoma cells, WERI retinoblastoma cells, U2OS osteosarcoma cells, and C33A cervical carcinoma cells after treatment with the indicated peptides. Error bars represent SEMs.

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retina and other ocular tissues (Figure 2B). Treatment of cells with Z-Val-Ala-Asp(OCH$_3$)-fluoromethylketone blocked approximately 65% of the apoptosis induced by Tat-αHDM2 (Figure 3A). In U2OS cells, which express low levels of wild-type p53 due to overexpression of HDM2, Tat-αHDM2 caused a rapid increase in p53 protein levels, which remained high for 6 hours after treatment. Tat-αHDM2 also caused an increase in p73 protein levels (Figure 3C). By semiquantitative RT-PCR, Tat-αHDM2 activated the p53 target genes p21, Pig3, and Bax, which reached peak protein levels 4 to 6 hours after treatment (Figure 3C).

An animal model of intraocular retinoblastoma was created by injecting $10^7$ WERI human retinoblastoma cells into the anterior chambers of rabbit eyes and allowing the tumors to implant and grow (Figure 5A). After injection of Tat-αHDM2 (approximate intraocular concentration, 200µM), tumors began to dissolve into a fine cloud within 24 hours. In contrast, tumors treated with the Tat-scrambled control peptide remained unchanged from their pretreatment appearance. Peptides were injected again 24 hours later, and the eyes were obtained. By histopathologic examination, Tat-αHDM2 caused extensive tumor destruction, with a 76% reduction in viable tumor mass compared with tumors treated with the control peptide (Figure 5B-E). A much larger proportion of tumor cells were positive for TUNEL staining in eyes treated with Tat-αHDM2 compared with eyes treated with the control peptide (Figure 5F and G). No histologic damage to the cornea, lens, retina, or other ocular tissues was detected.

**COMMENT**

In this study, we tested transducible peptides that inhibit HDM2 and Bcl-2 for their ability to induce tumor-specific apoptosis in uveal melanoma and retinoblastoma cells. An anti-Bcl-2 peptide induced apoptosis in tumor cells but also caused variable levels of toxicity in normal cells and tissues. In contrast, an anti-HDM2 peptide induced apoptosis in tumor cells, with little effect on normal cells in a therapeutic dose range. This peptide also caused regression of retinoblastoma in rabbit eyes, with minimal damage to normal ocular tissues. We conclude that inhibition of HDM2...
may be a promising strategy for the treatment of uveal melanoma and retinoblastoma and that transducible peptides may be an effective technology for local delivery of anticancer therapy to the eye.

Since Bcl-2 is frequently overexpressed in uveal melanomas and is thought to protect tumor cells from cell death, we tested whether inhibition of Bcl-2 might lead to apoptosis in uveal melanoma cells. For these experiments, we generated the peptide Tat-αBcl2, which is derived from the BH3 domain of the pro-apoptotic protein Bad, which has been shown to bind and inhibit the anti-apoptotic proteins Bcl-2 and Bcl-XL. Tat-αBcl2 efficiently induced apoptosis in each of the uveal melanoma cell lines, which were all derived from tumors that overexpressed Bcl-2 (Table 2). This peptide induced apoptosis that was largely caspase dependent, consistent with activation of the Bcl-2 mitochondrial apoptotic pathway. Tat-αBcl2 also killed U2OS osteosarcoma cells and Y79 and WERI retinoblastoma cells, although Bcl-2 was not overexpressed in these cells (Table 2). In addition, the peptide had a moderate cytotoxic effect on normal cells, suggesting that inhibition of Bcl-2 may trigger apoptosis in a broad spectrum of cells by destabilizing the delicate balance between pro-apoptotic and anti-apoptotic proteins in the Bcl-2 pathway. Activation of this pathway, which is downstream of the p53 tumor suppressor checkpoint, may then lead to generalized activation of the apoptotic program. Therefore, the anti–Bcl-2 peptide did not demonstrate a significant therapeutic window and was not studied further.

HDM2 binds and inhibits p53, maintaining it at low concentrations in normal cells. In cells that sustain oncogenic mutations, the HDM2-p53 interaction is disrupted, allowing p53 to accumulate, become activated, and induce growth arrest or apoptosis. Therefore, most tumors develop strategies for circumventing this tumor suppressor checkpoint, such as by mutating p53 or overexpressing HDM2. Because HDM2 is strongly expressed in most uveal melanomas and may serve to func-

Figure 4. Cultured normal primary choroidal cells (MM-23N) (A) and low-passage uveal melanoma cells (MM-23) (B) from the same patient. Treatment of cells with 200µM Tat-αHDM2 for 8 hours resulted in minimal change in the normal cells (C) and extensive death of melanoma cells, with nuclear blebbing and fragmentation consistent with apoptosis (arrow) (D) (hematoxylin-eosin, original magnification ×40).

Figure 5. Effect of Tat-αHDM2 peptide in a rabbit xenograft model of human retinoblastoma. A, Rabbit eye 2 weeks after injection of 10⁷ WERI retinoblastoma cells into the anterior chamber demonstrating implantation and growth. B and C, Low-power composite photomicrographs of intraocular tumors stained with hematoxylin-eosin after treatment with Tat-scrambled or Tat-αHDM2, respectively. Ir Indicates iris; co, cornea. D and E, High-power photomicrographs of the same tumors stained with hematoxylin-eosin after treatment with Tat-scrambled or Tat-αHDM2, respectively. Viable cells are blue, and nonviable cells are pink. F and G, TUNEL (terminal deoxynucleotidyl transferase-mediated fluorescein-dUTP nick-end labeling) staining of tumor cells treated with Tat-scrambled or Tat-αHDM2 (brown staining is positive for TUNEL assay) (original magnification ×40, respectively).
tionally inactivate p53, and we became interested in HDM2 as a potential therapeutic target. We hypothesized that a peptide that blocks HDM2 may liberate p53, which may then become activated in response to the oncogenic changes in cancer cells but may remain inactive in normal cells. For these experiments, we developed a novel peptide, Tat-αHDM2, which contains the Tat transduction domain linked to a sequence from p53 that contains the binding site for HDM2. A similar peptide has been shown to competitively inhibit the binding of HDM2 to p53 and to trigger the accumulation of activated p53.

For the initial studies, we used U2OS osteosarcoma cells because they overexpress HDM2 and express wild-type p53 (similar to uveal melanomas), and they are more practical to work with in culture. As expected, Tat-αHDM2 caused a rapid increase in p53 protein levels and activation of p53 target genes involved in cell cycle arrest and apoptosis (eg, p21, Bax, and PIG3). These molecular changes were accompanied by apoptosis in U2OS cells and in all 3 uveal melanomas that were tested. Tat-αHDM2 was also effective against Y79 and WERI retinoblastoma cells, which express wild-type p53 but do not overexpress HDM2 (Table 2), suggesting that HDM2 overexpression is not a requirement for this peptide to be effective. Tat-αHDM2 also killed C3A cells, which express a mutant form of p53, suggesting that expression of wild-type p53 may also not be a requirement for this peptide to be effective. This observation may be because Tat-αHDM2 also induces the accumulation of p73, a member of the p53 family that binds HDM2 and can mediate p53-independent apoptosis.

Tat-αHDM2 may also stabilize mutant p53, as has been observed with other peptide fragments of p53. These findings, along with the observation that Tat-αHDM2 triggers caspase-dependent and caspase-independent apoptotic mechanisms (Figure 4A), suggest that Tat-αHDM2 may have multiple mechanisms of action. Tat-αHDM2 caused minimal damage to normal cells, and injection of the peptide into the vitreous cavity of rabbit eyes did not result in histologic damage to the retina or other ocular tissues. The selective killing of tumor cells by p53 may be due to the unique ability of p53 to become activated in tumor cells to a greater extent than in normal cells.

Because Tat-αHDM2 showed the most specificity for tumor cells in cultured cells, we further tested this peptide in a rabbit xenograft model of retinoblastoma. Tat-αHDM2 caused tumor dissolution and apoptosis of tumor cells without significant damage to normal ocular tissues. In these preliminary studies, the peptide was delivered directly into the anterior chamber, but we would not anticipate intraocular injection in patients with eye cancer owing to concern about tumor dissemination. Instead, it may be possible to deliver transducible peptides by topical, subconjunctival, retrobulbar, or systemic routes because these peptides have been shown to rapidly cross cell membranes, diffuse through tissues, and cross the bloodbrain barrier. Because transducible peptides function independently of transport proteins, they may also be helpful in overcoming multidrug resistance in retinoblastoma resulting from overexpression of P-glycoprotein. These studies provide an initial framework for future studies to determine appropriate molecular targets, optimal routes of administration, and indications for and limitations of transducible peptide therapy for eye cancers.

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REFERENCES