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Abstract

Purpose: Because chemoradiotherapy selectively targets proliferating cancer cells, quiescent cancer stem–like cells are resistant. Mobilization of the cell cycle in quiescent leukemia stem cells sensitizes them to cell death signals. However, it is unclear that mobilization of the cell cycle can eliminate quiescent cancer stem–like cells in solid cancers. Thus, we explored the use of a genetically-engineered telomerase-specific oncolytic adenovirus, OBP-301, to mobilize the cell cycle and kill quiescent cancer stem–like cells.

Experimental Design: We established CD133+ cancer stem–like cells from human gastric cancer MKN45 and MKN7 cells. We investigated the efficacy of OBP-301 against quiescent cancer stem–like cells. We visualized the treatment dynamics of OBP-301 killing of quiescent cancer stem–like cells in dormant tumor spheres and xenografts using a fluorescent ubiquitination cell-cycle indicator (FUCCI).

Results: CD133+ gastric cancer cells had stemness properties. OBP-301 efficiently killed CD133+ cancer stem–like cells resistant to chemoradiotherapy. OBP-301 induced cell-cycle mobilization from G0–G1 to S/G2/M phases and subsequent cell death in quiescent CD133+ cancer stem–like cells by mobilizing cell-cycle–related proteins. FUCCI enabled visualization of quiescent CD133+ cancer stem–like cells and proliferating CD133– cancer stem–like cells. Three-dimensional visualization of the cell-cycle behavior in tumor spheres showed that CD133+ cancer stem–like cells maintained stemness by remaining in G0–G1 phase. We showed that OBP-301 mobilized quiescent cancer stem–like cells in tumor spheres and xenografts into S/G2/M phases where they lost viability and cancer stem–like cell properties and became chemosensitive.

Conclusion: Oncolytic adenoviral infection is an effective mechanism of cancer cell killing in solid cancer and can be a new therapeutic paradigm to eliminate quiescent cancer stem–like cells. Clin Cancer Res; 19(23); 6495–505. ©2013 AACR.
Translational Relevance

Current chemotherapy and radiotherapy target proliferating cancer cells, while having little effect on dormant cancer cells. Cancer stem–like cells can maintain a quiescent or dormant state, which contributes largely to their resistance to conventional therapies. Recently, several therapeutic strategies have targeted inhibition of the quiescent state in leukemia stem cells. However, it is still unclear whether cancer stem–like cells in solid tumors can also be eliminated by inhibition of their dormant state. Here, we showed that a telomerase-specific adenovirus, OBP-301, mobilizes quiescent cancer stem–like cells to cycle and lethally traps them into S-phase. Moreover, we showed by spatiotemporal treatment dynamics that OBP-301 decoyed quiescent cancer stem–like cells in tumor spheres and xenografts into an S-phase trap where they lost viability and cancer stem–like cell properties and become chemosensitive. Thus, our data demonstrated that cell-cycle mobilization and S/G2/M phase trapping induced by adenoviral infection is an effective mechanism of killing cancer stem–like cells in solid cancers.

Materials and Methods

Cell lines and radiation treatment

The human gastric cancer cell lines MKN45 and MKN7 were maintained according to the vendor’s specifications (21). Radiosensitive MKN45 and MKN7 cells were established by administration of radiation treatments using an X-ray generator (MBR-1505R; Hitachi Medical Co.).

Recombinant adenoviruses

The recombinant tumor-specific, replication-selective adenovirus vector OBP-301 (Telomelysin), in which the promoter element of the human telomerase reverse transcriptase (hTERT) gene drives the expression of E1A and E1B genes linked to an internal ribosome entry site, was previously constructed and characterized (19, 22).

Isolation of CD133+ and CD133− cells by flow cytometry

After incubation with an anti-CD133/2(293C)-allophycocyanin antibody (Miltenyi Biotec), CD133+ cells were sorted by flow cytometry using a FACSaria flow cytometer (Becton Dickinson). CD133+ and CD133− cells were separated by flow cytometry just before each experiment to ensure that the purity of the CD133+ population was greater than 70%, and the purity of CD133− cells was above 99%.

Cell viability assay

CD133+ and CD133− cells (5 × 102 cells/well) in 96-well plates were treated with OBP-301, cisplatin, or radiation at the indicated doses. Cell viability was determined on day 5 after treatment using the Cell Proliferation Kit II (Roche Diagnostics). The primary antibodies used were: mouse anti-CD133/2(293C)-allophycocyanin antibody (mAb; Miltenyi Biotec); rabbit anti-E2F1 polyclonal antibody (pAb) (Santa Cruz Biotechnology); mouse anti-Ad5 E1A mAb (BD Pharmingen); mouse anti-c-Myc pAb, rabbit anti-phospho-Akt mAb, rabbit anti-Akt mAb, mouse anti-p27 mAb (all from Santa Cruz Biotechnology); rabbit anti-Ad5 E1B mAb (BD Pharmingen); mouse anti-p21 mAb (both from CALBIOCHEM Merck4 Biochemicals); and mouse anti-β-actin mAb (Sigma-Aldrich). Immunoreactive bands on the blots were visualized using enhanced chemiluminescence substrates (ECL Plus; GE Healthcare).

Subcutaneous MKN45 tumor xenograft model

To evaluate the tumorigenicity of CD133+ and CD133− cells, purified CD133+ and CD133− cells were inoculated at a density of 1 × 105 cells/site on the right and left sides, respectively, of the flank of 5-week-old female NOD/SCID mice (Charles River Laboratories) or athymic nude mice (Charles River Laboratories). To evaluate the in vivo antitumor efficacy of OBP-301, cisplatin, or radiation, the radiosensitive MKN45 cells were inoculated at a density of 5 × 105 cells/site into the flank of 5-week-old female athymic nude mice. OBP-301 [1 × 10^8 plaque-forming units (PFU)] was injected into the tumors. Cisplatin (4 mg/kg body weight) was intraperitoneally injected and ionizing radiation (2 Gy) was administered to tumors after protection of normal tissues. Mice were treated every 3 days for a total of three treatments.
Imaging of MKN45 cells expressing cell-cycle–dependent fluorescent proteins

Time lapse images of FUCCI-expressing CD133+ and CD133− radioresistant MKN45 cells were acquired using a confocal laser scanning microscope (FV10i; Olympus). Cross-sections of FUCCI-expressing tumors were imaged using a confocal laser scanning microscope (FV-1000; Olympus).

Treatment of subcutaneous FUCCI-expressing MKN45 tumors

To evaluate the in vivo antitumor efficacy of OBP-301, cisplatin, paclitaxel, or their combination, the FUCCI-expressing MKN45 cells were inoculated at a density of 5 × 10^6 cells/site into the flank of 5-week-old female athymic nude mice (Charles River Laboratories). OBP-301 (1 × 10^8 PFU/tumor) was injected intraperitoneally. Mice were treated every 3 days for a total of 3 to 5 treatments.

Statistical analysis

Data are shown as means ± SD. For comparison between 2 groups, significant differences were determined using the Student t test. For comparison of more than 2 groups, statistical significance was determined with a one-way ANOVA followed by a Bonferroni multiple-group comparison test. P < 0.05 was considered significant.

Results

CD133+ cells in human gastric cancer cells are cancer stem–like

Cancer stem–like cells are more resistant to radiotherapy than non–cancer stem–like cells (24–26). To enrich cancer stem–like subpopulations, we established radioresistant MKN45 and MKN7 human gastric cancer cells. Radioresistant MKN45 and MKN7 cells had a significantly higher percentage of CD133+ cells than parental cells (Fig. 1A and Supplementary Fig. S1A). We hypothesized that CD133+ in gastric cancer would identify cancer cells with stem-like properties, such as asymmetric cell division, in vitro proliferation, dormancy, sphere formation, and in vivo tumorigenicity (5, 6). To investigate the asymmetric division of CD133+ cells, we determined whether CD133+ cells produce both CD133+ and CD133− cells. CD133+ cells generated both CD133+ and CD133− cells, whereas CD133− cells could not produce CD133+ cells (Supplementary Fig. S2). We compared in vitro proliferation of CD133+ and CD133− cells. CD133+ cells produced larger colonies than CD133− cells (Fig. 1B and Supplementary Fig. S3). CD133+ cells made significantly much more tumor spheres than CD133− cells (Fig. 1B). CD133+ cells produced tumors in immunodeficient nude mice and NOD/SCID mice, whereas CD133− cells did not generate tumors in either nude on NOD/SCID mice (Supplementary Fig. S4 and Fig. 1B). Furthermore, CD133+ cells in radioresistant MKN45 and MKN7 cells were significantly more resistant to 5-fluorouracil, cisplatin, paclitaxel, and radiation than CD133− cells (Fig. 1C and Supplementary Fig. S1B). These data indicate that CD133+ cells are cancer stem–like.

Quiescent CD133+ cancer stem–like cells and cycling CD133− non–cancer stem–like cells are independently visualized by fluorescent cell-cycle indicator technology

Sakaue-Sawano and colleagues have reported that the cell-cycle state in viable cells can be visualized using the FUCCI system (23). We established FUCCI-expressing CD133+ or CD133− radioresistant MKN45 cells, in which cell nuclei in G0–G1, S, or G2–M phases exhibit red, yellow, or green fluorescence, respectively. We compared the cell-cycle phase of FUCCI-expressing CD133+ or CD133− cells. Time-lapse imaging showed that most of CD133+ cells were quiescent in G0–G1 phase with red fluorescent nuclei compared with CD133− cells (Fig. 1D). Similar results were also observed in flow cytometric analysis of the cell cycle (Supplementary Fig. S5A and S5B). CD133+ cells had similar proliferation rates as CD133− cells until 3 days after seeding. CD133− cells showed lower proliferation rates than CD133+ cells 5 days after seeding (Fig. 1D). This result was consistent with the cell-cycle status of CD133+ cells which had an increased percentage of cells in G0–G1 phase. Moreover, we examined cell-cycle–related protein (27) expression in CD133+ and CD133− cells. CD133+ cells showed higher expressions of p53, p21, and p27 proteins compared with CD133− cells (Supplementary Fig. S8), suggesting that these proteins are involved in the maintenance of quiescent cancer stem–like cells.

OBP-301 efficiently kills cancer stem–like cells and reduces cancer stem–like cell frequency via enhanced viral replication

To evaluate the efficacy of OBP-301 against CD133+ cancer stem–like cells, we treated CD133− and CD133+ cells from radioresistant MKN45 and MKN7 cells with OBP-301. OBP-301 similarly killed CD133+ and CD133− cells (Fig. 2A and Supplementary Fig. S1B). Next we investigated whether OBP-301 could decrease cancer stem–like cell frequency. Flow cytometric analysis showed that OBP-301 significantly decreased the percentage of CD133+ cells compared with cisplatin or radiation (Fig. 2A). Expression of CD133 mRNA was closely associated with the population of CD133+ cells (Supplementary Fig. S6). OBP-301 significantly suppressed the expression of CD133 mRNA compared with cisplatin and radiation (Supplementary Fig. S7). Western blot analysis also showed that cisplatin and radiation, but not OBP-301, increased CD133 expression 3- to 5-fold in CD133+ cells (Fig. 2D). Moreover, pretreatment of CD133+ cells with OBP-301, but not cisplatin or radiation, significantly decreased the number of tumor spheres (Supplementary Fig. S13). These data indicated that OBP-301 kills both CD133+ and CD133− cells and reduces cancer stem–like cell frequency.

To further explore the efficacy of OBP-301 against CD133+ cancer stem–like cells, we assessed the relationship between hTERT activity and viral replication. OBP-301 contains the hTERT promoter, which allows it to tumor-specifically regulate the gene expression of E1A and E1B for viral replication (19). Quantitative reverse transcription
CD133– cancer stem–like cells in human gastric cancer exhibit cancer stem–like cell properties and are more quiescent. A, flow cytometric analysis of CD133 expression in parental (P) and radioresistant (R) MKN45 cells. Representative dot plots (top) and data from 5 experiments (bottom) are shown. B, CD133– MKN45 cancer cells exhibit cancer stem–like properties. Representative images of colonies from CD133– or CD133+ cells. Histogram shows the size of colonies from CD133– or CD133+ cells (left). Quantitative measurement of the tumor sphere–forming potential of CD133+ and CD133– cells (middle). Representative images of tumor spheres derived from CD133+ and CD133– cells. Histogram shows the numbers of tumor spheres from CD133+ or CD133– cells. Scale bars, 500 μm. Tumorigenicity of CD133+ or CD133– cells in immunodeficient NOD/SCID mice (right). Growth curve of each tumor and representative photographs are shown. C, sensitivity of CD133+ expressing CD133+ or CD133– cells. Scale bars, 50 μm. Data are shown as means ± SD (n = 5). * * P < 0.01.

OBP-301 mobilizes and lethally traps quiescent cancer stem–like cells into S-phase in monolayer culture

To examine whether OBP-301 could change the cell-cycle phase of quiescent CD133+ cells, we treated FUCCI-expressing CD133+ cells with OBP-301. Time-lapse imaging showed that OBP-301 infection significantly decreased the percentage of CD133+ cells in G0–G1 phase, increased the percentage of CD133+ cells in S-phase, and killed them in S-phase (Fig. 2C and Supplementary Movie S1). Similar results were also observed in flow cytometric analysis of the cell cycle (Supplementary Fig. S5C and S5D). These results suggest that OBP-301 induces cell-cycle activation of quiescent CD133+ cells from G0–G1 phase to S-phase and kills them. We next assessed the molecular mechanism by which OBP-301 induces mobilization of the cell cycle in quiescent cancer stem–like cells. OBP-301 increased the expression of E2F1, c-Myc, and phospho-Akt proteins that function as...
enhanced viral replication. A, OBP-301 efficiently kills CD133⁺ cancer stem–like cells. Left, viability of CD133⁺ and CD133⁻ MKN45 cells after OBP-301 infection. Right, CD133-positive ratio of MKN45 cells treated with OBP-301, cisplatin, or radiation was analyzed by flow cytometry. B, OBP-301 can replicate more in CD133⁺ cells that have more hTERT activity than in CD133⁻ cells. Expression of hTERT mRNA in CD133⁺ and CD133⁻ MKN45 cells assessed by qRT-PCR (top left). The relative levels of hTERT mRNA were calculated after normalization with reference to the expression of PBGD mRNA. Expression of E1A mRNA in CD133⁺ and CD133⁻ MKN45 cells after OBP-301 infection at an MOI of 10 PFU/cell for 2 hours. Expression of E1A mRNA was analyzed over the following 3 days by qRT-PCR (top right). The relative levels of E1A mRNA were calculated after normalization with reference to the expression of GAPDH mRNA. Western blot analysis of E1A expression in CD133⁺ and CD133⁻ MKN45 cells treated with OBP-301 for 48 hours (bottom left). Quantitative relative expression level of E1A protein, normalized to β-actin, using NIH ImageJ software (bottom left). Quantitative measurement of viral DNA replication in CD133⁺ and CD133⁻ MKN45 cells after OBP-301 infection at an MOI of 10 PFU/cell for 2 hours (bottom right). E1A copy number was analyzed over the following 3 days using qPCR. C, time-lapse imaging of Fucci-expressing CD133⁺ and CD133⁻ cells treated with OBP-301 at an MOI of 20 PFU/cell. The cells in G₀–G₁, S, and G₂–M phases appear red, yellow, or green, respectively. Histogram shows the cell-cycle phases of Fucci-expressing CD133⁺ and CD133⁻ cells treated with OBP-301 for 48 hours. The percentage of cells in G₀–G₁, S, and G₂–M phases are shown. D, Western blot analysis of E2F1, c-Myc, phospho-Akt, Akt, p53, p21, and p27 expression in CD133⁺ cells treated with OBP-301, cisplatin, or radiation for 48 hours. β-Actin was assayed as a loading control for all experiments. Data are shown as means ± SD (n = 5); *, P < 0.05; **, P < 0.01.

Figure 2. OBP-301 lethally induces S-phase transition of quiescent CD133⁺ cancer stem–like cells and decreases cancer stem–like cell frequency via enhanced viral replication. A, OBP-301 efficiently kills CD133⁺ cancer stem–like cells. Left, viability of CD133⁺ and CD133⁻ MKN45 cells after OBP-301 infection. Right, CD133-positive ratio of MKN45 cells treated with OBP-301, cisplatin, or radiation was analyzed by flow cytometry. B, OBP-301 can replicate more in CD133⁺ cells that have more hTERT activity than in CD133⁻ cells. Expression of hTERT mRNA in CD133⁺ and CD133⁻ MKN45 cells assessed by qRT-PCR (top left). The relative levels of hTERT mRNA were calculated after normalization with reference to the expression of PBGD mRNA. Expression of E1A mRNA in CD133⁺ and CD133⁻ MKN45 cells after OBP-301 infection at an MOI of 10 PFU/cell for 2 hours. Expression of E1A mRNA was analyzed over the following 3 days by qRT-PCR (top right). The relative levels of E1A mRNA were calculated after normalization with reference to the expression of GAPDH mRNA. Western blot analysis of E1A expression in CD133⁺ and CD133⁻ MKN45 cells treated with OBP-301 for 48 hours (bottom left). Quantitative relative expression level of E1A protein, normalized to β-actin, using NIH ImageJ software (bottom left). Quantitative measurement of viral DNA replication in CD133⁺ and CD133⁻ MKN45 cells after OBP-301 infection at an MOI of 10 PFU/cell for 2 hours (bottom right). E1A copy number was analyzed over the following 3 days using qPCR. C, time-lapse imaging of Fucci-expressing CD133⁺ and CD133⁻ cells treated with OBP-301 at an MOI of 20 PFU/cell. The cells in G₀–G₁, S, and G₂–M phases appear red, yellow, or green, respectively. Histogram shows the cell-cycle phases of Fucci-expressing CD133⁺ and CD133⁻ cells treated with OBP-301 for 48 hours. The percentage of cells in G₀–G₁, S, and G₂–M phases are shown. D, Western blot analysis of E2F1, c-Myc, phospho-Akt, Akt, p53, p21, and p27 expression in CD133⁺ cells treated with OBP-301, cisplatin, or radiation for 48 hours. β-Actin was assayed as a loading control for all experiments. Data are shown as means ± SD (n = 5); *, P < 0.05; **, P < 0.01.

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Three-dimensional tumor spheres maintain a CD133⁺ subpopulation by remaining quiescent

Formation of tumor spheres under serum-free conditions is frequently used to maintain cancer stem–like cell subpopulations (28). The addition of serum makes floating undifferentiated tumor spheres adherent and their cells differentiate into adherent cells (29). Therefore, we hypothesized that tumor spheres maintained their cancer stem–like cell frequency due to quiescence.

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CD133+ cells aggregated and formed tumor spheres, and arrested in G0–G1 phase (Fig. 3A). Tumor spheres formed from CD133+ cells contained more quiescent cells than those formed from CD133− cells (Fig. 3B). Moreover, established tumor spheres formed from CD133+ cells remained quiescent in 3-dimensional culture without serum (Fig. 3C). In contrast, established tumor spheres, after addition of serum, exited from the quiescent state and began to cycle, divide, and increase (Fig. 3C and Supplementary Movie S2).

Flow cytometric analysis showed that CD133+ cells could be maintained in tumor spheres cultured in serum-free medium for 2 weeks, whereas the percentage of CD133+ cells significantly decreased in monolayer cultures or in tumor spheres cultured in serum-containing medium (Fig. 3D). These data indicate that tumor spheres maintain their cancer stem-cell frequency by remaining dormant.

Real-time imaging spatiotemporally shows OBP-301 eliminates dormant tumor spheres by cell-cycle mobilization and S/G2/M phase trapping

To further evaluate OBP-301-induced cell-cycle mobilization and S-phase trapping in dormant tumor spheres, we visualized the treatment dynamics of FUCCI-expressing tumor spheres infected with OBP-301. Time-lapse imaging showed that OBP-301 infected quiescent CD133+ cells at the periphery of the spheres and then induced S and G2–M

Figure 3. Three-dimensional tumor spheres maintain CD133+ cells by the cell cycle arrest. A, time-lapse images of FUCCI-expressing CD133+ cells in 3-dimensional culture without serum. Purified FUCCI-expressing CD133+ cells were cultured on agar in serum-free medium containing EGF and bFGF for 48 hours (top). The cells in G0–G1, S, or G2–M phases appear red, yellow, or green, respectively. Histogram shows the cell-cycle phase of FUCCI-expressing CD133+ cells in 3-dimensional culture without serum (3D without serum) or tumor spheres in monolayer culture with serum (monolayer culture; top). The percentage of cells in G0–G1 phases are shown. B, representative images of tumor spheres formed from FUCCI-expressing CD133+ and CD133− cells (top). Histogram shows the cell-cycle phase of tumor spheres from FUCCI-expressing CD133+ cells in 3D culture without serum, or 3D culture with serum (3D with serum) (bottom). The percentage of cells in G0–G1 phases are shown. C, time-lapse images of FUCCI-expressing CD133+ cells in monolayer culture or FUCCI-expressing tumor spheres in 3-dimensional culture without serum (3D without serum) or tumor spheres in monolayer culture with serum (monolayer culture; top). Histogram shows the cell-cycle phase of FUCCI-expressing CD133+ cells in 2D culture, FUCCI-expressing established tumor spheres in 3D without serum, or tumor spheres on plastic culture with serum (monolayer culture; bottom). D, comparison of changes in the CD133+ positive ratio in monolayer culture, tumor spheres in 3D culture without serum, or with serum. Representative dot plots (left) and data from 3 experiments (right) are shown. Data are shown as means ± SD (n = 5). *, P < 0.01. Scale bars, 500 μm.
OBP-301 efficiently eradicates dormant tumor spheres resistant to conventional therapies by mobilizing them into an S/G2/M phase trap.

**OBP-301 efficiently kills dormant cancer stem–like cells in established human tumor xenografts by cell-cycle mobilization and S/G2/M phase trapping, thereby reducing cancer stem–like cell frequency**

To further confirm whether OBP-301 efficiently reduced CD133+ cancer stem–like cell frequency within tumor tissues (Supplementary Fig. S10A), we investigated the expression of CD133 mRNA and the CD133-positive ratio in subcutaneous tumors derived from radioresistant MKN45 cells after treatment of OBP-301, cisplatin, or irradiation. Suppression of tumor growth by OBP-301 (Fig. 5A) was accompanied by a significant decrease in CD133 mRNA at 2 weeks after the final treatment (Fig. 5B). In contrast, although cisplatin and radiation also suppressed tumor growth to a similar extent as OBP-301 (Fig. 5A), cisplatin did not affect, and radiation significantly increased CD133 mRNA expression at 1 week after the final treatment (Fig. 5B). Immunohistochemistry of CD133-stained tumor sections also showed that OBP-301 reduced the frequency of CD133+ cells, whereas cisplatin and radiation increased the frequency compared with control (Fig. 5B).

Next, we visualized treatment dynamics in established FUCCI-expressing MKN45 tumor xenografts with or without OBP-301 infection (Supplementary Fig. S10B). FUCCI-expressing MKN45 tumors had a distribution of cancer cells in G0–G1, S, and G2–M phases (Fig. 5A). As tumors grew bigger, cancer cells in G0–G1 phase increased (Fig. 5C) was accompanied by a significant decrease in CD133 mRNA at 1 week after the final treatment (Fig. 5B). In contrast, although cisplatin and radiation also suppressed tumor growth to a similar extent as OBP-301 (Fig. 5A), cisplatin did not affect, and radiation significantly increased CD133 mRNA expression at 1 week after the final treatment (Fig. 5B). Immunohistochemistry of CD133-stained tumor sections also showed that OBP-301 reduced the frequency of CD133+ cells, whereas cisplatin and radiation increased the frequency compared with control (Fig. 5B).
Figure 5. OBP-301 induces cell-cycle progression and efficiently kills dormant cancer cells resistant to conventional therapy in established human tumor xenografts. CD133⁺-rich radioresistant MKN45 cells (5 × 10⁶ cells/mouse) were injected subcutaneously into the left flanks of mice. When the tumors reached approximately 6 mm in diameter (tumor volume, 100–120 mm³), mice were administered OBP-301 intratumorally (1 × 10⁸ PFU/tumor), injected intraperitoneally with cisplatin (4 mg/kg), or exposed to 2 Gy of radiation for 3 cycles every 3 days. A, growth curves of tumors derived from radioresistant MKN45 cells after treatment with OBP-301, cisplatin, or radiation. Black arrows indicate the day of treatment. B, expression of CD133 mRNA in tumors treated with OBP-301, cisplatin, or radiation at 1, 2, and 3 weeks after treatment (top). Representative images of CD133-stained tumor section treated with OBP-301, cisplatin, or radiation (bottom left). Scale bars, 100 μm. Histogram shows the percentages of CD133⁺ cells in tumors treated with OBP-301, cisplatin, or radiation (bottom right). The percentage of CD133⁺ cells was calculated by dividing the number of CD133⁺ cells by the total number of cells. Data are shown as means ± SD (n = 3). *, P < 0.05. C and D, FUCCI-expressing MKN45 cells (5 × 10⁶ cells/mouse) were injected subcutaneously into the left flanks of mice. When the tumors reached approximately 7 mm in diameter (tumor volume, 150–180 mm³), mice were administered OBP-301 intratumorally (1 × 10⁸ PFU/tumor), injected intraperitoneally with cisplatin (4 mg/kg) or paclitaxel (5 mg/kg) for 3 cycles every 3 days. Representative images of cross-sections of FUCCI-expressing MKN45 subcutaneous tumors of control, OBP-301-, cisplatin-, or paclitaxel-treated mice (left). The cells in G0–G1, S, or G2–M phases appear red, yellow, or green, respectively. Histogram shows the cell-cycle phase of FUCCI-expressing MKN45 subcutaneous tumor from control, OBP-301-, cisplatin-, or paclitaxel-treated mice (right). The percentage of cells in G0–G1, S, and G2–M phases are shown. Data are shown as means ± SD (n = 5). *, P < 0.05. Scale bars, 500 μm.
After cisplatin or paclitaxel treatment, the tumor consisted mostly of red fluorescent cells (Fig. 5D), indicating that the cytotoxic agents killed only cycling cancer cells and had little effect on quiescent dormant cancer cells. These tumors regrew, with the quiescent cells re-entering the cell cycle 21 days after last treatment (Fig. 5D). In contrast, intratumor injection of OBP-301 mobilized the cancer cells into the S/G2/M phase trap, leading to elimination of cancer cells in S/G2/M phases (Fig. 5D). These data indicate that OBP-301 could efficiently kill quiescent cancer stem–like cells in tumors by inducing cell-cycle progression.

**OBP-301 sensitizes quiescent cancer stem–like cells to chemotherapy by cell-cycle mobilization and S/G2/M phase trapping**

As we previously showed that OBP-301 enhances the sensitivities to chemotherapeutic agents in various types of human cancer cells (30, 31), we further evaluated whether OBP-301 sensitizes quiescent CD133+ cancer stem–like cells to chemotherapy by inducing cell-cycle progression and S/G2/M phase trapping. OBP-301 infection significantly enhanced the inhibitory effect of chemotherapy on cell viability and tumor sphere formation of CD133+ cells (Fig. 6A and Supplementary

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**Figure 6.** OBP-301 sensitizes quiescent CD133+ cancer stem–like cells to chemotherapy by inducing cell-cycle progression. A, representative images of tumor spheres from FUCCI-expressing CD133+ cells after treatment with cisplatin, paclitaxel, OBP-301, and the combination of OBP-301 and chemotherapy (top). The cells in G0–G1, S, or G2–M phases appear red, yellow, or green, respectively. The tumor-sphere area was calculated using NIH ImageJ software (lower). Data are shown as means ± SD (n = 5). *, P < 0.05. Scale bars, 500 μm. B, histogram shows the cell-cycle phase of tumor spheres from FUCCI-expressing CD133+ cells after treatment with chemotherapy, OBP-301, and the combination of OBP-301 and chemotherapy. The percentage of cells in G0–G1, S, and G2–M phases are shown. Data are shown as means ± SD (n = 5). *, P < 0.05. C, FUCCI-expressing MKN45 cells (5 × 106 cells/mouse) were injected subcutaneously into the left flanks of mice. When the tumors reached approximately 8 mm in diameter (tumor volume, 300 mm³), mice were administered OBP-301 intratumorally (1 × 10⁶ PFU/tumor), injected intraperitoneally with cisplatin (4 mg/kg) or paclitaxel (5 mg/kg) for 5 cycles every 3 days. The growth curves of tumors derived from FUCCI-expressing MKN45 cells after treatment with chemotherapy, OBP-301, or the combination of OBP-301 and chemotherapy (left). Red and green arrows indicate the day of treatment with OBP-301 and chemotherapy, respectively. Macroscopic photographs of FUCCI-expressing tumors in untreated (control) or treated with OBP-301, cisplatin, paclitaxel, or the combination of OBP-301 and chemotherapy (right). Scale bars, 10 mm. D, representative image of cross-sections of FUCCI-expressing MKN45 subcutaneous tumors of control, OBP-301-, cisplatin-, paclitaxel-, or the combination of OBP-301- and chemotherapy-treated mice (top). Histogram shows cell-cycle phase of FUCCI-expressing MKN45 subcutaneous tumors of control, treated with OBP-301, cisplatin, paclitaxel, or the combination of OBP-301 and chemotherapy (bottom). Data are shown as means ± SD (n = 6). *, P < 0.05, ANOVA. Scale bars, 500 μm.
Fig S13). Tumor spheres treated with chemotherapy and OBP-301 contained an increased percentage of tumor cells in G2–M phases compared to OBP-301 alone (Fig. 6B). The combination of OBP-301 and chemotherapy (Supplementary Fig. S10C) significantly suppressed tumor growth compared to chemotherapy or OBP-301 alone (Fig. 6C and Supplementary Fig. S14). Cross-sections of tumor tissues showed that the combination of chemotherapy and OBP-301 induced an increased percentage of cancer cells in G2–M phases compared to OBP-301 alone (Fig. 6D). These results suggest that OBP-301 sensitizes the quiescent cancer stem–like cells to chemotherapy-mediated G2–M arrest by inducing cell-cycle progression and S/G2/M phase trapping.

Discussion

We have described that a bioengineered telomerase-specific oncolytic adenovirus, OBP-301, efficiently kills CD133+ cancer stem–like cells that have elevated telomerase activity through enhanced E1A-mediated cell-cycle mobilization and S-phase trapping. By using FUCCI technology in combination with tumor sphere culture, we visualized virus penetration, cell-cycle dynamics, and the subsequent elimination of quiescent cancer stem–like cells in dormant tumor spheres (Supplementary Fig. S15A).

Cancer stem–like cells have been shown to be highly resistant to chemotherapeutic agents (32, 33) and ionizing radiation (24–26). As expected, CD133+ human gastric cancer cells were more resistant to conventional therapies than CD133- cells; OBP-301, however, efficiently reduced the viability of CD133+ cells, similar to their reduction of viability of CD133- cells. Moreover, we showed that OBP-301 significantly reduced the stem cell properties of CD133+ cells in vitro and in vivo compared with conventional chemoradiotherapy and further sensitized CD133+ cancer stem–like cells to chemotherapy. These findings indicate that OBP-301 is a promising anticancer therapy to eliminate cancer stem–like cells more efficiently than conventional therapy in the clinical setting.

Recent studies have showed that p53 and p21cip1/waf1 maintain the quiescent state in hematopoietic stem cells (34, 35). Moreover, p21kip1 has been suggested to be involved in suppression of the transition from the G0 phase to G1–S phases (36, 37). Cancer stem–like cells maintain a more quiescent state than non–cancer stem–like cells, which is associated with cancer stem–like cell resistance to conventional therapies (9, 10). OBP-301 induced S and G2–M phase entry and subsequent cell death in quiescent CD133+ cells through upregulation of E2F1-related proteins and downregulation of p53-related and p27 proteins in an E1A-dependent manner. A recent report suggested that suppression of the p53-mediated G1 checkpoint is required for E2F1-induced S-phase entry (38). Furthermore, adenoviral E1A has been shown to suppress p53-mediated cell-cycle arrest after DNA damage (39). Thus, OBP-301 can inhibit cancer stem–like cells from maintaining a quiescent state and force them into cycling by not only upregulating E2F-related proteins but also downregulating p53-related and p27 proteins (Supplementary Fig. S15B), leading to the sensitization to chemotherapy.

FUCCI (23) is a powerful tool to visualize the quiescent state in cancer stem–like cells and the treatment dynamics of OBP-301. When tumor spheres were formed, CD133+ cells maintained a quiescent state, which was defined by red fluorescent nuclei expressed in G0–G1 phases. In contrast, S and G2–M phase entry induced by OBP-301 could be clearly visualized as yellow and green fluorescent nuclei, respectively. Our data indicate that 3-dimensional cultures are extremely important for the maintenance of the quiescence of CD133+ cells. FUCCI-based real-time imaging of the cell cycle provides a platform for the screening of candidate therapeutic agents that modulate the quiescent state of drug-resistant cancer stem–like cells.

In conclusion, we have clearly shown that a genetically-engineered oncolytic adenovirus, OBP-301, efficiently eradicates quiescent cancer stem–like cells in solid tumors by cell-cycle mobilization and S/G2/M phase trapping. A phase I clinical trial of intratumoral injection of OBP-301 in patients with advanced solid tumors was recently completed and OBP-301 monotherapy was well tolerated by these patients (20). However, the difficulty of adenoviral delivery to inaccessible primary and metastatic tumor tissues is a major obstacle for clinical translation of this treatment modality. In this study, the combination therapy of OBP-301 with chemotherapy was highly effective antitumor therapy to eliminate both cancer stem–like and non–cancer stem–like cells in a xenograft model. Future clinical trials of intratumoral injection of OBP-301 in combination with conventional antitumor therapy are suggested by the results of the present study.

Disclosure of Potential Conflicts of Interest

Y. Urata is President & CE0 of Oncolytic BioPharma, Inc., the manufacturer of OBP-301 (Telomelysin). H. Tazawa and T. Fujiwara are consultants of Oncolytic BioPharma, Inc. No potential conflicts of interest were disclosed by the other authors.

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