Bufalin Inhibits the Differentiation and Proliferation of Cancer Stem Cells Derived from Primary Osteosarcoma Cells through Mir-148a

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Abstract
Background/Aims: Osteosarcoma (OS) is the second leading cause of cancer-related death in children and young adults. Chemoresistance is the most important cause of treatment failure in OS, largely resulting from presence of cancer stem cells (CSCs). However, CSCs isolated from cancer cell lines do not necessarily represent those from primary human tumors due to accumulation of genetic aberrations that increase with passage number. Therefore, studies on CSCs from primary OS may be more important for understanding the mechanisms driving the chemoresistance of CSCs in OS. Methods: We established a primary culture of OS cells, known as C1OS, from freshly resected tumor tissue. We further isolated CSCs from C1OS cells (C1OS-CSCs). We analyzed the effects of bufalin, a traditional Chinese medicine, on the stemness of C1OS-CSCs. We also analyzed the microRNA (miR) targets of bufalin on the stemness of C1OS-CSCs. Moreover, we examined these findings in the OS specimen. Results: Bufalin inhibited the stemness of C1OS-CSCs. Moreover, we found that miR-148a appeared to be a target of bufalin, and miR-148a further regulated DNMT1 and p27 to control the stemness of OS cells. This mechanism was further confirmed in OS specimen. Conclusion: Our data suggest that bufalin may be a promising treatment for OS, and its function may be conducted through regulation of miR-148a.
Introduction

Osteosarcoma (OS) is a type of solid bone cancer mainly arising in young adults. It account for approximately 2.4% of all malignancies in young adults and is the second leading cause of cancer-related death of pediatric patients [1-3]. The standard care for OS today is based on a combination of aggressive surgical resection and different pre- and post-operative drugs, but it can provide just 65–70% 5-year survival rate without metastasis for OS patients [4-10]. Therefore, a great need for new treatments for osteosarcoma exits. However, the underlying cellular mechanisms of the development of OS chemoresistance and metastasis remain unclear.

Recently, it has been suggested that within a heterogeneous tumor there was a small subpopulation of cells called cancer stem cells (CSCs) that are responsible for chemoresistance and tumor metastasis [11]. Tumor shrinkage can be achieved by traditional treatment patterns, but most tumors will recur after treatment because of CSCs which could survive and then regenerate tumor growth [12, 13]. Specifically targeting the CSC population may be a more effective therapy strategy. Since the proposal of the CSC hypothesis, a lot of studies have been performed to isolate and identify OS stem cells using various methods [14-17]. In a recent study, we derived CSCs from the human hMG63 osteosarcoma cell line using a new strategy combining a suspension culture system with the chemotherapy drug cisplatin [18]. We also detected the expression of classic stem cell markers and confirm stem cell-like properties of hMG63 derived cancer stem cells.

Bufalin is the major component of the Chinese medicine Chan Su. It is an extract of dried toad venom from the skin glands of Bufo gargarizans. Previous studies suggest that bufalin inhibits the proliferation of transplanted human hepatocellular carcinoma in nude mice [19]. In addition, it has been reported that bufalin induces apoptosis in various human cancer cell lines, including leukemia [20], prostate cancer [21], gastric cancer [22], and osteosarcoma [23]. We also reported its potent impact on human osteosarcoma CSCs.

MicroRNAs, a type of noncoding small RNAs of 19–25 nt, can repress translation and induce cleavage of mRNA by binding to the 3' untranslated region (UTR) of the target genes. MicroRNAs play important roles in multiple physiological and pathological functions, including development, differentiation, cell proliferation, apoptosis, and stress responses [24, 25]. In addition, recent evidence suggests that some microRNAs are involved in OS tumorigenesis and chemoresistance. For example, the inhibition of miR-34c significantly stimulated OS cell invasion and chemoresistance in vitro. In contrast, restoring miR-34c inhibited OS cell invasion and chemoresistance [26]. miR-33a promotes OS cell resistance to cisplatin by down-regulating TWIST. Inhibition of miR-33a by antagonim-33a enhances cisplatin-induced apoptosis in OS cells by up-regulating TWIST expression [27]. The expression of miR-21 regulates cellular processes in osteosarcoma, perhaps through regulating RECK [28]. Down-regulation of miR-143 was found in both osteosarcoma cell lines and primary tumor samples. The restoration of miR-143 could reduce cell viability and promote cell apoptosis through repression of Bcl-2 [29]. miR-140 was found to play a role in chemosensitivity to chemicals such as 5-fluorouracil (5-FU) in osteosarcoma. Sensitivity to 5-FU treatment can be obtained by blocking expression of miR-140 in cancer cells; on the other hand, the overexpression of miR-140 made tumor cells more resistant. It suggested miR-140 as a potent target to overcome drug resistance [30]. Given the numerous studies, the mechanism details underlying the interaction of OS CSCs and miRNA are still not well understood.

In this study, we successfully established a primary culture of OS cells, named C1OS, from freshly resected tumor tissue. Then, we derived cancer stem cells from C1OS cells using methods we described previously [18]. Similar to the cancer stem cells that we derived from the hMG63 cell line in a previous study, the cancer stem cells from C1OS cells can respond to bufalin. We also found a significantly upregulated expression of miR-148a in bufalin-treated primary cancer stem cells derived from C1OS. Ectopic overexpression of miR148a inhibits the stemness of cancer stem cells by suppressing expression of DNMT1 directly.
Methods and Materials

Establishment of primary osteosarcoma cell lines
This study was approved by ethical committee of Shanghai University of Traditional Chinese Medicine. After receiving informed consent forms, human cancer tissues were obtained from patients with primary osteosarcoma. Tumor tissue obtained from patients was washed in medium (DMEM supplemented with penicillin-streptomycin) and then minced into small pieces by scissors. The tissues were then resuspended in culture medium (DMEM medium supplemented with 10% FBS) and explanted to dishes pre-coated with collagen. Explants with epithelial monolayer outgrowth were preserved and transferred to a new dish for subculture. Serial subculture was performed to obtain primary tumor cell lines. All primary tumor cells were maintained at 37°C in a humidified incubator with 5% CO₂.

Animals
This study was approved by the institutional animal care and use committee of Shanghai University of Traditional Chinese Medicine. Nude mice were purchased from Shanghai Laboratory Animal Company. Mice were housed under pathogen-free conditions according to the standard guidelines of the institutional animal care and use committee of Shanghai University of Traditional Chinese Medicine. For xenografts formation assay, the C1OS colonies consisting of different number of cells were injected into nude mice. The tumor size was monitored.

Cell culture
hMG-63 cells were obtained from American type culture collection (ATCC) and stored in our laboratory. hMG-63 and C1OS were cultured in medium (DMEM supplemented with 10% FBS) at 37°C in a humidified incubator with 5% CO₂. The medium was changed every three days.

Plasmids construction and lentiviral infections
pLemiR-148a was obtained by cloning human pre-miR-148a sequence (amplified from genomic DNA) into pLemiR-tRFP vector. For the production of lentiviruses, specific vectors were transfected into 293T cells by calcium phosphate. 48 hrs after the transfection, supernatants were harvested, filtered with 0.45μm filters. These supernatants were used to infect cells in presence of Polybrene (Sigma-Aldrich).

Realtime PCR
Total RNA was isolated using the TRIzol Reagent (Invitrogen) according to manufacturer’s protocol. Realtime PCR was performed on the LightCycler480 system (Roche) using SYBR Green Supermix (Takara). The realtime PCR reaction condition was 45 cycles of 30 s at 94°C, 5 s at 94 °C and 30 s at 60 °C.

Immunohistochemistry
Formalin-fixed samples were washed twice with PBS, followed by incubation with the blocking solution (0.2% Triton-100 and 5% goat serum in PBS) for 1h. Samples were then incubated with primary antibody and secondary antibody for 1h.

Western blotting assay
Whole cell lysates were prepared using pre-chilled RIPA. The samples were then centrifuged at 12000 g for 20min at 4°C and supernatants were collected for protein concentration determination. The total proteins was separated on SDS-PAGE gel, and transferred onto a nitrocellulose membrane. The membrane was then incubated with the blocking solution, followed by incubation overnight with appropriate primary antibodies at
4°C and subsequently with secondary antibodies for 1h at RT. The signals were visualized using LI-COR infrared imaging system (LI-COR) according to the manufacturer’s guidelines.

**Flow Cytometry**

Dissociated cells were incubated with primary antibodies for 20 min on ice, and washed twice with PBS. Cells were then incubated with corresponding secondary antibodies for 20 min. After washing, flow cytometry was carried out using a FACSA flow cytometer (BD Immunocytometry Systems). The antibodies used were anti-CD133, anti-CD44, anti-CD90, each at a dilution of 1:40.

**Statistical Analysis**

All data quantification and statistical analysis were performed with SPSS 13.0 software. Data are presented as the mean±SEM.

**Results**

**Establishment of primary osteosarcoma cell line C1OS**

Freshly resected osteosarcoma samples were minced with scissors into small pieces and explanted to pre-coated dishes. One week later, explants with epithelial monolayer outgrowth formed a halo (Fig. 1A). These explants were transferred into a new dish for subculture. After serial cultures, we derived a primary tumor cell line termed C1OS (Fig. 1B). To test whether C1OS cells may well represent osteosarcoma, an array-based gene
expression profile analysis was performed. We found that the gene expression profile of C1OS was similar to the commercial human OS cell line MG63 but not to skin fibroblast cells (Fig. 1C). In addition, the altered signaling pathways of C1OS resembled MG63, as indicated by an analysis on the array data (Fig. 1D). Moreover, the proliferation ability of C1OS resembled MG63 (Fig. 1E). The malignant potential of the C1OS was evaluated by injection of different amounts (10^6, 10^5, 10^4, 10^3, respectively) of C1OS cells into NOD/SCID mice. All four doses could form xenografts within 4 weeks after the injection, and the volume of the xenografts was correlated to the injection dose (Fig. 1F). The C1OS cell lines also displayed a significant ability to migrate and invade when tested using a trans-well system in vitro (Fig. 1G-1H). These data suggest that C1OS may well represent the original tumor.

Cancer stem cells derived from C1OS cells

Cancer stem cells were derived from C1OS following a workflow (Fig. 2A). Briefly, we generated a tumor sphere in a suspension culture, which was then injected into nude mice. The CSC populations were enriched under selection stress from cisplatin, and these drug-resistant cells were cultured in vitro to form cell colonies (Fig. 2A). The morphology of the acquired cancer stem cells could be seen in culture (Fig. 2B). When injected into NOD/SCID mice at same amount (10^4) as C1OS, C1OS-CSC formed a much bigger xenograft than C1OS, suggesting that C1OS-CSC cells grow faster (Fig. 2C). We thus analyzed the expression patterns of several cell surface markers and confirmed the stem
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Fig. 3. Bufalin inhibits the stemness of C1OS-CSCs. (A) CSCs were plated on the CSC culture system, and the cells treated with bufalin before and after 4- and 8-day incubations was shown. (B) Cleaved caspase3 was determined by western blotting. (C) Transcript levels of cancer stem cell markers were measured in the C1OS-CSCs cultured with bufalin or DMSO by quantitative PCR. (D) PCNA, Ki67 and sox-2 were measured in the C1OS and C1OS-CSCs cultured with or without bufalin by immunohistochemistry. (E) The xenograft tumor formation of C1OS-CSCs cultured with (up) or without bufalin (down). (F) miRNA profiling of C1OS-CSCs cultured with or without bufalin was performed using Affymetrix microarray analysis with miRNA array chips. Eight miRNAs were upregulated and ten were down-regulated in the C1OS-CSCs cultured with bufalin. *p<0.05.

Bufalin inhibits the proliferation of C1OS-CSCs

Recently, we reported that bufalin can inhibit the differentiation, proliferation and sphere formation of hMG63 cancer stem cells [18]. To test whether bufalin affects C1OS-CSCs, 10 µM bufalin was added to the culture of C1OS-CSCs cells. We found that bufalin induced shrinkage of C1OS-CSC spheres over 8 days of culture (Fig. 3A). This shrinkage of CSC spheres may be a result of the activation of caspase-3, which suggested enhanced apoptosis (Fig. 3B). To further determine of the effects of bufalin on the stemness of C1OS-CSCs, we measured the levels of several classic stem cell markers, such as ALDH1, TERT, NANO, CD133, Notch and Bim1, using quantitative real time PCR. In comparison to C1OS cultured with or without bufalin, the levels of stem cell markers were all down-regulated by the addition of bufalin (Fig. 3C). In addition, culturing with 10 µM bufalin for 4 days was enough to significantly inhibit the proliferation of C1OS-CSCs.
down-regulate the levels of the proliferation marker ki67 and PCNA and the stem cell marker SOX-2 (Fig. 3D). When injected into NOD/SCID mice, a lower ability of xenograft formation was found in bufalin-treated C1OS-CSCs compared to untreated C1OS-CSCs (Fig. 4E).

miRNAs were reported to be involved in carcinogenesis and stemness of OS cancer stem cell lines [32]. To identify the differentially expressed miRNAs, miRNA expression levels in C1OS-CSC cultured with or without bufalin expression was measured using a commercial microarray from Agilent (http://www.microrna.sanger.ac.uk/). miR-148a was found to have the greatest magnitude of increase in the 723 miRNAs tested after treatment with bufalin (Fig. 4F).

Overexpression of miR-148a significantly inhibits the stemness of C1OS-CSCs

Based on the above data, we postulated that overexpression of miR-148a may mimic the effects of bufalin on C1OS-CSCs. To test this hypothesis, we expressed miR-148a in C1OS-CSCs using the pLemiR vector. We found that overexpression of miR-148a inhibited the G2/M transition in C1OS-CSCs, which suggests an impaired self-renewing ability (Fig. 4A-B). In addition, miR-148a overexpression also inhibited the migration and invasion abilities of C1OS-CSCs (Fig. 4C-D).

Similar to bufalin, which can inhibit sphere formation in hMG63 cancer stem cells and C1OS-CSCs cultured in a non-adhesive culture system, overexpression of miR148a also inhibited the sphere formation of C1OS-CSCs (Fig. 4E). Moreover, the level of the stem cell marker SOX-2 was inhibited by transfection with miR-148a (Fig. 4F).
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The association of miR148a with human osteosarcoma

We have identified a critical role for miR-148a in cancer stem cells derived from primary OS cells. Then we further explored the association of miR-148a with human osteosarcoma. We found that the expression level of miR-148a in human osteosarcoma samples was approximately 60% of non-tumor tissues (Fig. 5A). DNMT1, the target of miR148a, was upregulated in these human samples (Fig. 5B). To identify the downstream target of DNMT1, we knocked down the expression of DNMT1 in C1OS-CSCs cell lines by siRNA. The expression levels of p27, a cyclin-dependent kinase inhibitor, were higher following the down-regulation of DNMT1 (Fig. 5C). In addition, inverse expression levels of DNMT1 and p27 were detected in the tumor formed in NOD-SCID mice by C1OS-CSCs treated with or without miR-148a (Fig. 5D).

Discussion

Over the past several decades, the survival rates of osteosarcoma patients have failed to improve and have reached a plateau, despite accumulating studies that have greatly increased our knowledge of this aggressive malignancy [33]. This is partially because the cellular mechanisms that lead to the development of OS chemoresistance and metastasis

Fig. 5. DNMT1 is the target of miR-148a. (A) Expression levels of miR-148a in osteosarcoma tumor or non-tumor tissue measured by quantitative PCR. (B) The level of DNMT1 in osteosarcoma tumor or non-tumor tissue measured by quantitative PCR. (C) Expression level of p27 in osteosarcoma tumor or non-tumor tissue measured by western blotting. (D) Representative immunohistochemistry images for miR-148a of tumors formed in NOD-SCID mice or untreated C1OS-CSCs. *p<0.05.
remain unclear. The emerging CSC theory has shed light on the study of the pathobiology of this disease. Based on this understanding, the strategy with which osteosarcoma is treated will also be updated. A new strategy that combines the CSC-targeted therapy and traditional chemotherapy is needed.

The base of developing a CSC-targeted therapy is the isolation of the tumor-type specific CSCs. Various methods, such as tumor spheres, sorting cells according to specific surface markers, side population cell sorting and other methods, were reported to be used in isolation and identification of osteosarcoma stem cells [14-17]. However, all these studies were based on established commercial cancer cell lines, whose ability to represent primary human tumors is limited by the genetic alternations that occur during increasing cultured period [34, 35]. We also need patient-derived primary tumor cells for the development of personalized therapy [36-38]. In this study, we successfully established a primary culture of OS cells, termed C1OS, from freshly resected tumor tissues, and derived a line of cancer stem cells from these primary cells. Because of their similar nature to tumor tissue, the establishment of cancer stem cells from primary tumors will facilitate the screening of new drugs specific to CSCs. However, taking the variability of patients into consideration, it is difficult to cover all the possible conditions by single cancer cell lines. More patient-derived primary tumor cell lines are needed in future studies.

A question arose once we have osteosarcoma CSC in hand. How can these CSCs be targeted and killed? miRNAs may play important roles in development of cancer [39]. However, targeting miRNAs have limitations on the treatment of human cancer because of the lack of appropriate in vivo delivery systems. To overcome such limitations, agents that can regulation expression levels of mRNA was used to target the CSCs. Natural agents could be a safer choice to be combined with conventional chemotherapeutics because of their non-toxic nature.

Our group has reported that bufalin can inhibit the proliferation and stemness of cancer stem cells derived from primary OS cells or the hMG63 cell line [18]. We compared the expression profile of miRNA in cancer stem cells cultured with or without bufalin and found miR148a to be the target of bufalin. miRNA expression profiling was performed in osteosarcomas by some researchers, but miR148a was not found to be significantly changed [40, 41]. It suggests that miR148a specifically mediates the effect of bufalin on osteosarcoma cancer stem cells.

DNA methyltransferases (DNMTs) was reported to be upregulated in cisplatin-resistant ovarian cancer [42]. One of the most widely used DNA methyltransferase inhibitors, decitabine (5-aza-2'-deoxycytidine, DAC), was also reported to have effects in targeting the human osteosarcoma HosDXR150 cell line [43]. Here we also found that DNMT1 severed as the target of mi-148a. The separated and combined effects of bufalin and DAC on osteosarcoma cancer stem cells are worth exploring in a future study.

In conclusion, we established a new and efficient approach for the establishment of a patient-derived cancer cell line, and we isolated CSCs from the primary cell line. Moreover, we found that bufalin was a potent agent in inhibiting the proliferation and differentiation of C1OS-derived CSCs. By examining the miRNA expression profile of C1OS cultured with or without bufalin, we identified miR-148a as a target that mediates the effects of bufalin. The downstream target of miR148a, DNMT1, was also identified in C1OS derived cancer stem cells. We further identified the function of bufalin, i.e., that it plays a role in the miR148a and DNMT1 pathway in osteosarcoma patients and targets p27 as a downstream signal of DNMT1. Through an in-depth study of biological characteristics and related signal pathways to identify specific targets, our data may offer hope for eradicating osteosarcoma using this compound.

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Disclosure Statement

No potential conflict of interest was declared.

References

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