MUC1 oncoprotein is a druggable target in human prostate cancer cells

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Abstract

Human prostate cancers are dependent on the androgen receptor for their progression. The MUC1 heterodimeric oncoprotein is aberrantly overexpressed in prostate cancers; however, it is not known if MUC1 is of functional importance to these tumors. To assess dependence on MUC1, we synthesized an inhibitor, designated GO-201, which interacts directly with the MUC1-C subunit at its oligomerization domain. Treatment of MUC1-positive DU145 and PC3 prostate cancer cells with GO-201, and not an altered version, resulted in inhibition of proliferation. GO-201 also induced necrotic cell death that was associated with increases in reactive oxygen species, loss of mitochondrial transmembrane potential, and depletion of ATP. By contrast, GO-201 had no effect against MUC1-negative LNCaP, CWR22Rv1, and MDA-PCa-2b prostate cancer cells. Significantly, GO-201 treatment of DU145 and PC3 xenografts growing in nude mice resulted in complete tumor regression and prolonged lack of recurrence. These findings indicate that certain prostate cancer cells are dependent on MUC1-C for growth and survival and that directly targeting MUC1-C results in their death in vitro and in tumor models. [Mol Cancer Ther 2009;8(11):3056–65]

Introduction

The mucin 1 (MUC1) oncoprotein is aberrantly expressed at high levels in human carcinomas (1) and has become an attractive target for the development of anticancer agents. However, there have been no available small molecules to date that directly target MUC1. In this regard, MUC1 is heterodimer that consists of NH2-terminal (MUC1-N) and COOH-terminal (MUC1-C) subunits (2), and much of the early work focused on MUC1-N, the mucin component. Importantly, however, the transmembrane MUC1-C includes a cytoplasmic domain that is sufficient for transformation (3, 4). Moreover, MUC1-C interacts with diverse effectors, such as the epidermal growth factor receptor (5, 6), β-catenin (7), p53 (8), IκB kinase β (9), and NF-κB p65 (10), which have been linked to transformation. MUC1-C contains a CQC motif in the cytoplasmic domain that is necessary for its oligomerization and thereby targeting of MUC1-C to the nucleus (11). MUC1-C is also targeted to the mitochondrial outer membrane in a complex with heat shock protein 70/90 that is dependent on formation of MUC1-C oligomers (12–14). Integration of MUC1-C in the mitochondrial outer membrane blocks stress-induced loss of the mitochondrial transmembrane potential (ΔΨm; ref. 12). Consistent with this effect, overexpression of MUC1 as found in human carcinomas blocks the induction of apoptosis and necrosis in the cellular response to DNA-damaging agents (12), reactive oxygen species (ROS; refs. 15, 16), hypoxia (17), and glucose deprivation (18). Based on these observations, a direct inhibitor of MUC1-C oligomerization was found to induce death of human breast cancer cells growing in vitro and as tumor xenografts (19).

MUC1 is overexpressed in ~60% of primary prostate cancers and 90% of lymph node metastases (20, 21). In addition, 86% of MUC1-positive primary prostate tumors were Gleason grade ≥7, supporting an association with more aggressive disease (20). Gene expression profiling of human prostate cancers has also shown that MUC1 is highly expressed in subgroups with aggressive clinicopathologic features and an elevated risk of recurrence (22). Notably, however, there are no reports that MUC1 contributes to the malignant phenotype of prostate cancer cells. Indeed, prostate cancer cells are dependent on androgen receptor (AR) signaling for growth and survival (23). Moreover, progression of prostate cancer, despite treatment to abrogate androgen action, occurs as a result of continued AR activation by mechanisms that include AR gene amplification and mutations (23–25). Production of AR ligands by prostate cancer cells (26), alterations in AR coactivators and repressors (27), and interactions with other signaling pathways (28) have also been associated with progression of prostate cancer to castrate-resistant disease. The importance of AR signaling for growth of androgen-insensitive prostate cancer cells has been further supported by the targeting of AR function in in vitro and animal tumor models (29, 30). These findings have provided the experimental basis for the development of new agents that inhibit AR function (31–33).
Aberrant AR regulation has also been linked to activation of Wnt/β-catenin (34) and NF-κB (35, 36); however, the effects of targeting these pathways on prostate cancer growth and survival are not known.

The present studies show that GO-201, an inhibitor of MUC1-C oligomerization, induces death of MUC1-positive, but not MUC1-negative, human prostate cancer cells in vitro. The results also show GO-201 is highly effective in the treatment of human prostate cancer xenografts in nude mice.

**Materials and Methods**

**Cell Culture**

Human LNCaP, DU145, PC3, and CWR22Rv1 prostate cancer cells (American Type Culture Collection) were grown in RPMI 1640 containing 10% heat-inactivated fetal bovine serum, 100 μg/mL streptomycin, 100 units/mL penicillin, and 2 mmol/L L-glutamine. MDA-PCa-2b prostate cancer cells (American Type Culture Collection) were grown in Ham’s modified F12-K medium according to the American Type Culture Collection guidelines. PC3/Neo and PC3/AR cells were...
Addiction to MUC1 in Prostate Cancer

provided by Dr. Mien-Chie Hung (M. D. Anderson Cancer Center). The stably transfected PC3 cells were grown in the presence of 400 μg/mL G418. Cells were treated with the GO-201 or CP-1 peptides (AnaSpec) as described (19). These peptides contain 24 amino acids (Fig. 2A) and were dissolved in PBS before use. Viability was determined by trypan blue exclusion.

**Immunoblot Analysis**

Whole-cell and nuclear lysates were prepared as described (11). Soluble proteins were analyzed by immunoblotting with anti-MUC1-C (Ab5; Neomarkers), anti-AR (H-280; Santa Cruz Biotechnology), anti-β-actin (Sigma), and anti-lamin B (EMD). Reactivity was detected with horseradish peroxidase–conjugated second antibodies and chemiluminescence.

**Analysis of Cell Cycle Distribution and Cell Membrane Integrity**

Cells were fixed with 80% ethanol and incubated in PBS containing 40 μg/mL RNase and 40 μg/mL propidium iodide. Cell cycle distribution and sub-G1 DNA content was determined by flow cytometry. For assessment of cell membrane integrity, cells were incubated with 1 μg/mL propidium iodide/PBS and then monitored by flow cytometry as described (17, 37).

**Measurement of ROS Levels**

Cells were incubated with 5 μmol/L DCFH-DA (Molecular Probes) for 20 min at 37°C. Fluorescence of oxidized DCF was measured at an excitation wavelength of 480 nm and an emission wavelength of 525 nm.

**Analysis of ΔΨm**

Cells were incubated with 50 ng/mL rhodamine 123 (Molecular Probes) in PBS for 30 min at 37°C and then monitored by flow cytometry.

**Measurement of ATP Levels**

ATP levels were measured using an ATP determination kit (Sigma).

**Prostate Tumor Xenograft Models**

BALB/c nu/nu male mice (Charles River Laboratories), 4 to 6 weeks old weighing 18 to 22 g, were injected with...
GO-201 induces cell cycle arrest and death. A and B, DU145 cells were left untreated and treated with 5 μmol/L GO-201 or CP-1 each day for 3 and 4 d. Cells were fixed and analyzed for cell cycle distribution by flow cytometry (A). The percentage of cells in S phase is included in the panels. Cells were stained with propidium iodide and analyzed by flow cytometry (B). The percentage of cells with loss of cell membrane integrity is included in the panels.
1 × 10^7 DU145 or PC3 cells s.c. in the flank. When tumors were detectable, the mice were pair-matched into control and treatment groups. Each group contained 6 to 10 mice, each of which was ear-tagged and followed throughout the study. PBS (vehicle), GO-201, and CP-1 were administered daily by i.p. injection. Mice were weighed twice weekly. Tumor measurements were done with calipers. Tumor volume \( V \) was calculated using the formula: 
\[
V = \frac{L^2 \times W}{2},
\]
where \( L \) and \( W \) are the larger and smaller diameters, respectively. Tumors and sites of tumor implantation were evaluated by H&E staining.

**Results**

**Expression of MUC1-C in Human Prostate Cancer Cell Lines**

To identify models for targeting MUC1-C function in prostate cancer cells, we first assessed levels of MUC1-C expression. Immunoblot analysis of androgen-dependent, AR-positive LNCaP cells showed undetectable MUC1-C expression (Fig. 1A). By contrast, MUC1-C was detectable at high levels in DU145 cells and, to a lower extent, in PC3 cells, both of which are androgen-independent and have low to undetectable AR expression compared with LNCaP cells (Fig. 1A). CWR22Rv1 prostate cancer cells express a mutant AR, proliferate in the absence of androgens, and are responsive to androgens (38). MDA-PCa-2b cells also express AR and are sensitive to androgens (39). Compared with DU145 cells, MUC1-C expression was low to undetectable in both CWR22Rv1 and MDA-PCa-2b cells (Fig. 1B). PC3 cells have been stably transfected with an empty vector or one expressing the human AR coding region (40). AR expression in the PC3 cells confers androgen responsiveness (40). Immunoblot analysis of the PC3/AR cells showed suppression of MUC1-C levels (Fig. 1C). These prostate cancer cells without and with MUC1 expression thus represented models for assessing the selective targeting of MUC1-C function.

**GO-201 Blocks Localization of MUC1-C to the Nucleus**

MUC1-C forms oligomers through a CQC motif in the cytoplasmic domain (Fig. 2A) and oligomerization is necessary for MUC1-C nuclear transport (11). To block nuclear targeting of MUC1-C, we synthesized a peptide, designated GO-201, containing the CQC motif and a similar control peptide (CP-1) in which CQC was changed to AQA (Fig. 2A). A poly-d-arginine protein transduction domain was included in both peptides to enhance their entry into cells (41). As determined by BIACore analysis, GO-201 and not CP-1 binds to the MUC1-CD oligomerization domain with a dissociation

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**Figure 4. Continued.** C, PC3 cells were left untreated and treated with 5 μmol/L GO-201 or CP-1 each day for 4 d. Cells were fixed and analyzed for cell cycle distribution by flow cytometry. The percentage of cells in S phase is included in the panels. D, PC3 cells were left untreated and treated with 5 μmol/L GO-201 or CP-1 each day for 10 d. Cells were stained with propidium iodide and analyzed by flow cytometry. The percentage of cells with loss of cell membrane integrity is included in the panels.
constant of 30 nmol/L, which is comparable with that for
dimers of the full-length protein (11, 19). To assess effects
on nuclear targeting of MUC1-C, DU145 cells were treated
with 5 μmol/L GO-201 or CP-1. There was no apparent ef-
fect of either agent on MUC1-C levels in whole-cell lysates
(Fig. 2B, left). However, treatment with GO-201, but not
CP-1, was associated with a decrease in nuclear MUC1-C
levels (Fig. 2B, right). Similar effects of GO-201 were found
when treating PC3 cells (Fig. 2C). These findings indicated
that GO-201 is effective in targeting MUC1 function in
DU145 and PC3 prostate cancer cells.

**GO-201 Is a Selective Inhibitor of MUC1-Positive
Prostate Cancer Cell Growth**

Treatment of DU145 cells with GO-201, but not CP-1, was
associated with an initial slowing of growth and then a de-
cline in cell number (Fig. 3A). By contrast, GO-201 had no
apparent effect on growth of the MUC1-negative LNCaP
cells (Fig. 3B). Treatment of PC3 cells with GO-201 also
resulted in a slowing of growth and then decline in cell num-
ber, a response similar to that in DU145 cells but kinetically
less rapid (Fig. 3C, left). Notably, downregulation of MUC1
as found in PC3/AR cells attenuated the growth-inhibitory
effects of GO-201 compared with that in PC3 cells (Fig. 3C,
right). Moreover, GO-201 had little, if any, effect on growth
of the MUC1-negative CWR22Rv1 and MDA-PCa-2b cells
(Fig. 3D). These results show that the growth-inhibitory ef-
facts of GO-201 are selective for MUC1-positive prostate
cancer cells.

**GO-201 Induces Death of DU145 and PC3 Cells**

To further define the effects of GO-201, DU145 cells
were treated with GO-201 for 3 days and monitored for
cell cycle distribution. GO-201 treatment, but not a similar
exposure to CP-1, was associated with an accumulation of
cells in S phase, consistent with the growth-inhibitory ef-
facts (Fig. 4A). GO-201 treatment was also associated with
the appearance of cells with substantial DNA degradation
(Fig. 4A). Similar results were obtained on day 4 of treat-
ment (Fig. 4A). In addition, treatment with GO-201, and not
CP-1, was associated with uptake of propidium iodide, con-
sistent with loss of cell membrane integrity, on days 3 and
4 (Fig. 4B). PC3 cells similarly responded to GO-201 with
arrest in S phase (Fig. 4C) and loss of cell membrane integrity
(Fig. 4D; Supplementary Fig. S1), although this effect was
delayed compared with that in DU145 cells.

**GO-201 Disrupts Redox Balance and Mitochondrial
Function**

Previous work has shown that MUC1 suppresses disrup-
tion of redox balance and that silencing MUC1 is associated
with increases in ROS (15–18). To define the basis for GO-
201–induced death, cells were thus monitored for changes
in ROS levels. Treatment of DU145 cells with GO-201, but
not CP-1, was associated with over a 2-fold increase in
ROS (Fig. 5A and B). Disruption of redox balance con-
btributes to loss of ΔΨm and depletion of ATP (42, 43). As
determined by rhodamine 123 uptake, GO-201 treatment of
DU145 cells resulted in ~50% decrease in ΔΨm (Fig. 5C
and D, left). Increases in ROS and loss of ΔΨm were also
observed in the response of PC3 cells to GO-201 (Supplemen-
tary Fig. S2A-D, left). Moreover, the demonstration that GO-
201 treatment is associated with decreases in ATP levels
(Fig. 5D, right; Supplementary Fig. S2D, right) indicated that
the extensive DNA degradation and loss of cell membrane
integrity are associated with induction of a necrotic death
response (37, 44).

**GO-201 Induces Complete Regressions of DU145 and
PC3 Tumors**

To assess antitumor activity, DU145 tumor xenografts
(~225 mm3) were established in the flanks of nude mice. Ad-
ministration of GO-201 at 30 mg/kg/d × 21 days slowed
growth compared with that obtained with vehicle (PBS),
whereas CP-1 also given at 30 mg/kg/d × 21 days had no ap-
parent effect (Fig. 6A, left). Histopathology of GO-201-treated
DU145 tumors harvested on day 21 showed a predominance
of cells with pyknotic nuclei and decreased cytoplasm
(Fig. 6A, right).

To assess the long-term effects of targeting MUC1-C, addi-
tional groups of 10 mice bearing DU145 tumors were treated
with GO-201 and followed for longer periods. Dosing of GO-
201 at 30 mg/kg/d × 21 days and on a different schedule at
30 mg/kg/d × 5 days/wk for 3 weeks was associated with an
initial cessation of tumor growth and then a progressive de-
crease in volume (Fig. 6B, left). Notably, the tumors were no
longer palpable by day 40 (Fig. 6B, right). On day 42, one mouse
from each group was sacrificed to assess the tumor implanta-
tion site. There was no visual evidence for remaining tumor
or extension to other organs. Histologic examination of the tu-
mor implantation sites for both GO-201 treatment groups fur-
ther indicated that there were no remaining tumor cells
(Fig. 6B, right; data not shown). The remaining mice in both
GO-201 treatment groups are being followed; as of week 29,
there has been no evidence for reappearance of tumors.

Treatment of PC3 tumors (~200 mm3) with GO-201 at 30
mg/kg/d × 21 days or 30 mg/kg/d × 5 days each week
for 3 weeks had little effect on growth (Fig. 6C, left). Con-
sequently, treatment was continued for an additional week,
and at the end of dosing, there was evidence of growth in-
hibition for both dose schedules (Fig. 6C, left). Analysis of
PC3 tumors on day 28 showed loss of tumor architecture
and decreased abundance of tumor cells compared with
that for control and CP-1–treated tumors (Fig. 6C, right).
Importantly, and despite having discontinued dosing, tumor
regression continued through day 43, at which point tumors
that had been treated with both dose schedules were no lon-
ger palpable. As of week 18, there has been no evidence for
recurrence of the GO-201–treated tumors.

**Discussion**

**GO-201 Selectively Blocks Growth of MUC1-Positive
Prostate Cancer Cells**

MUC1 is overexpressed in primary prostate cancers and
predominantly in those with more aggressive disease
(20–22, 45, 46). However, there has been no direct evidence
that MUC1 is of importance to prostate cancer cell growth
and survival. In the present studies, an inhibitor of MUC1-C,
designated GO-201 (19), was used to assess MUC1 dependence
of prostate cancer cells. The MUC1-C transforming function is dependent on the formation of oligomers that are mediated by a CQC motif in the cytoplasmic domain (4, 11, 19). The present results show that treatment of MUC1-positive DU145 and PC3 cells with GO-201, a direct inhibitor of MUC1 oligomerization (19), is initially associated with inhibition of growth. The antiproliferative effects of GO-201 were more pronounced for DU145 cells, which express higher levels of MUC1-C compared with PC3 cells. By contrast, GO-201 had no effect on growth of MUC1-negative LNCaP, CWR22Rv1, or MDA-PCa-2b prostate cancer cells. The selectivity of GO-201 was further supported by the absence of an effect on PC3/AR cells, which were found to have downregulation of MUC1 expression and served as an additional control. Decoy peptides derived from the MUC1-C cytoplasmic domain have been used to block interactions between MUC1-C and certain binding partners, such as β-catenin (7, 47, 48). In this regard, recent studies have shown that the PMIP peptide slows proliferation of human breast cancer cells (48). Unlike decoy peptides, GO-201 binds to the MUC1-C CQC motif and thereby directly blocks MUC1 function. Indeed, the control CP-1, which has an AQA motif, does not bind to MUC1-C and had no effect on growth of MUC1-positive prostate cancer cells.

Inhibiting MUC1-C Induces Complete Regression of MUC1-Positive Prostate Tumors in Xenograft Models

Redox balance is regulated by MUC1-dependent signaling (15–18). In this context, targeting MUC1-C function

Figure 5. GO-201 increases ROS and induces loss of ΔΨm and depletion of ATP. A to D, DU145 cells were left untreated and treated with 5 μmol/L GO-201 or CP-1 each day for 3 d. Cells were incubated with DCFH-DA and fluorescence of oxidized DCF was measured by flow cytometry (A). Results are the relative ROS level (mean ± SD of three determinations) compared with that obtained for the control (B). Cells were incubated with rhodamine 123 and analyzed by flow cytometry (C). Results are the percentage ΔΨm (mean ± SD of three determinations) compared with that obtained for the control (D, left). ATP levels are expressed as the mean ± SD of six determinations relative to that of the control (D, right).
with GO-201 in DU145 and PC3 cells was associated with increases in ROS. GO-201–induced disruption of redox balance was also associated with a substantial loss of ΔΨ_m, consistent with the effects of increased ROS levels on mitochondrial dysfunction (42, 43). Notably, MUC1-C localizes to the mitochondrial outer membrane where it attenuates loss of ΔΨ_m in the response to stress (12–14). Thus, GO-201–induced loss of ΔΨ_m may have been related

Figure 6. GO-201 induces regression of DU145 and PC3 tumors. A, 4- to 6-week-old male BALB/c nu/nu mice were injected s.c. in the flank with $1 \times 10^7$ DU145 cells. When tumors were 225 mm$^3$ (range, 200-275 mm$^3$), the mice were pair-matched into groups of 6 and injected i.p. with PBS (vehicle control; squares), 30 mg/kg GO-201 each day for 21 d (triangles), or 30 mg/kg CP-1 each day for 21 d (circles). Results are the mean tumor volume with a SD of <15% (left). There was no evidence of weight loss in any of the groups. Tumors harvested on day 21 from the control, GO-201, and CP-1 treatment groups were stained with H&E (right). B, male BALB/c nu/nu mice were injected s.c. in the flank with $1 \times 10^7$ DU145 cells. When tumors were 175 to 250 mm$^3$, the mice were pair-matched into groups of 10 and injected i.p. with PBS (closed squares), 30 mg/kg GO-201 each day for 21 d (closed triangles), or 30 mg/kg GO-201 each day for 5 d/wk × 3 wk (open circles; left). There was no evidence of weight loss in any of the groups. Control DU145 tumor harvested on day 34 and the DU145 implantation site from mice treated with GO-201 each day for 5 d/wk × 3 wk obtained on day 42 were stained with H&E (right). C, male BALB/c nu/nu mice were injected s.c. in the flank with $1 \times 10^7$ PC3 cells. The mice were pair-matched into groups of 10 when the tumors reached 200 mm$^3$ (range, 175-250 mm$^3$). The mice were injected i.p. with PBS (squares), 30 mg/kg GO-201 each day × 28 d (closed circles), 30 mg/kg GO-201 each day for 5 d/wk × 4 wk (open circles), or 30 mg/kg CP-1 each day × 28 d (triangles; left). There was no weight loss in any of the groups. Tumors were harvested on day 28 and stained with H&E (right).
Addiction to MUC1 in Prostate Cancer

3064

Addiction to MUC1 in Prostate Cancer

D. Raina and S. Kharbanda: employees, Genus Oncology. D. Kufe: founder and consultant, Genus Oncology. No other potential conflicts of interest were disclosed.

Disclosure of Potential Conflicts of Interest

References


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