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# Myc is a prognostic biomarker and potential therapeutic target in osteosarcoma

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## Abstract

**Background:** Over the past four decades, outcomes for osteosarcoma patients have plateaued as there have been few emerging therapies showing clinical results. Thus, the identification of novel biomarkers and therapeutic strategies are urgently needed to address these primary obstacles in patient care. Although the Myc-oncogene has known roles in oncogenesis and cancer cell growth, its expression and function in osteosarcoma are largely unknown.

**Methods:** Expression of Myc was determined by Western blotting of osteosarcoma cell lines and patient tissues, and by immunohistochemistry of a unique osteosarcoma tissue microarray (TMA) constructed from 70 patient samples with extensive follow-up data. Myc specific siRNA and inhibitor 10058-F4 were applied to examine the effect of Myc inhibition on osteosarcoma cell proliferation. The clonogenicity and migration activity was determined by clonogenic and wound-healing assays. A mimic *in vivo* assay, three-dimensional (3D) cell culture model, was performed to further validate the effect of Myc inhibition on osteosarcoma cell tumorigenic markers.

**Results:** Myc was significantly overexpressed in human osteosarcoma cell lines compared with normal human osteoblasts, and also highly expressed in fresh osteosarcoma tissues. Higher Myc expression correlated significantly with metastasis and poor prognosis. Through the addition of Myc specific siRNA and inhibitor, we significantly reduced Myc protein expression, resulting in decreased osteosarcoma cell proliferation. Inhibition of Myc also suppressed the migration, clonogenicity, and spheroid growth of osteosarcoma cells.

**Conclusion:** Our results support Myc as an emerging prognostic biomarker and therapeutic target in osteosarcoma therapy.

**Keywords:** Myc, osteosarcoma, prognostic marker, therapeutic target, tissue microarray

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## Introduction

Osteosarcoma is a primary bone tumor most often affecting adolescents and young adults.<sup>1</sup> Current treatment strategies consist of surgical resection combined with cytotoxic chemotherapeutics. Aggressive treatment measures have resulted in a 5-year survival rate for non-metastatic osteosarcoma of 70%, and only 15–30% for those patients with metastatic and recurrent disease.<sup>2,3</sup> Despite advances of targeted chemotherapeutics in other cancers, they have not been implemented in osteosarcoma. This has, in part, caused overall survival of osteosarcoma patients

to plateau over the past few decades.<sup>4</sup> In addition, there are no reliable prognostic biomarkers for osteosarcoma. Given these limitations, there is a clear need for novel biomarkers and therapeutic targets in osteosarcoma therapy.

Myc (avian myelocytomatosis viral oncogene homolog) is one of the most commonly activated oncogenes in human cancers and indicative of poor outcomes when amplified.<sup>5–8</sup> Its roles in cancer are ubiquitous, as it promotes growth, cell cycle progression, metabolism, and survival.<sup>9–11</sup> In response to these observations, multiple studies have

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targeted Myc expression and subsequently shown favorable results, making it an attractive therapeutic target in cancer.<sup>12–14</sup> However, the expression of Myc, its prognostic significance, and the potential of its precise targeting within osteosarcoma are not well defined. We have, therefore, examined Myc expression in osteosarcoma patient specimens and found them to correlate with metastasis and poor prognosis. We also demonstrated the function of Myc in osteosarcoma cell proliferation, colonization, and migration *in vitro*.

## Materials and methods

### Cell lines and cell culture

Human osteoblast cells hFOB were purchased from the American Type Culture Collection (ATCC), and NHOst were purchased from Lonza Walkersville Inc. (Walkersville, MD, USA). These cell lines were cultured in osteoblast growth medium (PromoCell) with 10% fetal bovine serum (FBS, Sigma-Aldrich, St. Louis, MO, USA). Human osteosarcoma cell line KHOS was kindly provided by Efstathios Gonos (Institute of Biological Research and Biotechnology, Athens, Greece), while other cell lines U2OS, MG63, MNNG/HOS, Saos-2, and 143B were purchased from ATCC. The osteosarcoma cell lines were cultured in RPMI 1640 (GE Healthcare Life Sciences, Logan, UT, USA) supplemented with 10% FBS and 1% penicillin/streptomycin (Thermo Fisher Scientific, Waltham, MA, USA), at 37°C and 5% CO<sub>2</sub> in a humidified incubator. Cells were resuspended with 0.05% trypsin-EDTA before subculture.

### Human sarcoma tumor tissues

Eight of the osteosarcoma tissue samples (OST1–OST8) were obtained from the sarcoma tissue bank of the department of orthopaedic surgery, David Geffen School of Medicine at University of California Los Angeles (UCLA). The study was approved by the institutional review board of the hospital (IRB#19-000096; Collection of tissue specimens and clinical data from subjects with sarcoma). Informed consent was received from all patients included in the current study or their direct relatives. All diagnoses were confirmed histologically.

### Protein extraction and western blotting

Total protein was extracted from osteosarcoma cells or tissues using a mixture of 1× RIPA

(radioimmunoprecipitation assay) lysis buffer (Sigma-Aldrich) and protease inhibitor cocktail tablets (Roche Applied Science, Indianapolis, IN, USA). Protein concentration was determined with a protein determination reagent (Bio-Rad, Hercules, CA, USA) and spectrophotometer (Molecular Devices, Inc., San Jose, CA, USA). Equal amounts of protein were separated in NuPAGE 4–12% Bis-Tris Gel (Thermo Fisher Scientific) then transferred to a nitrocellulose membrane (Bio-Rad). After blocking for 1 h, the membrane was incubated overnight with the following specific primary antibodies at 4°C: Myc (#13987 1:1000 dilution, Cell Signaling Technology, Danvers, MA, USA), and β-Actin (#A1978, 1:2000 dilution, Sigma-Aldrich). The second day, the membrane was washed three times for 5 min each with Tris-buffered saline containing Tween 20. A diluted secondary antibody was then applied: goat anti-rabbit IRDye 800CW and goat anti-mouse IRDye 680LT (1:10,000 dilution Li-Cor Biosciences, Lincoln, NE, USA). Then, 1 h later, the secondary antibody was aspirated and washed with 1× phosphate-buffered saline (PBS). The protein band was detected by Odyssey CLx equipment. Finally, Odyssey v.3.0 software (Li-Cor Biosciences) was used to quantify protein bands by optical density measurement.

### Immunofluorescence

The osteosarcoma cell lines were placed at a concentration of  $5 \times 10^4$  cells/ml in 24-well plates for 48 h and fixed with 4% paraformaldehyde for 15 min at room temperature before being permeabilized with 100% ice-cold methanol in a –20°C refrigerator for 10 min. They were then blocked with 5% goat serum for 1 h. The Myc primary antibody (1:200 dilution, Cell Signaling Technology), and β-Actin (1:1000 dilution, Sigma-Aldrich) were applied and incubated overnight in a 4°C cold room. The next day, the cells were incubated with a fluorochrome-conjugated secondary antibody for 1 h at room temperature in the dark. The secondary antibodies Alexa Fluor 488 (Green)-conjugated goat anti-rabbit antibody, and Alexa Fluor 594 (Red) goat anti-mouse antibody (1:1000 dilution, Invitrogen, New York, NY, USA) were diluted in 5% goat serum at 1:1000. Finally, Hoechst 33342 (1 μg/ml, Invitrogen) was added to counter-stain the cell nucleus. Pictures were obtained with a Nikon Eclipse Ti-U fluorescence microscope (Diagnostic Instruments Inc., New York, NY, USA) equipped with a SPOT real-time

transactional memory (RTTM) digital camera (Diagnostic Instruments Inc.).

#### *Osteosarcoma TMA construction and immunohistochemistry*

A total of 114 formalin-fixed paraffin-embedded tumor specimens, comprising primary, recurrent, and metastatic specimens, were obtained from 70 patients with osteosarcoma. The primary antibody of Myc for immunohistochemistry (IHC) was purchased from Abcam (ab32072, 1:50 dilution in 1% bovine serum albumin; Abcam, Cambridge, UK). The construction of TMA and IHC staining was conducted as previously described.<sup>15</sup>

#### *Analysis of IHC staining in TMA*

Nuclear staining patterns of Myc on the TMA slide were scored. The percentage of nuclear Myc immunostaining was assessed independently by two scientists without knowledge of the clinical information using the following criteria: 0, no nuclear staining; 1+, <10% positive cells; 2+, 10–25% positive cells; 3+, 26–50% positive cells; 4+, 51–75% positive cells; 5+, >75% positive cells. Low Myc expression subset included group 0; 1+ and 2+, while the high Myc expression subset included group 3+, 4+ and 5+. Myc staining images were obtained using a Nikon Eclipse Ti-U fluorescence microscope (Diagnostic Instruments Inc.) with a SPOT RTTM digital camera (Diagnostic Instruments Inc.). We divided the patients who received neoadjuvant chemotherapy into two groups; good response:  $\geq 90\%$  necrosis; poor response: <90% necrosis.

#### *siRNA knockdown of Myc*

We used synthetic Myc siRNA to knockdown the expression of Myc in osteosarcoma cells. Human nonspecific small interfering RNA (siRNA; Catalog #:AM4637) was purchased from Applied Biosystems (Foster City, CA, USA) and Myc siRNA (target sequence: 5'-CGUCCAAGCAGAGGA GCAA-3'; antisense:5'-UUGCUCUCUCU GCUUGGACG-3') was purchased from MilliporeSigma (Burlington, MA, USA). Lipofectamine RNAiMax was purchased from Thermo Fisher Scientific. Transfection of siRNA and methyl thiazolyl tetrazolium (MTT) were performed as previously described. In brief, osteosarcoma cell lines KHOS and U-2OS were prepared at a concentration of  $2 \times 10^4$  cells/ml for siRNA and methyl thiazolyl tetrazolium assay

(MTT) in 96-well plates, and  $5 \times 10^4$  cells/ml for protein extraction in 12-well plates. Concentration of Myc siRNA at 10, 30, and 60 nM were transfected with the Lipofectamine RNAiMax reagent (Thermo Fisher Scientific) following the manufacturer instructions. Non-specific siRNA (60 nM) was used as a negative control.

#### *Inhibition of Myc by inhibitor 10058-F4*

The role of Myc expression in osteosarcoma cell growth and proliferation was further assessed by Myc inhibitor. Myc inhibitor 10058-F4 was purchased from Thermo Fisher Scientific. 10058-F4 induces cell-cycle arrest and apoptosis. It is a cell-permeable compound that specifically inhibits the Myc–Max interaction and prevents transactivation of Myc target gene expression. 10058-F4 inhibits tumor cell growth in a Myc-dependent manner both *in vitro* and *in vivo*.<sup>16–19</sup> Osteosarcoma cell lines KHOS and U2OS were grown in 96-well plates for treatment of 10058-F4 incubated with various concentrations for 2, 3, or 5 days, and subsequently used for MTT cell proliferation assays. KHOS and U2OS cells were also grown in 12-well plates with treatment of 10058-F4 for extraction of protein and for Western blotting analysis as previously described.<sup>15</sup>

#### *Clonogenic assay*

Clonogenic assay was performed to evaluate the effect of Myc inhibition on cell viability and proliferation. Osteosarcoma cell lines KHOS and U2OS were prepared in 12-well plates with 100 cells/well, and treated with 10058-F4 with different concentrations (0, 20, 30  $\mu\text{M}$ ). After a 15-day incubation period, the colonies were then fixed with methanol for 10 min, washed three times with PBS, then stained for 20 min with 10% Giemsa stain (MilliporeSigma). The colonies were then washed with flowing water and dried. A digital camera (Olympus, Tokyo, Japan) was used to capture pictures of the stained colonies.

#### *Three-dimensional cell culture*

In order to simulate the *in vivo* environment, a three-dimensional (3D) cell culture assay was used to evaluate the effect of Myc on osteosarcoma cell growth. According to the manufacturer's protocol, we mixed the hydrogel with the osteosarcoma cells at a density of  $1 \times 10^4$  cells/ml, then seeded them in a 24-well VitroGel 3D cell culture plate (The Well Bioscience, Newark, NJ,

USA) covered with different cell culture media (with or without 10  $\mu$ M 10058-F4). The plate was placed in an incubator and the covering medium was changed every 48h. Every 3 days, spheroids were selected based on their size, volume, and morphology, and imaged by microscope equipped with a digital camera. A cell culture medium containing 0.25  $\mu$ M calcein AM (Thermo Fisher Science) was applied 15 days later to cover the hydrogel. Spheroids were imaged 15 min after incubation, with an Eclipse Ti-U fluorescence microscope (Nikon) equipped with a SPOT real-time (RT) digital camera. The diameter of spheroids was measured three times using ImageJ software as previously described (<https://imagej.nih.gov>).<sup>15,20</sup>

#### Wound-healing assay

Cell migration ability was measured by a wound-healing assay. In short, osteosarcoma cells were inoculated in 12-well plates at a density of  $4 \times 10^4$  cells/ml for 24h. In each well, we scraped two parallel lines with a 30  $\mu$ l sterile tip. Next, the cells were incubated with 3% fetal bovine serum medium, with the experimental group wells receiving 10  $\mu$ M 10058-F4. Images were obtained at 0, 24, 48, and 72h with a Diagnostic Instruments equipped with Zen Imaging software (Carl Zeiss, Oberkochen, Germany). The width of the wound was assessed by measuring the distance between the two edges of the scratches at five locations in each image. The following formula was used to determine the cell migration distance: (wound width at 0h – wound width at observation point)/2.

#### Statistical analysis

GraphPad Prism v.8.0 software and SPSS 24.0 software were used for statistical analysis. One-way analysis of variance (ANOVA) tests were performed for multiple comparisons. Difference in survival were analyzed by Kaplan–Meier plots and log-rank tests. The relationship between Myc expression and clinicopathological parameters in patients with osteosarcoma was evaluated by the  $\chi^2$  test. A Cox proportional hazard regression model was employed to analyze the prognostic factors related to overall survival in a stepwise manner. Multivariate analysis was involved only in those factors that had statistical significance with univariate survival analysis ( $p < 0.05$ ). The therapeutic effect of Myc siRNA and inhibitor on osteosarcoma cells was analyzed by one-way

ANOVA assay. In all cases, the results were presented as mean  $\pm$  SD, and  $p < 0.05$  was considered statistically significant.

## Results

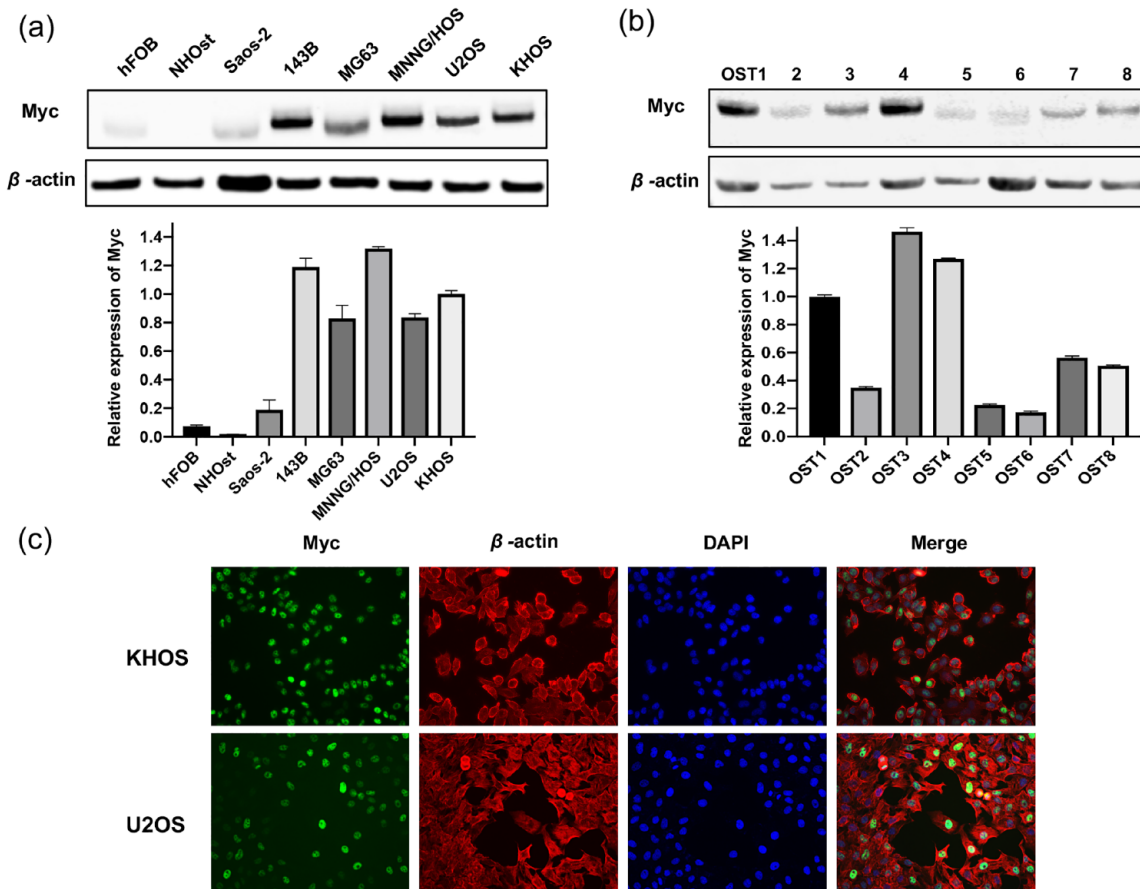
#### *Myc expression in human osteosarcoma cell lines and fresh patient tissues*

We first determined the level of Myc protein expression in osteosarcoma cell lines. Western blotting showed Myc to be higher expressed in the 143B and MNNG/HOS osteosarcoma cell lines. These are highly tumorigenic cell lines with a penchant for pulmonary metastases in xenograft mouse models.<sup>21,22</sup> Other osteosarcoma cell lines (Saos-2, MG63, U2OS, and KHOS) also had higher Myc expression relative to normal osteoblasts (hFOB, NHOst) (Figure 1A). To further validate the presence of Myc at the clinical level, we analyzed eight fresh patient-derived osteosarcoma tissues, which were subsequently revealed as Myc positive (Figure 1B). Immunofluorescence showed that Myc resides predominantly within the nucleus of osteosarcoma cells (Figure 1C), as is expected for this transcription factor.<sup>23</sup>

#### *Myc expression correlates with osteosarcoma patient clinical characteristics and prognosis*

To evaluate the significance of Myc expression, we compared Myc levels in an osteosarcoma tissue microarray (TMA) to patient clinical characteristics and outcomes. Similar to the cell lines and fresh tissues, immunohistochemistry showed Myc immunoreactivity to reside mainly within osteosarcoma cell nuclei (Figure 2A). Of the 70 osteosarcoma patient tissues assessed, one sample was excluded due to fall-out of the tissue core from the TMA slide. Levels of Myc expression of the 69 remaining patient tissues were as follows: non-staining 0 (16 of 114, 14%); 1+ staining (30 of 114, 26%); 2+ staining (21 of 114, 18%); 3+ staining (26 of 114, 23%); 4+ staining (12 of 114, 11%); and 5+ staining (9 of 114, 8%) (Figure 2B). We divided the specimens into two groups based on Myc staining scores, where low Myc expression was defined as  $\leq 2+$  (59%), and high Myc expression was defined as  $\geq 3+$  (41%) (Figure 2C).

According to disease status, Myc expression was significantly lower in primary tumor tissues (patients without metastasis) compared with tissues with metastatic involvement ( $p = 0.033$ ,



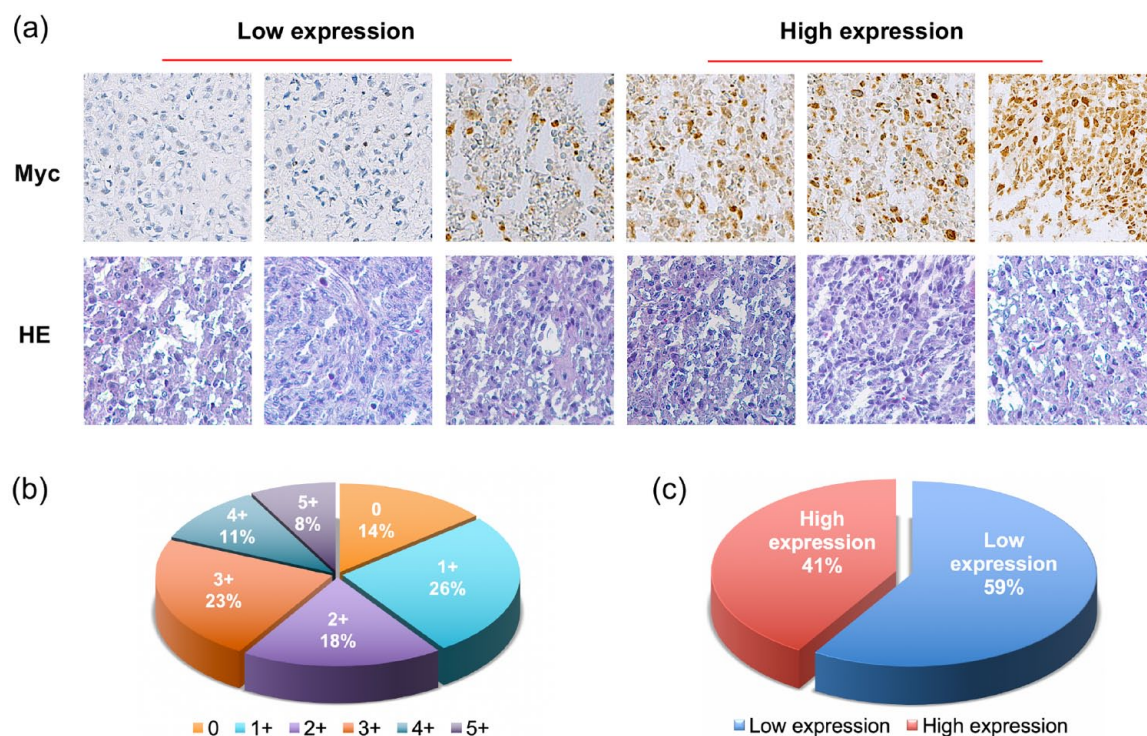
**Figure 1.** Myc expression in human osteosarcoma cell lines and fresh tissues. (A) Myc expression in human osteosarcoma cell lines and normal osteoblast cell lines. Relative expression of Myc and  $\beta$ -actin as below. (B) Expression of Myc from eight fresh tissues from osteosarcoma patients *via* western blotting. (C) Expression of Myc in KHOS and U2OS osteosarcoma cell lines were assessed by immunofluorescence with antibodies to Myc (green) and  $\beta$ -actin (red). Hoechst 33342 was added to counterstain the cell nucleus (blue). Green fluorescence of Myc protein was localized mainly in the osteosarcoma cell nucleus. DAPI, 4',6-diamidino-2-phenylindole; Myc, avian myelocytomatosis viral oncogene homolog.

independent two-tailed Student *t* test) (Figure 3A). Myc expression was not significantly different between primary tumor tissues and recurrent tumor tissues ( $p=0.469$ , independent two-tailed Student *t*-test) (Figure 3A).

With respect to disease progression, higher Myc expression was observed in the primary tumors of those who developed metastasis relative to those without eventual metastatic lesions ( $p=0.0097$ , independent two-tailed Student *t* test) (Figure 3B). There was, however, no significant difference of Myc expression between patients who did or did not develop recurrent osteosarcoma (Figure 3C). We also evaluated whether Myc expression is associated with percent of tumor necrosis in osteosarcoma specimens, as post neoadjuvant necrosis is the most significant predictor of clinical outcomes. However, no significant difference in Myc

expression was observed according to good chemotherapeutic response ( $\geq 90\%$  necrosis) or poor response ( $< 90\%$  necrosis) (Figure 3D). Based on the clinical data (Supplementary Table S1), Myc expression significantly correlated with tumor grade ( $p=0.007$ ,  $\chi^2$  test) and metastasis ( $p=0.005$ ,  $\chi^2$  test) (Table 1).

Kaplan–Meier analysis demonstrated patients with low Myc expression to have significantly better prognostic measures in terms of overall survival (OS) ( $p=0.0001$ ) and progression-free survival (PFS) ( $p=0.0003$ ) by log-rank test (Figure 4A and B). Additionally, the 5-year survival rate of patients with low Myc expression was much better at 79.4% compared with 37.3% in those with high Myc expression ( $p=0.0004$ ,  $\chi^2$  test) (Figure 4C). According to log-rank analysis of Myc expression data from TCGA (The Cancer



**Figure 2.** Myc expression in an osteosarcoma TMA by immunohistochemistry. (A) Representative images of HE and Myc nuclear staining intensity in osteosarcoma tissues. Myc staining patterns were divided into six groups: no staining (0); <10% positive cells (1+); 10–25% positive cells (2+); 26–50% positive cells (3+); 51–75% positive cells (4+); >75% positive cells (5+). (Original magnification, 200 $\times$ ). (B) The pie chart shows the distribution of different Myc expression levels in the osteosarcoma tissue microarray. (C) Tumors with the staining score of  $\leq 2+$  were defined as the low Myc expression group (blue),  $\geq 3+$  as the high Myc expression group (red). The pie chart illustrates the relative frequencies of the two groups in the osteosarcoma TMA. HE, hematoxylin and eosin; Myc, avian myelocytomatosis viral oncogene homolog; TMA, tissue microarray.

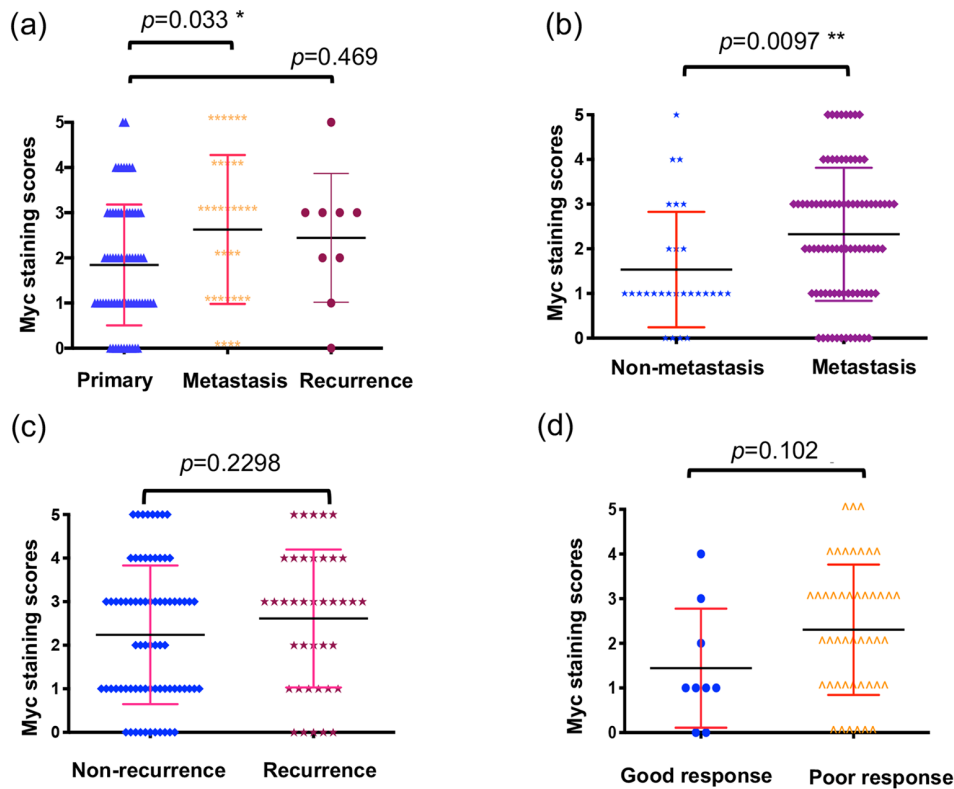
Genome Atlas) (Supplementary Table S2), percentage survival is significantly reduced in patients with elevated Myc expression ( $p=0.09$ ) (Figure S1). This is consistent with our TMA analysis. Linear regression analysis showed osteosarcoma patient OS was inversely related to Myc levels ( $p=0.0017$ ,  $r=-0.4843$ , Spearman's rank correlation) (Figure 4D). In summary, Myc expression correlated with worse osteosarcoma patient outcomes.

Finally, we performed a univariate Cox regression analysis to assess whether Myc overexpression is an independent prognostic risk factor. We found higher tumor grade, Myc expression, and metastatic disease were all associated with decreased osteosarcoma patient survival. Other clinicopathological features, however, showed no significant correlation (Table 2). Importantly, the multivariate Cox regression analysis showed Myc expression as an independent predictor of survival in osteosarcoma patients ( $p=0.034$ , Cox

proportional risk regression model) (Table 2). Collectively, these results support Myc expression as an independent predictor of osteosarcoma patient outcomes.

#### *Myc downregulation by siRNA decreases osteosarcoma cell proliferation*

After validating the expression and clinical significance of Myc in osteosarcoma cell lines and patient tissues, we sought to determine the function of Myc in osteosarcoma cell proliferation and growth. Accordingly, we used Myc-specific siRNA to knockdown Myc expression and observe osteosarcoma cell viability. At 5 days post-Myc-siRNA transfection, KHOS and U2OS cell viability decreased sharply in a dose-dependent manner compared with control cells treated with non-specific siRNA (Figure 5A and B). Western blotting confirmed Myc-specific siRNA down-regulated Myc protein expression, with an overall inhibition of cell proliferation and viability (Figure 5C and



**Figure 3.** Relationship of Myc expression and disease status. (A) Distribution of Myc immunohistochemistry staining scores among tissues taken from patients with primary, metastatic, or recurrent disease. "Primary" means tumor tissues were taken from patients without metastatic or recurrent disease. "Recurrence" means the tissues were taken initially from the patients' original site of tumors but patients developed recurrent disease afterward. "Metastasis" means tumor tissues were taken initially from patients' original site of tumors but patients developed metastatic disease afterward. (B) Distribution of Myc protein immunohistochemical staining scores in primary osteosarcoma patients who did or did not eventually develop metastases. (C) Expression of Myc between patients who did or did not eventually experience recurrence. (D) Expression of Myc between patients with good or poor chemotherapy response. We divided the patients who received neoadjuvant chemotherapy into two groups; good response:  $\geq 90\%$  necrosis; poor response:  $< 90\%$  necrosis. Myc, avian myelocytomatosis viral oncogene homolog.

D). The downregulation of Myc expression by siRNA was further supported by the marked reduction of green fluorescence observed in the immunofluorescence assay (Figure S2). Overall, these data illustrate the critical role of Myc in osteosarcoma proliferation and viability.

#### *Myc inhibitor 10058-F4 suppresses osteosarcoma viability and migration*

10058-F4 is a small-molecule inhibitor that prevents the binding of Myc by virtue of its ability to inhibit the formation of Myc-Max heterodimers.<sup>24,25</sup> The osteosarcoma cell lines KHOS and U2OS were cultured with 10058-F4 at increasing concentrations over 5 days, and were found to reduce osteosarcoma cell viability in a dose- and time-dependent manner, with IC<sub>50</sub> values for

10058-F4 at 13.80  $\mu\text{M}/\text{ml}$  and 17.50  $\mu\text{M}/\text{ml}$ , respectively (Figures 6A and S3). We also observed morphological changes and decreased osteosarcoma cell viability with progressively increased 10058-F4 concentrations over 72 h (Figure 6B). Assessment of the Myc protein by western blotting subsequent to 10058-F4 treatment demonstrated osteosarcoma growth and Myc expression were concomitantly depressed (Figure 6C and D), consistent with previous study.<sup>26</sup>

In addition to rapidity of growth and proliferation, cancer cell migration has a crucial role in cancer invasion, and is an indirect measure of cancer cell metastatic potential. We therefore explored the function of Myc in osteosarcoma cell migration *in vitro*. As shown in Figure 7A and B, after treatment with 10  $\mu\text{M}$  10058-F4 for 24, 48, and 72 h, the



**Table 1.** The relationship between Myc expression and clinicopathological features of osteosarcoma patients.

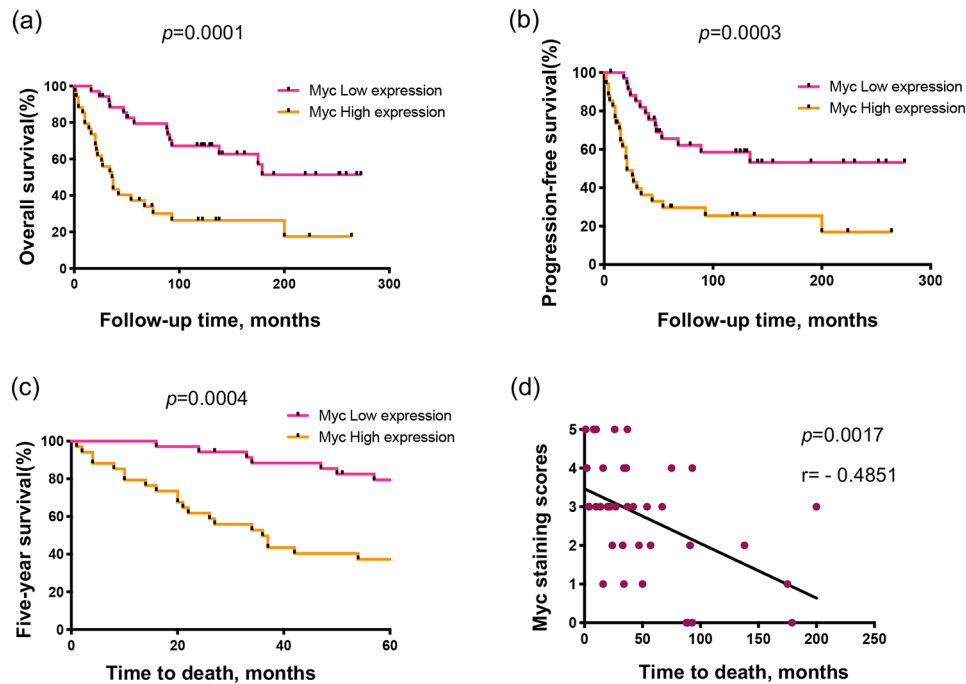
	Cases, n (%)	Myc expression low, n (%)	Myc expression high, n (%)	p value
All patients	69 (100)	35 (50.7)	34 (49.3)	
Age				0.702
≤18years	20 (29.0)	9 (45.0)	11 (55.0)	
18–50years	36 (52.2)	20 (55.6)	16 (44.4)	
≥50years	13 (18.8)	6 (46.2)	7 (53.8)	
Gender				0.103
Male	42 (60.9)	18 (42.9)	24 (57.1)	
Female	27 (39.1)	17 (63.0)	10 (37.0)	
Tumor site				0.809
Femur	31 (44.9)	16 (51.6)	15 (48.4)	
Tibia	12 (17.4)	5 (41.7)	7 (58.3)	
Humeral bone	7 (10.1)	3 (42.9)	4 (57.1)	
Other	19 (27.5)	11 (57.9)	8 (42.1)	
Tumor grade				0.007*
Low	5 (7.2)	5 (100.0)	0 (0)	
Medium	25 (36.2)	16 (64.0)	9 (36.0)	
High	39 (56.5)	14 (35.9)	25 (64.1)	
Metastasis				0.005*
Present	48 (69.6)	19 (39.6)	29 (60.4)	
Absent	21 (30.4)	16 (76.2)	5 (23.8)	
Recurrence				0.934
Present	22 (31.9)	11 (50.0)	11 (50.0)	
Absent	47 (68.1)	24 (51.1)	23 (48.9)	
*Statistically significant. Myc, avian myelocytomatosis viral oncogene homolog.				

migration distance of KHOS and U2OS were significantly inhibited in a time-dependent manner, as compared with the untreated control group.

#### *Inhibition of Myc reduces osteosarcoma clonogenicity and spheroid growth*

We assessed the effect of 10058-F4 on the colony-forming ability of osteosarcoma cells with a clonogenic assay. After 15 days of 10058-F4 treatment,

KHOS and U2OS clonogenicity was reduced in a dose-dependent manner whereas untreated cells were not (Figure 7C). Because flat surfaces in two-dimensional (2D) culture systems do not adequately mimic the *in vivo* conditions by which osteosarcoma cells attach, spread, and grow,<sup>27</sup> we employed 3D culture. This unique growth platform better mimics the *in vivo* environment in which cancer cells naturally form 3D spheroids with the customizability of *in vitro* experimentation. Specifically,



**Figure 4.** Prognostic value of Myc expression in osteosarcoma patients. (A, B) Correlation between Myc expression in the osteosarcoma patients' tissues and OS (A) or PFS (B) by Kaplan–Meier survival analysis. (C) Comparison of the 5-year survival rate between patients with differential Myc expression levels. (D) Correlation between OS of osteosarcoma patients and Myc expression.

Myc, avian myelocytomatosis viral oncogene homolog; OS, overall survival; PFS, progression-free survival.

the KHOS and U2OS cell lines were exposed to 10  $\mu$ M 10058-F4 for 15 days in 3D culture with their spheroids photographed at multiple time points. Although the spheroids grew continuously, the Myc inhibitor-treated spheroids were significantly smaller than the untreated spheroids (Figure 7D and E). Overall, Myc was a prominent and independent promoter of osteosarcoma growth and progression.

## Discussion

In our present work, we show Myc protein levels to be significantly greater in osteosarcoma cell lines compared with normal osteoblasts, with 143B and MNNG/HOS having especially notable overexpression. This is clinically significant, as the cell lines 143B and MNNG/HOS are well-known to cause spontaneous pulmonary metastasis.<sup>21,22</sup> In addition to our cell line work, the osteosarcoma tumor specimens were Myc expression positive. As expected of a transcription factor, Myc was localized in osteosarcoma nuclei within TMA and fresh tumor specimens. As a predictor of disease status, Myc expression was greatly enhanced in tumor tissues of patients with metastatic disease compared with those without metastasis. Of note, patients

with high Myc expression were also more likely to develop metastasis in the future, which is the major cause of death in osteosarcoma patients. These results support Myc overexpression as a driver of metastasis in osteosarcoma.

Previous works note Myc expression as a poor prognostic marker in various cancers,<sup>28–31</sup> with high levels of Myc seen in aggressive prostate cancer, liver cancer, and breast cancer.<sup>32–34</sup> Consistent with these observations, we showed high Myc expression to be associated with worse OS and disease PFS in osteosarcoma. In addition, the 5-year survival of patients with strong Myc expression was greatly reduced compared with those with weak Myc expression. In an additional validation step, we analyzed sarcoma patient data of Myc expression from TCGA, confirming shorter osteosarcoma patient survival times in those with high Myc expression. There was an inverse correlation between osteosarcoma patient survival and Myc expression in a linear regression analysis. Lastly, by way of Cox regression analysis, we further confirmed Myc protein expression to independently predict osteosarcoma patient survival. In summary, our work support Myc as a novel prognostic biomarker for osteosarcoma patients.

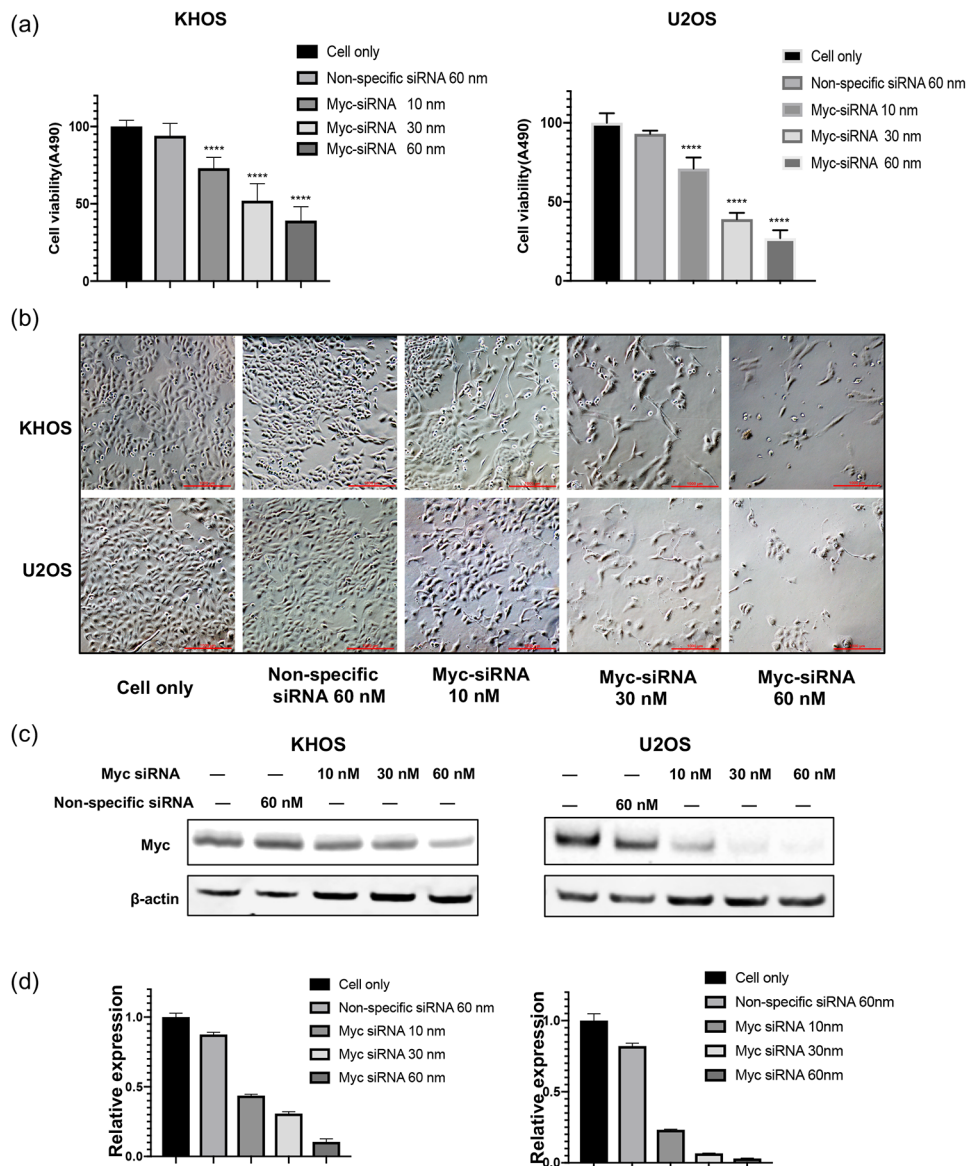
**Table 2.** Prognostic factors of osteosarcoma from univariate and multivariate survival analysis.

Viable	Univariate analysis multivariate analysis					
	HR	95% CI	p value	HR	95% CI	p value
All patients						
Age	1.381	0.856–2.226	0.185			
≤18years						
18–50years						
≥50years						
Gender	0.72	0.374–1.387	0.327			
Male						
Female						
Tumor site	0.95	0.737–1.226	0.695			
Femur						
Tibia						
Humeral bone						
Other						
Recurrence	0.544	0.288–1.028	0.061			
Present						
Absent						
Tumor grade	1.986	1.12–3.522	0.019*	1.25	0.653–2.393	0.5
Low						
Medium						
High						
Metastasis	0.081	0.019–0.336	0.001*	0.105	0.025–0.445	0.002*
Present						
Absent						
Myc expression	0.295	0.152–0.574	0.0001*	0.458	0.223–0.944	0.034*
Low						
High						

\*Statistically significant.  
CI, confidence interval; HR, hazard ratio; Myc, avian myelocytomatosis viral oncogene homolog.

The Myc oncogene encodes a critical transcription factor in oncogenesis.<sup>11,23,35</sup> Amplification and overexpression of Myc is a hallmark of cancer initiation and maintenance<sup>36</sup>; conversely, Myc

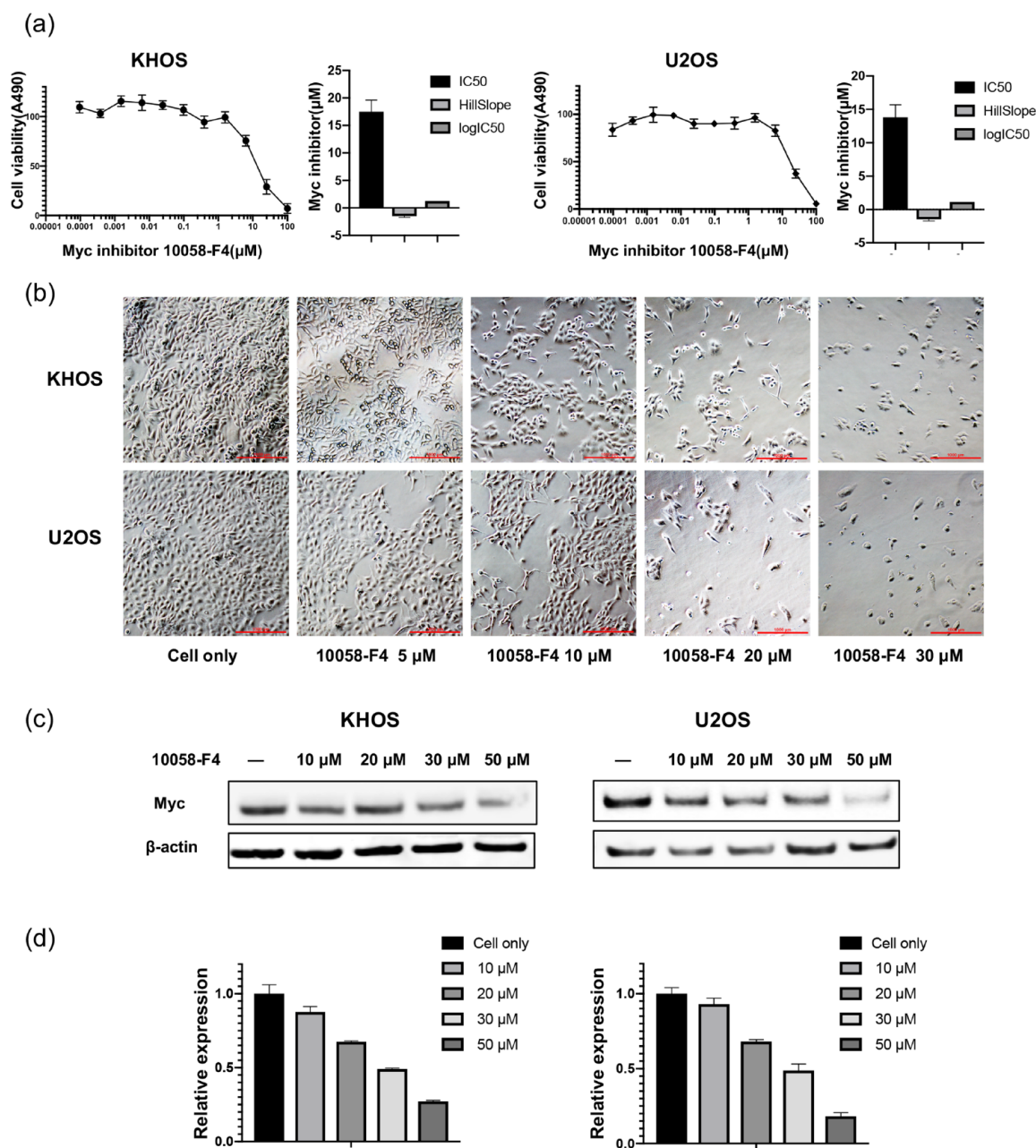
inactivation may reverse tumorigenesis.<sup>37</sup> Recently, a broad and unified analysis of genomic and expression data from the TCGA dataset of approximately 9000 tumor samples of 33 tumor



**Figure 5.** Knockdown of Myc by siRNA inhibits osteosarcoma cell proliferation and decreases viability. (A) Cell viability of osteosarcoma was measured by MTT assay after Myc-specific siRNA transfection. (B) Representative images of osteosarcoma cell morphologic changes after transfection of Myc siRNA. (Original magnification value,  $\times 100$ . Scale bar 1000  $\mu\text{m}$ ). (C) The expression of Myc measured by western blotting after Myc siRNA transfection. (D) Densitometry quantification of Myc western blots from (C) presented as relative to  $\beta$ -actin expression. MTT, methyl thiazolyl tetrazolium; Myc, avian myelocytomatosis viral oncogene homolog; siRNA, small interfering RNA.

types demonstrated that Myc paralogs are significantly amplified in 28% of all tumor samples. As may be expected, the Myc antagonist genes MGA and MNT are frequently mutated or deleted in tumors.<sup>38</sup> For solid and hematopoietic human tumors, the Myc protein is overexpressed at a rate of 60–70%.<sup>39</sup> Functionally, Myc overexpression changes chromatin structure, ribosome biogenesis, metabolic immune response, and cell

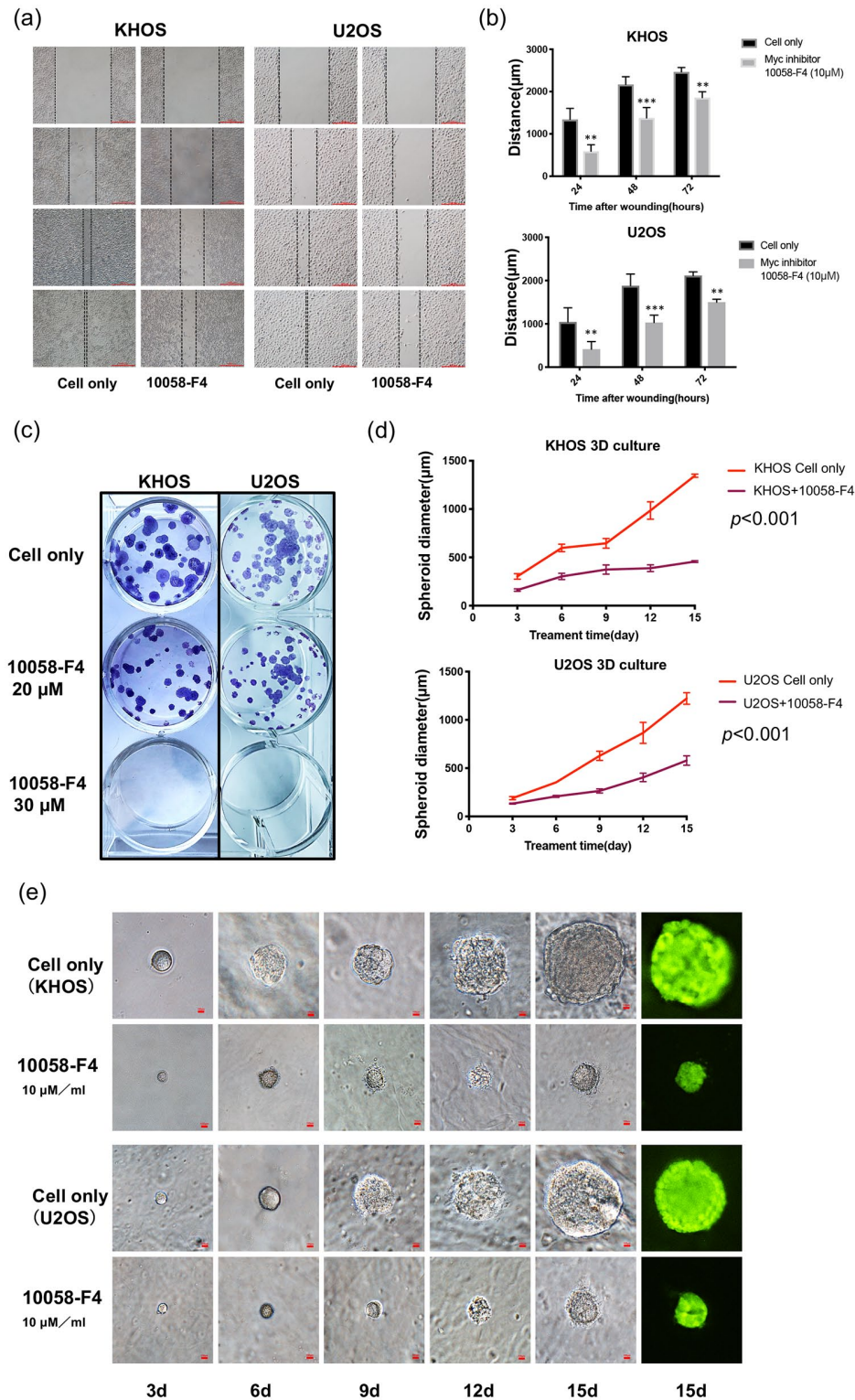
adhesion.<sup>40–44</sup> Myc downregulation mediated by siRNA is known to inhibit cell proliferation and induce apoptosis in cancers such as acute myeloid leukemia, nasopharyngeal carcinoma, fibrosarcoma, and non-small-cell lung cancer.<sup>45–48</sup> In a study where specialized transgenic mouse models had inducible Myc expression, their established tumors regressed upon withdrawal of Myc ectopic expression, giving credence to the view that Myc



**Figure 6.** Myc inhibitor reduced osteosarcoma cell proliferation relative to Myc knockdown. (A) Osteosarcoma cell viability was measured by MTT after incubation with Myc inhibitor. (B) Representative images of osteosarcoma cell morphologic changes after Myc inhibitor treatment. (Original magnification value,  $\times 100$ . Scale bar 1000  $\mu\text{m}$ ). (C) Myc expression as measured by Western blotting after Myc inhibitor treatment. (D) Densitometry quantification of the Western blots of Myc from (C) presented as relative to  $\beta$ -actin expression. MTT, methyl thiazolyl tetrazolium; Myc, avian myelocytomatosis viral oncogene homolog.

is an essential mediator of tumor maintenance.<sup>14</sup> In another study, expression of dominant-negative Myc heterodimers (Myc-interfering mutants) induced lung tumor regression *in vivo*, further supporting the therapeutic potential of targeting Myc.<sup>13</sup> With regards to osteosarcoma, an early study showed Myc to be amplified in 7–78% of osteosarcomas, as well as 9–48% of breast

cancers.<sup>49</sup> A more recent genome-based study revealed Myc as the most commonly amplified (39%) gene in osteosarcoma.<sup>50</sup> Current works that targeted Myc in osteosarcoma Myc-amplified patient derived tumor xenografts (PDX) caused tumor shrinkage.<sup>50</sup> Other recent works employed nanocarriers encapsulated with Myc siRNA that afforded low-toxicity tumor therapy in mouse



**Figure 7.** Inhibition of Myc suppressed osteosarcoma cell migration, clonogenicity, and spheroid growth. (A) Relative migration distance of KHOS and U2OS cells at different time points (0, 24, 48, and 72 h) when treated with the Myc inhibitor 10058-F4. (Original magnification value,  $\times 100$ . Scale bar 1000  $\mu\text{m}$ ). (B) Quantification of cell migration distance of KHOS and U2OS cells after 10058-F4 treatment.  $**p < 0.01$ ,  $***p < 0.001$  compared with the untreated control group. (C) Representative images of KHOS and U2OS cell colony formation after treatment with 10058-F4 at different concentrations (0, 20, 30  $\mu\text{M}$ ) for 15 days. (D) Spheroid diameters of KHOS and U2OS cells cultured in 3D gels.  $p < 0.001$  compared with the untreated control group. (E) Representative images of osteosarcoma spheroids after treatment with the Myc inhibitor at different time points (3, 6, 9, 12, and 15 days). Original magnification,  $\times 200$ . Scale bar 100  $\mu\text{m}$ . 3D, three-dimensional; Myc, avian myelocytomatosis viral oncogene homolog.

models.<sup>47,48</sup> In line with these findings, we have successfully reduced cell growth and viability of KHOS and U2OS osteosarcoma cell lines by siRNA-induced Myc silencing.

Myc mechanistically forms a heterodimer with its partner Max to bind target DNA sequences and initiate tumorigenic gene transcription.<sup>51,52</sup> In principle, interrupting the Myc–Max complex is, therefore, a logical approach to inhibit Myc signaling. While Myc is an attractive target, it has been largely considered undruggable, due mainly to barriers of nuclear localization. Various Myc inhibitors have been synthesized to directly inhibit the protein/protein interaction of Myc and Max. Of these, 10058-F4 inhibits growth of Myc-expressing cells *via* disruption of Myc–Max DNA binding.<sup>24,25,53</sup> This inhibitor induces tumor cell-cycle arrest, apoptosis, and death in several leukemias and human hepatocellular carcinomas.<sup>16–19,54</sup> We therefore chose to implement 10058-F4, and demonstrated a dose-dependent decrease of osteosarcoma cell viability, with cell migration suppression in a time-dependent manner. We further verified the effect of 10058-F4 on cell growth and survival by clonogenic assay and 3D modeling to simulate *in vivo* cell biology.<sup>27,55</sup> KHOS and U2OS had significantly reduced colony count and size following 10058-F4 treatment. The velocity of spheroid growth was also greatly reduced. Our results show Myc is an important component of osteosarcoma cell proliferation and viability.

The focus of this study was to determine the significance of Myc as a prognostic biomarker in osteosarcoma patient tissues and potential as a therapeutic target in osteosarcoma. Limitations of our study include the lack of targeting Myc in xenograft mouse models of osteosarcoma. Our future follow-up work will include *in vivo* study and examination of the mechanism of Myc driving osteosarcoma growth.

### Conclusion

In summary, our work shows Myc overexpression to significantly correlate with osteosarcoma patient metastasis and worse survival. It is, therefore, a biomarker at initial biopsies predictive of osteosarcomas more likely to become rapidly aggressive. As a therapeutic, knockdown and inhibition of Myc significantly reduces osteosarcoma cell growth and migration, and, therefore, represents a promising strategy in osteosarcoma treatment.

These findings are especially promising given the limited use of targeted therapies in osteosarcoma and relative stagnation of patient outcomes over the past decades.

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### Author contributions

Formal analysis, WF; funding acquisition, ZD; methodology, WF, DS, RH; project administration, HS and ZD; resources, FH; software, WF; supervision, HS and ZD; writing – original draft, WF; writing – review and editing, DD, HS and ZD. All authors read and approved the final manuscript.

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### Conflict of interest statement

The authors declare that there is no conflict of interest.

### Supplemental material

Supplemental material for this article is available online.

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