RNAi-mediated silencing of the Bmi-1 gene causes growth inhibition and enhances doxorubicin-induced apoptosis in MCF-7 cells

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Abstract

The oncogene Bmi-1 is a member of the Polycomb group gene family. Its expression is found to be greatly increased in a number of malignant tumors including breast cancer. This could suggest Bmi-1 as a potent therapeutic target. In this study, RNAi was introduced to down-regulate the expression of Bmi-1 in a highly malignant breast adenocarcinoma cell line, MCF-7. A thorough study of the biological behavior and chemosensitivity changes of the MCF-7 cells was carried out in context to the therapeutic potential of Bmi-1. The results obtained indicated that siRNA targeting of Bmi-1 could lead to an efficient and specific inhibition of endogenous Bmi-1 activity. The mRNA and protein expression of Bmi-1 were determined by RT-PCR and Western blot, respectively. Furthermore, silencing of Bmi-1 resulted in a drastic inhibition of the growth of MCF-7 cells as well as G1/S phase transition. The number of target cells was found to increase in phase G0/G1 and decrease in the S phase, but no increase in the basal level of apoptosis was noticed. On the other hand, a reduction in the expression of cyclin D1 and an increase in the expression of p21 were also noticed. Silencing of Bmi-1 made the MCF-7 cells more sensitive to the chemotherapeutic agent doxorubicin and induced a significantly higher percentage of apoptotic cells. Here, we report on a study regarding the RNAi-mediated silencing of the Bmi-1 gene in breast cancer.

Key words: RNA interference, Bmi-1, retrovirus vector, doxorubicin, breast cancer.

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Introduction

Breast cancer is one of the most common malignancies affecting women worldwide. Despite the recent development of various therapeutic strategies, the prognosis for this cancer still remains poor. Thus, more efforts are needed to understand its molecular pathway in order to develop an effective therapy to achieve cure.

Bmi-1 (B-cell-specific moloney murine leukemia virus insertion site 1) was originally identified as an oncoprotein partner of c-Myc in murine lymphomagenesis (Haupt et al., 1993; Van Lohuizen et al., 1991). It is a component of the Polycomb repressive complex 1, which represses gene expression through chromatin modifications (Valklingbeek et al., 2004). Previous studies have revealed that Bmi-1 is involved in the regulation of stem-cell-associated genes to control cell self-renewing and differentiation (Park et al., 2003; Molofsky et al., 2005). Other studies also demonstrated that Bmi-1 regulates the differentiation and clonogenic self-renewal of I-type neuroblastoma cells (Cui et al., 2006).

Bmi-1 is overexpressed in several malignancies, such as non-small cell lung cancer (Vonlanthen et al., 2001), colorectal cancer (Kim et al., 2004a), nasopharyngeal carcinoma (Song et al., 2006) and oral cancer (Kang et al., 2007). On the other hand, loss of Bmi-1 with RNA interference (RNAi) was effective in suppressing growth and tumorigenicity of cancer cells (such as SH-SY5Y neuroblastoma and ovary adenocarcinoma) (Liu et al., 2006a). This is consistent with the study of Cui et al. (2007) that showed that down-regulation of Bmi-1 impaired the ability of neuroblastoma cells to grow in soft agar and tumorigenicity in immunodeficient mice. Therefore, silencing of Bmi-1 may be of great importance in the design and development of anticancer therapy. However, to our best knowledge, there is so far no study in the literature on the therapeutic potential of Bmi-1 in breast cancer cell lines.

Notably, Bmi-1 was found to regulate self-renewal of breast cancer stem cells and to alter mammary development in a humanized nonobese diabetic-severe combined...
immunodeficient (SCID) mouse model (Liu et al., 2005; 2006b). Overexpression of Bmi-1 induces telomerase activity and immortalizes human mammary epithelial cells (MECs), suggesting a potential role for Bmi-1 in the development of human breast cancer (Dimri et al., 2002). Amplification of the Bmi-1 gene is detected in approximately 85% of human invasive ductal breast cancers and this genomic alteration is correlated with axillary lymph node metastases and positive estrogen receptor status (Kim et al., 2004b). Furthermore, the Bmi-1 mRNA transcript levels are higher in plasma from breast carcinoma patients than in healthy controls, and this amplification of Bmi-1 is predictive of poor clinical outcome (Silva et al., 2007).

Doxorubicin has emerged as one of the most widely used chemotherapeutic agents for breast cancer. Although there is initial response to this chemotherapeutic agent, resistance is seen to develop over a period of time. This leads to a phenotypically more aggressive cell variant with an increased likelihood of metastasize. So, increasing chemosensitivity is very important for breast cancer therapy.

A study on Bmi-1 mRNA levels in several breast cancer cell lines (MCF-7, MDA-MB-468, MDA-MB-231, T47D) was carried out. In MCF-7 and MDA-MB-231 Bmi-1 expression was found to be maximal. In order to investigate the possibility of turning Bmi-1 into a novel therapeutic agent for the treatment of breast cancer, MCF-7 was chosen to silence the expression of Bmi-1 with highly specific post-transcriptional suppression of RNAi. Therefore, proliferation, cell cycle status, apoptosis, and chemosensitivity to doxorubicin were also studied. The results obtained suggest that targeting of Bmi-1 may be used as a potential and specific therapeutic tool for the treatment of breast cancer.

Materials and Methods

Cell line and reagents

The highly malignant human breast adenocarcinoma cell line MCF-7 was obtained from Dr. Y. In (Third Military Medical University, China). The human Bmi-1 gene short hairpin RNA (shRNA)-expressing plasmid pSuper-retro/Bmi-1 si and a control plasmid pSuper-retro/GFP si expressing Green Fluorescent Protein (GFP) shRNA (Cui et al., 2007) were used. The Bmi-1 siRNA sequence was 5'-AATGGACTACCTACTAATCT-3', position 546 to 564 bp relative to the start codon. The GFP target sequence was 5'-AATGGACATACCTAATACT-3', position 546 to 554 bp. The PCR target sequence was 5'-CGTCCTTCCACGATAAG-3' (sense), and 5'-CATTTGTCAGTCCATCTCTC-3' (anti-sense). GAPDH, 5'-CATGAGAAGTATGACAAAGG-3' (sense), and 5'-CATTTGTCAGTCCATCTCTC-3' (anti-sense)."
tion of the mixture of ProLong mounting medium and Pro-
Long Antifade reagent onto the slides. Fluorescent images
were taken by confocal laser-scanning microscopy using a
Leica TCS SP confocal system attached to a Leica DM
IRBE microscope; 568 nm laser wavelength was used for
analysis.

Western blot analysis

Total protein was isolated and quantified. Cells transfec-
ted for 48 h were harvested, washed with ice-cold PBS
and lysed in lysis buffer containing 25 mM Tris-HCl, pH
8.0, 137 mM NaCl, 2.7 mM KCl, 1% Triton X-100 and pro-
tease inhibitor mixture (Sigma, USA) at 4 °C for 30 min,
followed by brief sonication. All the experimental steps
were performed on ice. After centrifugation at 16,220 g at
4 °C for 10 min, supernatants were collected, and the pro-
tein concentration was measured with the BCA assay re-
agent (Biotek, China) according to the manufacturer’s
protocol. Following sodium dodecyl sulfate-polyacryl-
amide gel electrophoresis (SDS-PAGE), the proteins were
transferred onto a PVDF membrane (Immobilon, USA).
After saturation, the membranes were incubated at room
temperature for 2 h in TBS with 0.1% Tween-20 (TBS-T)
containing 5% nonfat dry milk, and subsequently incubated
with primary antibodies against Bmi-1 (1:600 dilution),
cyclin D1 and p21 (1:200 dilution, Santa Cruz, USA) over-
with primary antibodies against Bmi-1 (1:600 dilution),
cyclin D1 and p21 (1:200 dilution, Santa Cruz, USA) over-
night at 4 °C. Peroxidase conjugated IgG antibodies
were used as secondary antibod-
ies. The protein was detected using the ECL detection
kit (keygen, China) following the manufacturer’s protocol.
β-actin immunoblotting was used as protein loading con-
control.

MTT assay

The MTT assay was used to detect the effect of plasmids
on the growth of MCF-7 cells and to determine the
50% inhibitory concentration (IC50) of doxorubicin. For measurement of cell growth curves, cells (10^5/well) were
plated into 96-well plates and allowed to grow for 4 days af-
ter transfection with pSuper-retro/Bmi-1 si and pSuper-
retro/GFP si. Growth curves were plotted as optical density (570 nm) versus days after transfection. To study the IC50,
48 h after transfection, cells were treated with various con-
centrations of doxorubicin (0.03-100 μg/mL) for 72 h. At
each time point, 10 μL of MTT stock solution (5 mg/mL in
PBS) were added to each microtiter well and incubated for
4 h at 37 °C. After aspiration of the medium, 150 μL of
dimethyl sulfoxide was added and mixed, and absorbances
were measured at a wavelength of 570 nm. The rate of cell
growth inhibition (IR) was calculated according to the fol-
lowing equation: IR = [1–A_{570}(drug)/A_{570}(control)] 100%,
where A_{570}(drug) is the absorbance of the cells exposed to
doxorubicin and A_{570}(control) is the absorbance of the cells
without doxorubicin treatment.

Cell cycle assay

The cell cycle was analyzed by using flow cytometry
(FCM) with propidium iodide staining. Both floating and
attached cells were collected by trypsin digestion and low-
speed centrifugation, washed with cold PBS, and then fixed
in ice-cold 70% ethanol overnight. The fixed cells were col-
lected by brief centrifugation and resuspended in PBS, after
which the cells were treated with RNaseA and stained with
propidium iodide for 1 h at room temperature, and finally
analyzed by FCM.

Apoptosis assay

Apoptosis was assayed using the Annexin V-FITC
Apoptosis Kit (keygen, China) according to the manufac-
turer’s instructions. Briefly, the cells were harvested and
washed twice with PBS, followed by resuspension in
Annexin-V binding buffer, and then FITC-conjugated Annexin V and PI were added. After incubation for 10 min
at room temperature in the dark, another binding buffer was
added, and the samples were immediately analyzed using
FCM.

Statistical analysis

All experiments were performed at least three times
and statistical analysis was done using the SPSS13.0 pack-
age (SPSS Inc., Chicago, USA). The values were expressed
as mean ± SD. The ANOVA test was used whenever more
than two groups were compared, and the significance level
was set at p < 0.05. Dunnett’s post hoc test was used to ana-
yze multiple comparisons. P values of less than 0.05
(p < 0.05) were considered to be statistically significant.

Results

Inhibition of Bmi-1 expression at the mRNA and
protein levels

In the first phase of our study, we determined the si-
encing of the Bmi-1 gene activity in the targeted MCF-7
cells. MCF-7 cells were transiently transfected with
pSuper-retro/Bmi-1 si and pSuper-retro/GFP si. After
transfection for 48 h, total RNA and whole-cell lysates
were prepared and subjected to semiquantitative RT-PCR
and Western blot, respectively. Figure 1 clearly indicates
that the Bmi-1/GAPDH ratio of band density in Bmi-1si
was significantly lower and also shows a 67% reduction
in density compared to the blank control. In GFPsi, the same
ratio showed a 5.2% reduction compared to the blank con-
trol. The differences between Bmi-1si and controls were
statistically significant (p < 0.05). Similarly, the protein
level of Bmi-1 in Bmi-1si showed a reduction of up to 70%,
clearly indicating a marked difference from that of the
blank control and GFPsi (p < 0.05) (Figure 2B). Compared
with the blank control and GFPsi, immunofluorescent
staining showed a significantly weaker fluorescence in the
Bmi-1si MCF-7 cells (Figure 2A).
**Bmi-1 silencing inhibited MCF-7 cell proliferation**

The MTT assay indicated strong inhibition in the growth rate of Bmi-1si MCF-7 cells compared to that of the blank control and GFPsi. After 24 h and 48 h of transfection, the optical density (570 nm) in Bmi-1si showed no significant differences compared to the blank control and GFPsi. However, 72 h after transfection, there were significant differences between Bmi-1si and controls (Figure 3).

**Bmi-1 silencing induced G0/G1 cell cycle arrest and abnormal expression of cyclin D1 and p21**

The effect of Bmi-1 silencing on cell cycle progression was analyzed using FCM. Bmi-1 silencing induced an obvious increase in the number of cells at G0/G1 phase and reduction in S phase, as 77.10% of the MCF-7 cells in Bmi-1si were noticed at G0/G1 phase, compared to 63.75% and 64.84% cells in the blank control and GFPsi, respectively (Figure 4A). There were significant differences between Bmi-1si and controls (p < 0.05). Western blot results clearly showed a reduction in the expression of cyclin D1 and an increase of p21 in Bmi-1si compared to the blank control and GFPsi (Figure 4B, C).

**Apoptosis not induced by Bmi-1 silencing**

The apoptotic rate was examined in three groups 48 h after transfection and the results are shown in Figure 5A. The basal level of apoptosis in Bmi-1si was 4.94%, compared to 3.18% and 2.84% in the blank control and GFPsi, respectively. No significant differences in cell apoptosis were noticed among these three groups.

**Bmi-1 silencing increased doxorubicin-induced apoptosis**

The apoptotic rate was further examined in cells after treatment with 1 μg/mL doxorubicin for 48 h. The FCM data showed that the apoptotic rate in Bmi-1si treated with doxorubicin was 37%, as compared to 21% in the blank control also with doxorubicin. The levels of apoptosis in the

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**Figure 1** - RT-PCR analysis of Bmi-1 mRNA level of MCF-7 cells 48 h after transfection. The ratio of band density for Bmi-1 to GAPDH in Bmi-1si was significantly lower, showing a 67% reduction in density as compared to the blank control; in GFPsi, the ratio showed a 5.2% reduction compared to the blank control. There were significant differences between Bmi-1si and controls (p < 0.05). Bar graphs represent the results of the densitometry analysis of Bmi-1, expressed as a percentage of the ratio (molecule of interest/GAPDH mRNA) detected in the control (*p < 0.05 vs. control).

**Figure 2** - Effect of Bmi-1 silencing on the expression of Bmi-1 protein in MCF-7 cells. (A) Immunofluorescent staining of Bmi-1 48 h after transfection, showing a significantly weaker fluorescence in MCF-7 cells of Bmi-1si compared to the blank control and GFPsi (Scale bars, 100 μm). (B) Western blot analysis of Bmi-1 expression 48 h after transfection, showing a reduction of up to 70% in the protein level of Bmi-1, clearly indicating a marked difference from that of the blank control and GFPsi (p < 0.05).

**Figure 3** - Effect of Bmi-1 silencing on proliferation of MCF-7 cells. Growth curves of MCF-7 cells were analyzed by MTT assay. At 24 h and 48 h after transfection, the optical density (570 nm) in Bmi-1si showed no significant differences compared to the blank control and GFPsi. However, 72 h after transfection, there were significant differences between Bmi-1si and controls. The MTT assay indicated strong inhibition in the growth rate of MCF-7 cells in Bmi-1si. Each value represents the mean standard deviation (SD) of triplicate cultures.
Bmi-1 silencing affects growth and apoptosis of MCF-7

blank control and Bmi-1si were 6.70% and 6.72%, respectively (Figure 5B). The differences between Bmi-1si treated with doxorubicin and the blank control treated with doxorubicin were significant (p < 0.05).

**Bmi-1 silencing made the cells more sensitive to doxorubicin**

After treatment with various concentrations of doxorubicin for 72 h, we found that the Bmi-1si cells showed a

![Figure 4 - Effect of Bmi-1 silencing on cell cycle progression and expression of cyclin D1, p21 of MCF-7 cells.](image)

**Figure 4** - Effect of Bmi-1 silencing on cell cycle progression and expression of cyclin D1, p21 of MCF-7 cells. (A) The effect of Bmi-1 silencing on cell cycle progression as shown by FCM. Cells were harvested 48 h after transfection and then stained with propidium iodide (PI). Bmi-1 silencing induced an obvious increase in the number of cells at G0/G1 phase and reduction in S phase; 77.10% of the MCF-7 cells in Bmi-1si were found at G0/G1 phase, compared to 63.75% and 64.84% cells in blank control and GFPsi, respectively. There were significant differences between Bmi-1si and controls (p < 0.05). (B) and (C) Western blot analysis of cyclin D1 and p21 in MCF-7 cells 48 h after transfection. Relative levels of protein are indicated. β-actin levels are shown as loading control. Compared with blank control and GFPsi, a reduction in the expression of cyclin D1 and an increase in the expression of p21 were also noticed (p < 0.05).

![Figure 5 - (A) Effect of Bmi-1 silencing on cell apoptosis in MCF-7 cells.](image)

**Figure 5** - (A) Effect of Bmi-1 silencing on cell apoptosis in MCF-7 cells. Cells were harvested 48 h after transfection and then stained with Annexin/PI for apoptosis detection. (a) Blank control, (b) GFPsi, (c) Bmi-1si. The basal level of apoptosis in Bmi-1si was 4.94%, while in the blank control and GFPsi it was 3.18% and 2.84%, respectively. No significant differences in cell apoptosis were noticed among these three groups. (B) Effect of Bmi-1 silencing on doxorubicin-induced apoptosis. The apoptotic rate was examined in cells after treatment with 1 μg/mL doxorubicin for 48 h. (a) Blank control, (b) blank control treated with 1 μg/mL doxorubicin, (c) Bmi-1si, (d) Bmi-1si treated with 1 μg/mL doxorubicin. The level of apoptosis in the blank control and Bmi-1si was 6.70% and 6.72%, respectively. The apoptotic rate in Bmi-1si treated with doxorubicin was 37%, while in the blank control treated with doxorubicin it was 21%. This difference was significant (p < 0.05).
higher IR than the blank control and GFPsi. The IC_{50} value of doxorubicin in Bmi-1si was 0.12 ± 0.07 μg/mL, compared to 0.86 ± 0.02 μg/mL in the blank control and 0.84 ± 0.02 μg/mL in GFPsi, respectively (Figure 6). There were significant differences between the IC_{50} of Bmi-1si and that of controls.

**Discussion**

Previously, BE(2)-C cells infected with Bmi-1 siRNA expressing retrovirus showed a 70%-80% reduction in the Bmi-1 protein level (Cui et al., 2006). In the present study, the same retrovirus vector was used to transiently transfect MCF-7 cells, resulting in 67% and 70% reductions of Bmi-1 mRNA and protein levels, respectively. These data indicate that the RNAi strategy to silence Bmi-1 is specific and effective.

In this study, we found that the growth of MCF-7 cell was significantly retarded by Bmi-1 silencing. Because the Bmi-1-specific growth retardation was mediated by a delayed cell cycle progression and/or an increased level of apoptosis (Meng et al., 2005; Liu et al., 2006a; Yu et al., 2007), we measured the cell cycle distribution and apoptosis ratio by FCM, in order to determine the relation between inhibition of cell growth and cell cycle arrest or apoptosis.

According to our results, Bmi-1 silencing both disrupted cell cycle progression and inhibited G1-S phase transition significantly. The increase in the number of cells in G0/G1 phase and decrease in S phase are consistent with the previous results observed in K562 (Meng et al., 2005) and leukemic cells (Lessard and Sauvageau, 2003). Bmi-1 negatively regulates p16^{INK4a} (Jacobs et al., 1999), which acts in the P16^{INK4a}-pRb pathway. P16^{INK4a} affects pRb by inhibiting the cyclin D/cyclin-dependent kinase 4/6 kinase complex. In the absence of Bmi-1, p16^{INK4a} may get up-regulated and prevent binding of cyclin-dependent kinase 4/6 to cyclin D, thus inhibiting kinase activity. This in turn results in hypophosphorylation of pRb, which ultimately leads to cell cycle arrest, senescence, or apoptosis, depending on context (Sherr, 2001). Our study shows that the marked down-regulation of cyclin D1 might be related to the inhibition of the G1-S phase transition.

Our results indicate that the expression of p21 protein was increased. Bmi-1 can negatively regulate ARF, which probably promotes senescence by regulating the ARF-p53-p21 pathway (Jacobs et al., 1999; Dimri et al., 2000). Evidence has shown the key role of p21 in senescence. Abrogation of the p53-p21 pathway by various strategies can bypass senescence in human and mouse cells, a variety of stimuli induce senescence in a p53/p21-dependent manner and enforced expression of p21 in certain cell types can induce a senescence-like phenotype (Dimri, 2005). So, we conjectured that p21 might be involved in the senescence induced by Bmi-1 silencing.

Bmi-1 may negatively regulate p19ARF, which sequesters the p53 inhibitor MDM2 and thereby prevents the degradation of p53, resulting in p53-mediated apoptosis (Jacobs et al., 1999). So, loss of Bmi-1 may promote cell apoptosis (Liu et al., 2006a). However, in agreement with previous findings in human I-type neuroblastoma cells (Cui et al., 2006) and in A549 lung cancer cells (Yu et al., 2007), we observed no significant cell apoptosis. This suggests that Bmi-1 silencing affects cell apoptosis, which may vary in different cell lines. We therefore conclude that Bmi-1 silencing may induce the inhibition of MCF-7 cell proliferation through a mechanism that is largely dependent on cell cycle regulation, but not on apoptosis.

We also studied the role of Bmi-1 on chemotherapy-induced apoptosis in MCF-7 cells and found that the down-regulation of Bmi-1 resulted in an increased sensitivity of these cells to doxorubicin, expressed by apoptosis. This report is consistent with a previous result observation in nasopharyngeal carcinoma cells (Qin et al., 2008).

Altogether, our study demonstrates that siRNA targeting of Bmi-1 led to the efficient and specific inhibition of endogenous Bmi-1 mRNA and protein expression of MCF-7 cells in vitro. Down-regulation of Bmi-1 inhibited the proliferation and increased the chemosensitivity of MCF-7 cells, indicating that Bmi-1 can be developed into a therapeutic option for the treatment of breast cancer. Further studies will be directed toward uncovering the mechanism underlying the enhancement of doxorubicin-induced apoptosis by the silencing of Bmi-1.

**References**

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