

microRNA expression is likely to be a major contributing factor in CSC phenotypes. Therefore, targeting EMT pathways and CSC maintenance is a promising therapeutic strategy, one that seems to be feasible since several studies have successfully shown that pharmacological agents can modulate the differentiation state of a tumor. Thus, 'differentiation-inducing' agents such as salinomycin or metformin may have therapeutic value. The use of a natural miRNA to suppress the CSC phenotypes also promises to lead to a new therapeutic strategy for the treatment of CSCs.

Finally, the CSC phenotypes, which lead to high tumorigenicity, drug resistance, and metastasis, are responsible for many problems affecting cancer patients. Therefore, understanding and overcoming the CSC phenotypes will improve conventional cancer therapy.

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miR-22 represses cancer progression by inducing cellular senescence

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Cellular senescence acts as a barrier to cancer progression, and microRNAs (miRNAs) are thought to be potential senescence regulators. However, whether senescence-associated miRNAs (SA-miRNAs) contribute to tumor suppression remains unknown. Here, we report that miR-22, a novel SA-miRNA, has an impact on tumorigenesis. miR-22 is up-regulated in human senescent fibroblasts and epithelial cells but down-regulated in various cancer cell lines. miR-22 overexpression induces growth suppression and acquisition of a senescent phenotype in human normal and cancer cells.

miR-22 knockdown in presenescent fibroblasts decreased cell size, and cells became more compact. miR-22-induced senescence also decreases cell motility and inhibits cell invasion *in vitro*. Synthetic miR-22 delivery suppresses tumor growth and metastasis *in vivo* by inducing cellular senescence in a mouse model of breast carcinoma. We confirmed that CDK6, SIRT1, and Sp1, genes involved in the senescence program, are direct targets of miR-22. Our study provides the first evidence that miR-22 restores the cellular senescence program in cancer cells and acts as a tumor suppressor.

Introduction

Tumor progression is a multistep process wherein several defined events are common to cancer cells, such as uncontrolled proliferation and invasion (Hahn and Weinberg, 2002). Cellular senescence is characterized by an irreversible arrest of cell proliferation, so that it can prevent the aberrant and unlimited proliferation of tumor cells (Campisi, 2005). Senescent cells exhibit enlarged morphological changes and less motility than young cells, which may contribute to the suppression of cell migration, invasion, and metastasis (Chen et al., 2000). Oncogene-induced senescence is a cellular response, which can occur *in vivo* and provides a bona fide barrier to tumorigenesis (Narita and Lowe, 2005). Oncogene-induced senescence was found in premalignant tumors but not in more advanced malignant tumors (Braig et al., 2005; Collado et al., 2005). Therefore, cellular senescence acts as an important barrier to cancer and plays an important role in tumor suppression.

microRNAs (miRNAs) are a class of naturally occurring small noncoding RNAs that negatively regulate the stability and translation of target protein-coding mRNAs at the 3' untranslated region (UTR). miRNAs typically target a cluster of genes rather than one specific gene (Bartel, 2004), a characteristic which allows them to play critical roles in a variety of biological processes such as cell proliferation, differentiation, apoptosis, and carcinogenesis (He and Hannon, 2004). Recently, a growing number of studies have documented the miRNA expression profiles in human cancers (Calin and Croce, 2006), suggesting that miRNAs emerge as novel biomarkers for various cancers. However, there is currently little information about miRNA profiling studies and biological effects of miRNAs in cellular senescence.

The senescence program is established and maintained by p53 and retinoblastoma protein (pRb) tumor suppressor pathways. The requirements of p53 and pRb for the induction of cellular senescence vary in their prominence depending on the genetic context, species, and cell type (Adams, 2007; Schmitt, 2007;

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Abbreviations used in this paper: cont miR, control miRNA; HPA, hybridization protection assay; hTERT, human telomerase reverse transcriptase; LNA, locked nucleic acid; miRNA, microRNA; PDL, population doubling level; pRb, retinoblastoma protein; SA- β -gal, senescence-associated β -galactosidase; SAHF, senescence-associated heterochromatin foci; SA-miRNA, senescence-associated miRNA; UTR, untranslated region; WT, wild type.

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Haferkamp et al., 2009). Recently, various studies have indicated that some miRNAs, such as miR-34a and miR-20a, induce senescence-like growth arrest through regulating cell cycle genes and senescence-associated genes involved in the p53 and/or pRb pathway (Tazawa et al., 2007; Poliseno et al., 2008; Sun et al., 2008). Such miRNAs play a direct role in senescence and are called senescence-associated miRNAs (SA-miRNAs; Lafferty-Whyte et al., 2009).

In the present study, we attempted to screen SA-miRNAs that control cellular senescence in human fibroblasts, and we report here that miR-22 is a novel SA-miRNA that functions in mediating cellular senescence. We studied the role of miR-22 in cellular senescence using human normal cells and cancer cell lines as an *in vitro* culture system as well as an *in vivo* mouse breast tumor model. Upon senescence, cells become flattened and enlarged and exhibit biochemical changes such as the increased perinuclear activity of senescence-associated β -galactosidase (SA- β -gal; Dimri et al., 1995; Narita et al., 2003). Another critical event during the cellular senescence process is a decrease in cell growth and cell motility. We found a widespread decrease of miR-22 expression in various human cancer cell lines. Introduction of miR-22 into cancer cells inhibits cell proliferation, accompanied by senescence-like cell morphology and a decrease in cell motility and invasiveness. We predicted the putative direct targets of miR-22 by the computational prediction of targets based on sequence match to the miRNA. We identified three targets, including CDK6, Sp1, and SIRT1, which are directly regulated by miR-22. Furthermore, silencing of these targets resulted in growth arrest and increased SA- β -gal activity, accompanied by pRB dephosphorylation. We confirmed that miR-22 regulated the pRb pathway of cellular senescence through targeting of CDK6 and SIRT1. Ectopic expression of CDK6, SIRT1, or Sp1 could partially rescue the senescence phenotypes in miR-22-transfected cells. Significantly, miR-22 injection suppresses tumor growth and metastasis *in vivo* by induction of senescence in breast tumor, suggesting that SA-miRNA miR-22 acts as an important barrier to cancer and plays an important role in tumor suppression. Our findings provide new insight for the role of SA-miRNAs between cellular senescence and tumorigenesis.

Results

miR-22 overexpression induces cellular senescence in human fibroblasts

To identify miRNAs that control cellular senescence, we analyzed miRNA expression profiling by miRCURY locked nucleic acid (LNA) miRNA array in young and senescent TIG-3 fibroblasts (Fig. 1 A). We found that a set of altered expression miRNAs has been reported to be involved in cell growth and tumorigenesis (Fig. 1 A and Table S1). Among them, the majority of antigrowth miRNAs were expressed two- to fourfold more in senescent TIG-3 cells than in young cells. To confirm and validate the results, we performed 3D-Gene miRNA microarray to evaluate miRNA expression levels. Two kinds of microarray analysis showed that five miRNAs are uniformly up-regulated by twofold or greater in senescent compared with young cells.

These include miR-22, miR-34a, miR-125a-5p, miR-24-2*, and miR-152, several of which, namely miR-34a and miR-125a-5p, are closely associated with senescence-like growth arrest and metastasis in cancer cells (Tazawa et al., 2007; Li et al., 2009; Wang et al., 2009). Here, we focused on miR-22 and evaluated the expression of miR-22 in young and senescent human diploid fibroblast strains. Quantitative (q) RT-PCR analysis confirmed that miR-22 expression was increased in senescent TIG-3 and other fibroblasts and even up-regulated by more than fivefold in senescent MRC-5 cells (Fig. 1 B). These findings suggest that miR-22 up-regulation is universal in senescent human fibroblasts.

To investigate the involvement of miR-22 in cellular senescence in human fibroblasts, we enforced miR-22 expression by introduction of mature miR-22 duplex into young fibroblasts. We first examined miR-22 expression level by qRT-PCR analysis at day 6 after direct transfection with miR-22 duplex into young MRC-5 cells (Fig. 1 C). Compared with the endogenous level of miR-22 in the senescent MRC-5 cells (fivefold higher than young cells), miR-22 was up-regulated by 2.9-fold (1 nM), 4-fold (5 nM), and 15.7-fold (10 nM) in MRC-5 cells, relative to control miRNA (cont miR) in each transfection group. Furthermore, miR-22 also increased SA- β -gal activity (Fig. 1 D), a well known senescence cytosolic biomarker, in a transfection dose-dependent manner, whereas cont miR did not induce SA- β -gal activity. These results imply that up-regulation of miR-22 expression is significant for the induction of senescence phenotypes. Because the cessation of cell proliferation is a hallmark of cellular senescence, we examined whether cell proliferation is altered by overexpression of miR-22. We observed that transfection of 10 nM miR-22 caused a remarkable inhibition of cell proliferation compared with that of cont miR (Fig. 1 E), and this growth inhibition by miR-22 is in a dose-dependent manner (not depicted). Senescence-associated heterochromatin foci (SAHF) formation is thought to be a senescence nuclei biomarker and is often observed in senescent fibroblasts (Dimri et al., 1995; Narita et al., 2003; Adams, 2007). We observed obvious SAHF formation in miR-22-transfected cells, and the percentage of SAHF-positive cells was significantly increased by miR-22 overexpression and was also increased in senescent MRC-5 cells (Fig. 1 F). This result is not cell type specific because other fibroblasts, such as IMR90, transfected with miR-22 appeared to be senescence phenotypes (unpublished data).

To ensure that the function of mature miRNA is not at a supraphysiological level, we repeated these experiments using a stable miRNA vector that mimics miRNA biological processing. Pre-miR-22 lentiviral construct (Lenti-Pre22), stably expressing miR-22 precursor in its native context, was used to study the effect of miR-22 on cellular senescence in MRC-5 fibroblasts. Lenti-Pre22-infected cells exhibited the enlarged senescence morphology and SA- β -gal-positive staining (Fig. 2 A). Compared with Lentiviral empty vector (Lenti-C), Lenti-Pre22 infection significantly increased SA- β -gal activity and caused growth arrest in MRC-5 cells (Fig. 2, A and B), which is similar to the effect of mature miR-22. Collectively, these results suggest that miR-22 is associated with cellular senescence, accompanied by the induction of major specific senescence-associated markers in human diploid fibroblasts.

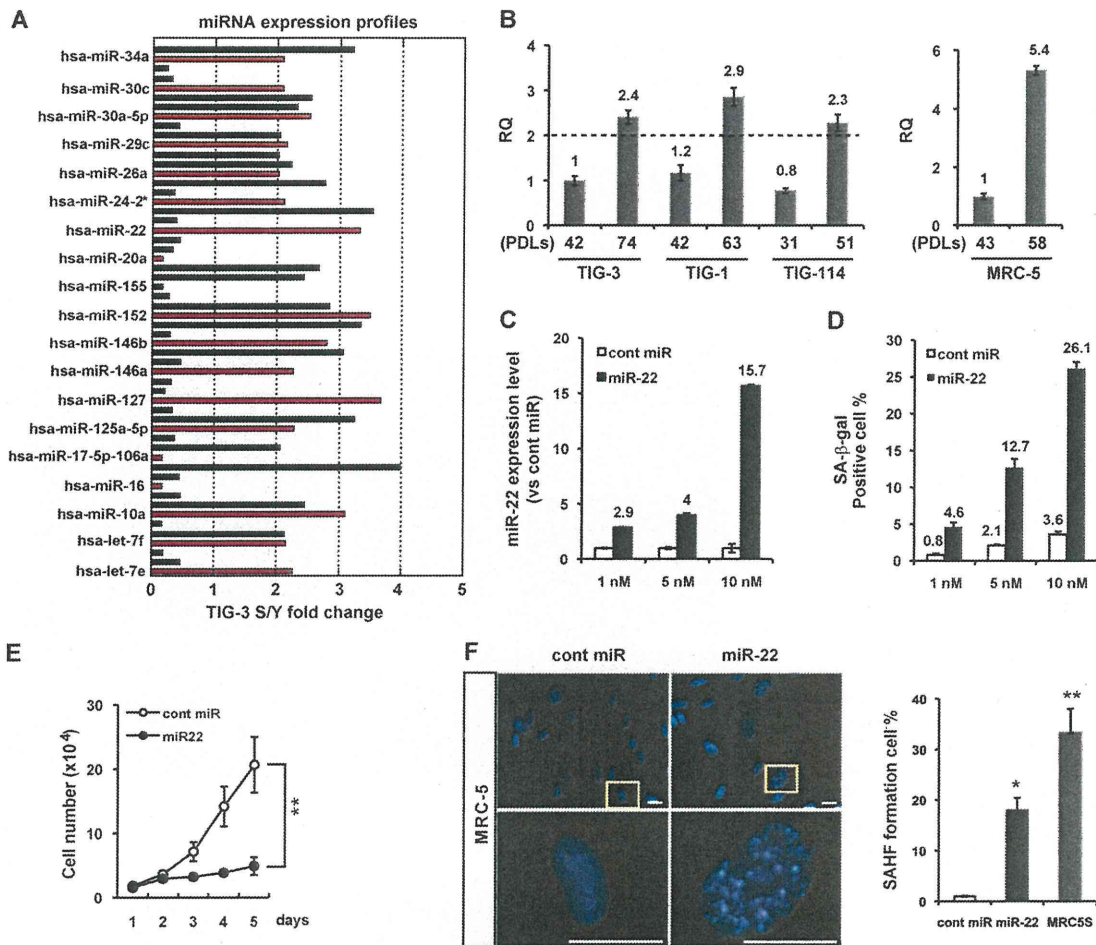
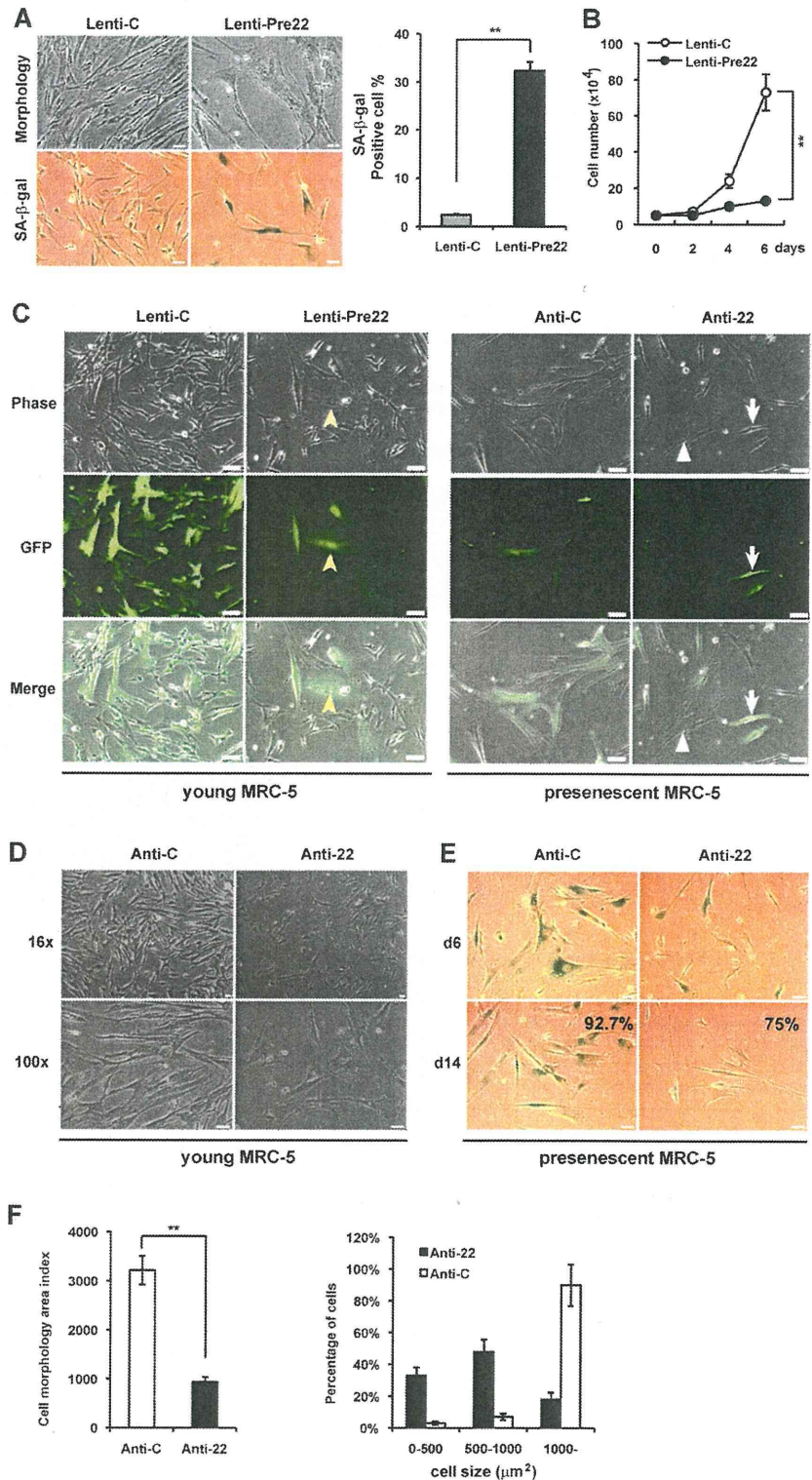


Figure 1. miR-22 is up-regulated in senescent human fibroblasts, mediating cellular senescence. (A) miRNA expression profile of TIG-3 fibroblasts was analyzed by miRNA microarray, presented as fold changes in miRNA expression between TIG-3S (senescent) and young (Y) cells. A set of altered expression miRNAs is indicated by red columns (see Table S1). RQ, relative quantitation. (B) Relative quantitation of miR-22 expression in different PDLs of fibroblasts was analyzed by qRT-PCR analysis. miR-22 expression levels in human fibroblasts were indicated, relative to those in TIG-3 (42 PDL) set at 1 in the left histogram and MRC-5 (43 PDL) set at 1 in the right histogram. U6 was used as an internal normalization control. The dashed line represents the threshold of expression level (twofold vs. TIG-3 42 PDL). (C and D) MRC-5 cells were transfected with cont miR or mature miR-22 (miR-22) for 6 d at indicated concentration. (C) qRT-PCR analysis shows the relative quantitation of miR-22 expression (vs. cont miR) in each transfection group. miR-22 expression levels in miR-22-transfected MRC-5 cells were indicated, relative to that in cont miR-transfected cells set at 1. U6 was used as an internal normalization control. (D) SA-β-gal activity was presented by the percentage of SA-β-gal-positive cells, which was indicated in different dose groups. (E) Cell proliferation assay was performed after transfection of 10 nM miR-22 or cont miR, and cells were counted for the indicated days. Each value was determined in triplicate. **, $P < 0.01$. (F) Representative photos for SAHF formation in MRC-5 cells at day 6 after transfection. Images were taken with fluorescence microscopy. Enlarged images of the boxed area from the top are shown in the bottom. SAHF formation was quantified by counting 200 cells from >10 random fields, and the results were shown in the right histogram in contrast to MRC5S (senescent; 58 PDL). Data in all the panels represent mean \pm SEM ($n = 3$). *, $P < 0.05$; **, $P < 0.01$. Bars, 20 μ m.

Furthermore, we wondered how knockdown of miR-22 impacts cellular senescence phenotypes and whether a reduced expression of miR-22 would impede the progression of senescence and extend the life span in fibroblasts. miRZip anti-miR-22 expression lentivector (anti-22), which can stably express anti-miR-22 and provide permanent miR-22 inhibition, was used to infect young (44 population doubling level [PDL]) and presenescent (54 PDL) MRC-5 cells. We observed that Leni-Pre22-infected young MRC-5 cells demonstrated enlarged senescent morphological changes (Fig. 2 C, GFP-labeled cells marked with yellow arrowheads). In contrast, anti-22-infected young MRC-5 cells seemed smaller and younger than anti-22 empty

vector (anti-C)-treated cells (Fig. 2 D). For presenescent MRC-5 cells, stable knockdown of miR-22 caused obvious morphological changes, exhibiting small and thin morphology (Fig. 2 C, GFP-labeled cells marked with arrows), whereas those cells that failed to be infected exhibited enlarged senescent morphology (Fig. 2 C, white triangles) within the same field under the fluorescent microscope. Presenescent MRC-5 cells entered senescence and demonstrated obvious SA-β-gal staining as time passed. Anti-22-infected presenescent MRC-5 cells maintained small and thin morphology for >2 wk with a decreased percentage of SA-β-gal-positive cells (Fig. 2 E), and there appeared to be a significant decrease in cell size and percentage of cells

Figure 2. Stable expression and knockdown of miR-22 affect senescence phenotypes in MRC-5 cells. (A) Cell morphology and SA- β -gal activity were analyzed by phase-contrast microscopy at day 6 after infection with empty vector (Lenti-C) or premiR-22 (Lenti-Pre22). The percentage of SA- β -gal-positive cells is presented in the right histogram. (B) Cell proliferation assay was performed after infection of Lenti-Pre22, and cells were counted for the indicated days, compared with control cells. Each value was determined in triplicate. **, $P < 0.01$. (C) Cell morphology was analyzed with fluorescence microscopy at day 6 after infection. GFP-labeled cells indicate infected cells (middle). Yellow arrowheads and white arrows depict miR-22 overexpression in young MRC-5 cells and miR-22 knockdown in presenescent MRC-5 cells, respectively. Those cells that failed to be infected are marked with white triangles. (D) Cell morphology of anti-22-infected young MRC-5 was analyzed by phase-contrast microscopy and compared with anti-C. (E) Presenescent MRC-5 cells infected with anti-C or anti-22 were subjected to SA- β -gal assay at days 6 and 14 after infection. The percentage of SA- β -gal-positive cells at day 14 after infection is presented in the bottom panels. (F) Cell morphology area and cell size distribution were analyzed using ImageJ by counting GFP-expressed presenescent MRC-5 cells after infection with anti-C or anti-22 for 6 d. Cell morphology area index represents cell size (micrometers squared). Cell size distribution was divided into three groups: 0–500, 500–1,000, and 1,000 μm^2 and up. Data in all the panels represent mean \pm SEM ($n = 3$). **, $P < 0.01$. Bars: (A, D, and E) 50 μm ; (C) 20 μm .



distributed in a large-sized group (Fig. 2 F), compared with senescent anti-C-treated cells. Although stable knockdown of miR-22 exhibited neither the promotion of cell proliferation nor the extension of the life span (not depicted), this might be a result

of irreversible growth arrest in senescent cells. These findings suggest the requirement of miR-22 in mediating senescence and indicate that miR-22 inhibition is indeed an obstacle for the progression of senescence in fibroblasts.

miR-22 overexpression induces growth suppression and senescence-like phenotypes in human breast epithelial and cancer cells

Senescence has been most widely studied in fibroblasts *in vitro* but is also well defined in other cell types, such as epithelial cells which are the origin of most carcinoma (Narita et al., 2003). Expression of human telomerase reverse transcriptase (hTERT) in certain cell types has been shown to extend cellular life span without malignant transformation. To investigate the effect of miR-22 on cellular senescence in human epithelial cells, we used hTERT-infected HMEC184 (184hTERT) cells that possess the unlimited proliferation capacity of HMEC184 cells and are regarded as immortalized. We found that miR-22 was expressed higher by >2.5-fold in senescent HMEC184 (22 PDL) than in 184hTERT cells that have a similar miR-22 expression level to that of normal young HMEC184 (Fig. 3 A). Compared with immortalized 184hTERT cells, a widespread decrease in miR-22 level was observed in various human cancer cells (Fig. 3 A), indicating that miR-22 may have an intrinsic function in tumor suppression associated with various human malignancies.

To test this notion, we first evaluated the effect of miR-22 on cell growth and SA- β -gal activity in human breast epithelial cells and two breast cancer cell lines. We found that miR-22 significantly inhibited cell growth in 184hTERT, MCF7, and MDA-MB-231-luc-D3H2LN (called MDA-D3 for short; Fig. 3 B). We noted that mature miR-22 caused remarkable and characteristic morphological alterations, including enlarged cellular size and a flattened shape (Fig. 3 C), and significantly increased SA- β -gal activity in the three cells (Fig. 3 D). Furthermore, we confirmed that overexpression of premiR-22 in MDA-D3 cells also significantly induced senescence-specific morphological changes, increased SA- β -gal activity (Fig. 3 E), and inhibited cell growth (Fig. 3 F), similar to the effect of mature miR-22.

The marked induction of senescence by miR-22 in human breast cancer cells prompted us to investigate whether miR-22 induces cellular senescence in other human cancer cells. Therefore, we further studied the effect of miR-22 in the human cervical carcinoma cell line SiHa. We confirmed the dose-dependent increase in miR-22 expression level (Fig. 4 A) and SA- β -gal activity (Fig. 4 B) after direct transfection of miR-22 in SiHa cells, whereas cont miR affected neither the cell growth nor the SA- β -gal activity. Introduction of 10 nM miR-22 resulted in cells exhibiting a senescence-like flattened shape and SA- β -gal-positive staining (Fig. 4 C), and it induced remarkable growth suppression compared with that of cont miR (Fig. 4 D). Because senescent cells never reenter the cell cycle and appear to decrease in DNA synthesis, we performed FACS analysis and quantity analysis of BrdU incorporation in SiHa cells. miR-22 overexpression induced cell cycle arrest at G1 phase, accompanied by the decrease in percentages of S phase (Fig. 4 E). The inhibitory effect of miR-22 on cell cycle progression has also been recently reported in other cancer cells (Ting et al., 2010). Furthermore, miR-22 resulted in the decrease of BrdU incorporation in comparison with cont miR or miR-34a (Fig. 4 F), indicating impaired DNA replication in miR-22-transfected cells during the S phase of the cell cycle. In addition, we confirmed

that miR-22 expression was increased in Lenti-Pre22-infected SiHa cells (Fig. 4 G) close to the expression level of miR-22 (10 nM). Lenti-Pre22 also induced senescence-specific morphological changes, increased SA- β -gal activity, and inhibited cell growth (Fig. 4, H and I), indicating the induction of cellular senescence by miR-22 overexpression in SiHa cells.

Moreover, we did not observe any significant increase in TUNEL-positive apoptotic cells in miR-22-transfected SiHa and MDA-D3 cells (Fig. S1, A and B). These findings suggest that the growth suppression induced by miR-22 overexpression was caused by the induction of G1 arrest in cellular senescence rather than apoptosis. In reverse, miR-22 knockdown in cancer cells resulted in various morphological changes and differential timing of apoptosis in different cell lines. Anti-22-infected SiHa cells appeared to be small and underwent apoptosis at day 6 after infection (Fig. S1 C), whereas MDA-D3 cells became rounded and apoptotic cells were observed in anti-22-infected cells from the third day after infection (Fig. S1 D), which might be because the timelines for the progression of different cells through apoptosis vary in different cell lines (Jessel et al., 2002).

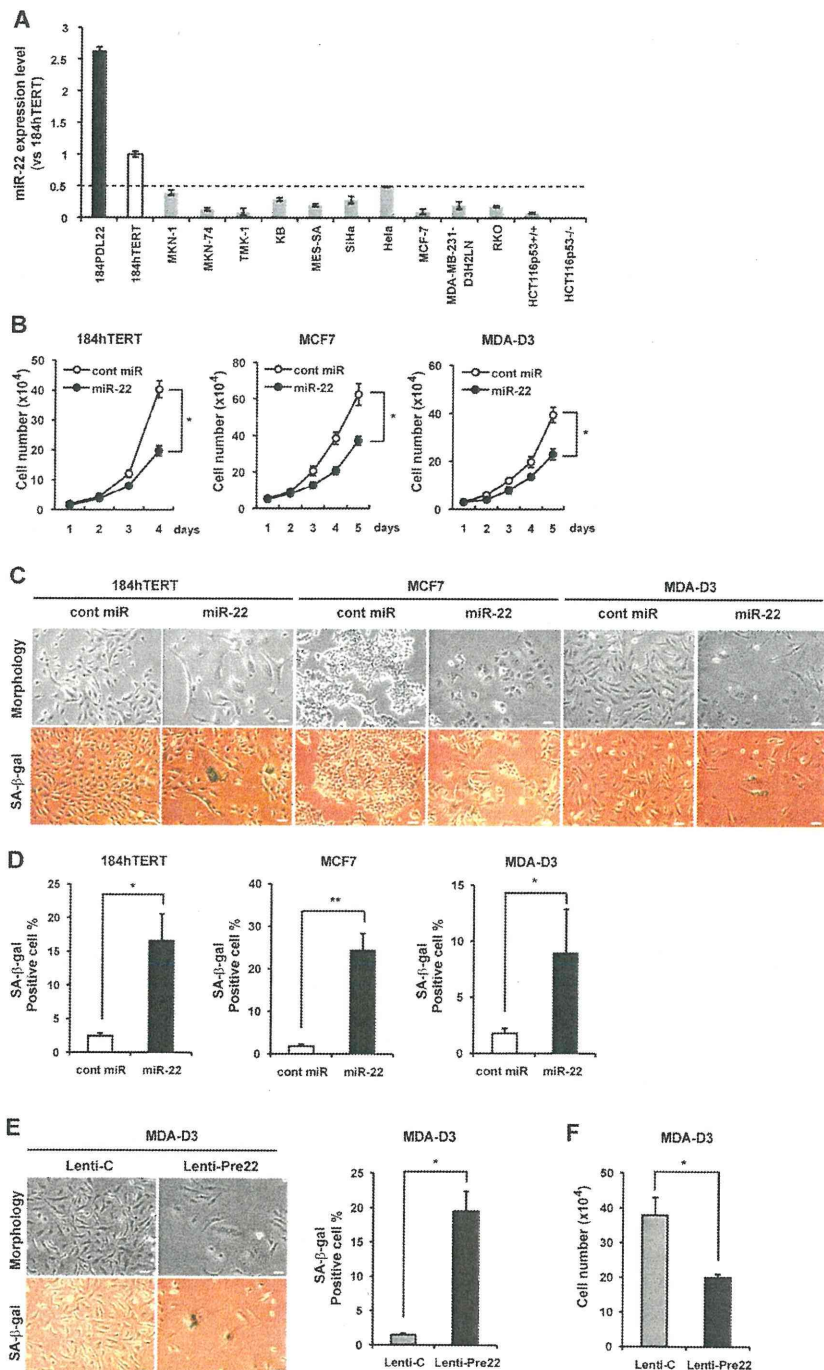
Various findings have suggested the critical role of telomere shortening in contributing to cellular senescence in human cells (Deng et al., 2008). Telomeric 3'-overhang (G-tail) is essential for proper telomere function (Tahara et al., 2005). Here, overexpression of miR-22 had no effect on the length of either total telomere or G-tail (Fig. S2), indicating that miR-22-induced senescence is possibly independent of telomere shortening.

SIRT1, Sp1, and CDK6 are direct targets of miR-22

miRNAs are known to suppress hundreds of mRNA targets, resulting in global changes in the cellular phenotype of cells (He and Hannon, 2004). We therefore make an effort to identify potential targets for miR-22 using both *in silico* and experimental approaches. We used a consensus approach with three widely used types of software (miRanda, TargetScan, and PicTar) to perform the target prediction. After overlapping prediction analysis, we screened those genes that were down-regulated upon senescence and implicated in cell growth and cell cycle regulation. Based on this, SIRT1, Sp1, and CDK6 were selected to be putative miR-22 target genes. The mRNAs of SIRT1 and Sp1 contain putative binding sites for miR-22 in their 3'-UTRs, and each site is broadly conservative among mammals. CDK6 mRNA contains three miR-22 binding sites in the 3'-UTR, whereas it is different in conservation for each site (Fig. 5 A).

To address those genes directly regulated by miR-22, we performed luciferase reporter assay. We constructed pmirGLO full-length 3'-UTR of both SIRT1 and Sp1. Because the full-length 3'-UTR of CDK6 is too long (~10 kbp), human CDK6 3'-UTR containing three binding sites (6 kbp) was amplified and cloned into pmirGLO vector. Furthermore, to study which site in the 3'-UTR of each gene is important, we engineered luciferase reporters that have exact binding sites of 3'-UTRs of these genes including the wild type (WT) and two mutant UTRs (Mut1 and Mut2), as shown in Fig. 5 C. In SiHa and MDA-D3 cells, miR-22 significantly reduced the luciferase activities of the full-length 3'-UTR (Fig. 5 B) or WT SIRT1, SP1, and CDK6

Figure 3. Overexpression of miR-22 induces senescence-like phenotypes in human breast epithelial and breast cancer cells. (A) qRT-PCR analysis shows relative quantitation of miR-22 expression level (vs. 184hTERT) in human epithelial and various cancer cells. Expression levels of miR-22 in various cells were relative to that in 184hTERT cells set at 1. U6 was used as an internal normalization control. The dashed line represents the threshold of expression level (0.5-fold vs. 184hTERT). (B) Cell proliferation assay was performed after transfection of miR-22, and cells were counted for the indicated days, compared with control cells. Each value was determined in triplicate. *, $P < 0.05$. (C–E) Cell morphology and SA- β -gal activity were analyzed by phase-contrast microscopy at day 6 after transfection (C and D) or infection (E) in indicated cells. SA- β -gal activity was presented by the percentage of SA- β -gal-positive cells. (F) Cell proliferation assay was performed at day 6 after MDA-D3 cells were infected with Lenti-Pre22 and compared with control cells. Data in all the panels represent mean \pm SEM ($n = 3$). *, $P < 0.05$; **, $P < 0.01$. Bars, 50 μ m.



(site 1 and site 3) reporters (Fig. 5 D), compared with the negative cont miR. In contrast, neither Mut1 (deletion of seed region) nor Mut2 of mutant reporters was repressed by miR-22, which indicates that these target sites directly mediate the repression (Fig. 5 E). In addition, this down-regulation was not seen in WT construct of CDK6 site 2, possibly because of poorly conserved sites among mammals. These results provide experimental evidence that miR-22 can directly repress translation initiation of SIRT1, SP1, and CDK6.

Western blot analysis showed that overexpression of miR-22 markedly down-regulated SIRT1, SP1, and CDK6 in SiHa and MDA-D3 cells (Fig. 5 F). Moreover, we confirmed that SIRT1 and CDK6 were down-regulated in senescent MRC-5 fibroblasts and HMEC184 epithelial cells, accompanied by a decrease in pRb phosphorylation at ser807/811 (Fig. 5 G). This indicates that SIRT1 and CDK6 are senescence-associated genes that are involved in cellular senescence possibly through the pRb pathway. Sp1 was not detected because of its low expression level in these cells.

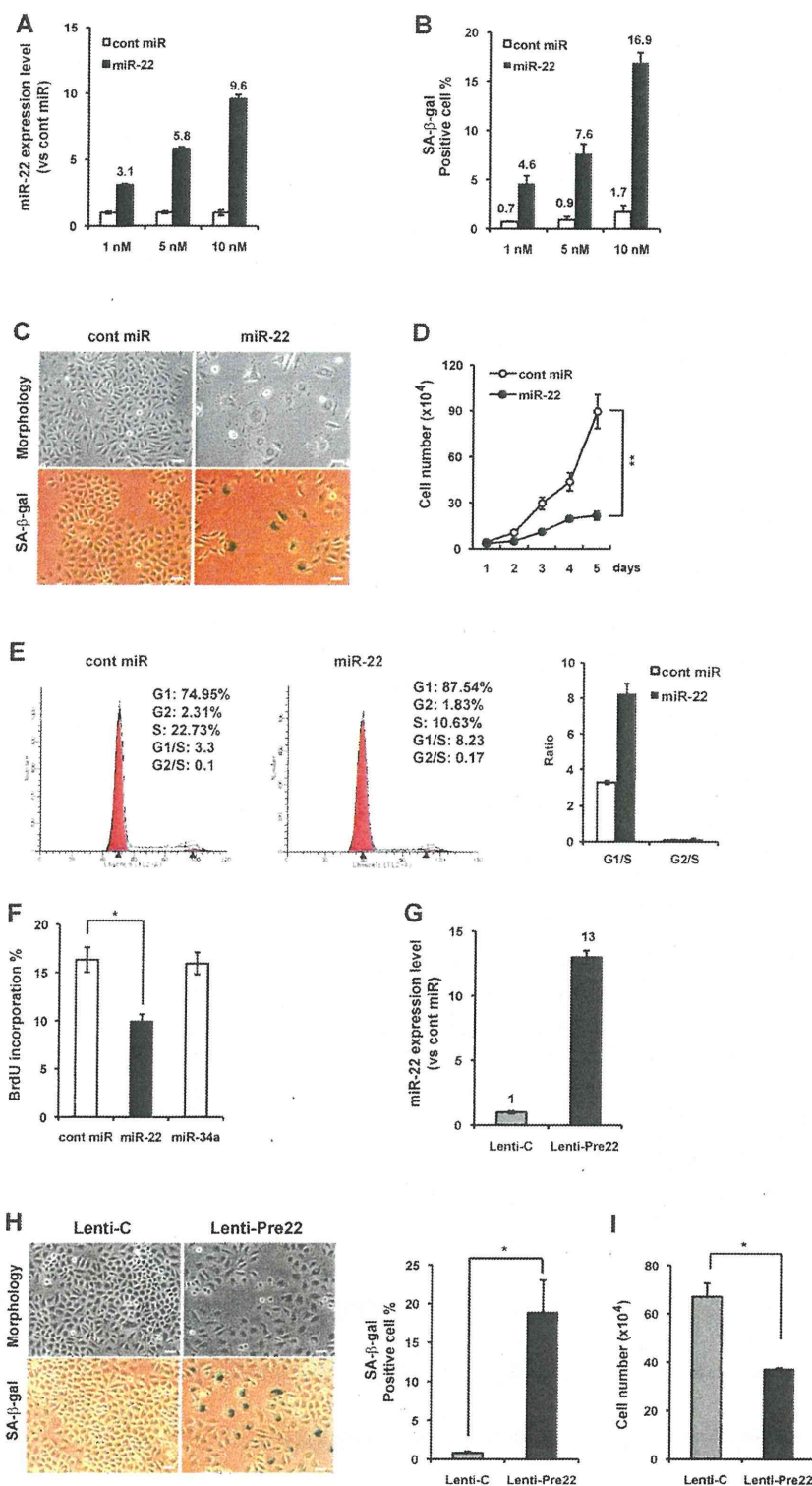


Figure 4. Overexpression of miR-22 induced cellular senescence, cell cycle G1 arrest, and the decrease in BrdU incorporation in SiHa cells. (A and B) SiHa cells were transfected with cont miR or miR-22 at the indicated concentration for 6 d. qRT-PCR results show the relative level of miR-22 expression to cont miR in each transfection group (A). SA-β-gal activity was presented by the percentage of SA-β-gal-positive cells (B). (C) Cell morphology and SA-β-gal activity were analyzed by phase-contrast microscopy at day 6 after transfection of 10 nM miR-22 or cont miR. (D) Cell proliferation assay was performed after transfection of 10 nM miR-22, and cells were counted for the indicated days, compared with control cells. Each value was determined in triplicate. **, $P < 0.01$. (E) Cell cycle analysis was performed at 48 h after transfection. The percentage of G1, S, and G2 are demonstrated as shown. The histogram displays the relative changes of G1 and G2 phase compared with S phase. (F) BrdU quantitative analysis was performed at 72 h after transfection, presented by the percentage of BrdU incorporation. (G) Stable expression of miR-22 (Lenti-Pre22) was evaluated by qRT-PCR analysis, presented by the relative quantitation of miR-22 expression level at day 6 after infection. Expression level of miR-22 in Lenti-Pre22-transfected cells was relative to that in Lenti-C-transfected cells set at 1. U6 was used as an internal normalization control. (H) Cell morphology and SA-β-gal activity were analyzed by phase-contrast microscopy at day 6 after infection. The percentage of SA-β-gal-positive cells is presented in the right histogram. (I) Cell proliferation assay was performed at day 6 after infection with Lenti-Pre22 and compared with control cells. Data in all the panels represent mean \pm SEM ($n = 3$). *, $P < 0.05$; **, $P < 0.01$. Bars, 50 μ m.

Furthermore, silencing of these target genes by siRNAs resulted in growth arrest (Fig. 6 A) and increased SA-β-gal activity in MRC-5 fibroblasts and MDA-D3 cells (Fig. 6 B), as well as morphological changes (not depicted), similar with miR-22-induced senescence phenotypes. We confirmed that

the siRNAs against SIRT1 and CDK6 knocked down the expression of SIRT1 and CDK6 and caused dephosphorylation of pRB at ser807/811 (Fig. 6, C and E), which was also induced by either mature miR-22 or premiR-22 overexpression in various different cells (Fig. 6, D and F). In addition,

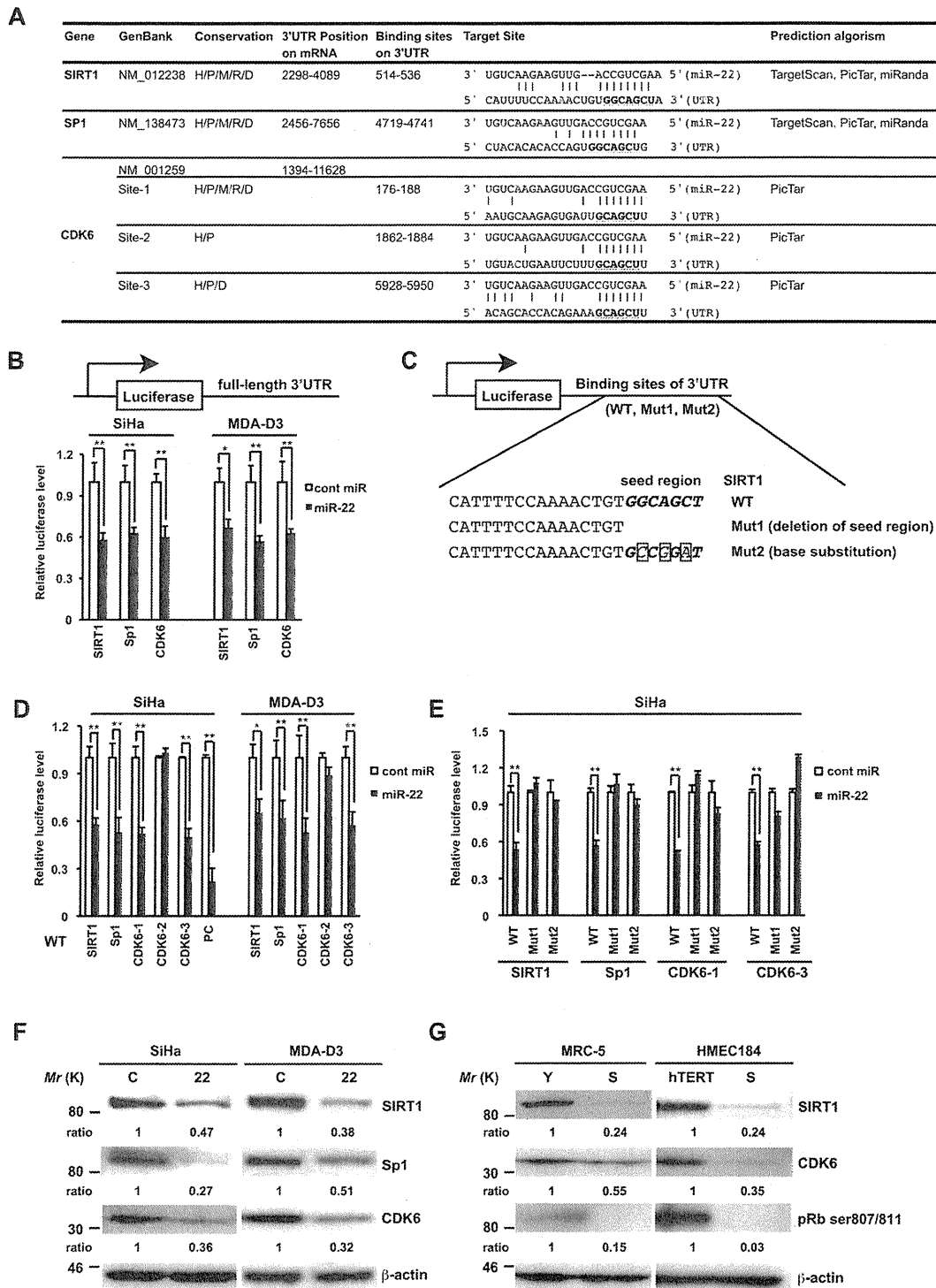


Figure 5. **SIRT1, Sp1, and CDK6 are direct targets of miR-22.** (A) Summary of miR-22 target sites in the 3'-UTR of SIRT1, Sp1, and CDK6. H, human; P, chimp; M, mouse; R, rat; D, dog. The underlined bold nucleotides indicate target sites. (B-E) Target validation of SIRT1, Sp1, and CDK6 was confirmed in the luciferase reporter assay. (C) Scheme of the luciferase reporter constructs containing conserved miR-22 target sites (WT), deletion of seed region (Mut1), or base substitution of seed region (Mut2) was indicated using SIRT1 as an example. The seed region is italic bold, and point mutations are boxed in the seed region. Each construct, including full-length 3'-UTR (B), WT (D), or Muts (E), was cotransfected with miR-22 or cont miR into SiHa or MDA-D3 cells. Relative luciferase level = $(S_{luc}/S_{renilla})/(C_{luc}/C_{renilla})$ in relative light units (RLUs). S_{luc} , RLUs of firefly luciferase activity in miR-22-transfected sample. $S_{renilla}$, RLUs of renilla luciferase activity in miR-22-transfected sample. C_{luc} , RLUs of firefly luciferase activity in cont miR-transfected groups. $C_{renilla}$, RLUs of renilla luciferase

p53 protein level did not change in MRC-5 and MDA-D3 cells, but p53 expression is up-regulated in miR-22-transfected SiHa cells (Fig. 6 F). These findings indicate that miR-22 may affect the pRb pathway of cellular senescence by targeting SIRT1 and CDK6.

Lastly, we attempted to determine whether overexpression of any of the three genes could rescue the senescence phenotype in cells overexpressing miR-22. We forced SiHa or MDA-D3 cells to express SIRT1, Sp1, or CDK6 using plasmid constructs lacking 3'-UTRs of these genes. Indeed, miR-22-induced cell growth repression and SA- β -gal activity were partially rescued by the introduction of SIRT1, CDK6, or Sp1 in either SiHa cells (Fig. 6, G and H) or MDA-D3 cells (not depicted), although it seemed weak for the effect of Sp1 overexpression on cell growth, which might be because of the indirect role of Sp1 in the pRb pathway of senescence. Collectively, these findings suggest that SIRT1, Sp1, and CDK6 play an important role in miR-22-induced senescence.

miR-22 alters tumor cell morphology and suppresses cell invasiveness in vitro

Changes in cell morphology are important parameters of cancer invasion and metastasis. We performed high content analysis using Operetta to measure the morphology area of all the cells transfected with miR-22, miR-34a, or cont miR on each well of a 96-well plate (Fig. 7 A and Fig. S3 B) and analyzed cell size distribution (Fig. 7 B). We found there were significant differences in cell size distribution between miR-22-treated cells and other cells. miR-22 remarkably increased cell morphology area up to 1.6-fold overall and raised percentages of cells distributed in large cell size groups in comparison with cont miR or miR-34a, revealing that miR-22 triggers senescence morphological changes in tumor cells. In addition, miR-22-treated cells contain enhanced actin stress fibers (Fig. 7 A) similar to senescent fibroblasts, indicating that those cells are less motile (Chen et al., 2000; Belguise et al., 2005). We observed that senescent fibroblasts and Lenti-Pre22-infected cancer cells exhibiting large flattened senescence-like morphology appeared to decrease in cell movement (Fig. S4 and Videos 1–4, large GFP-positive cells), indicating that miR-22-induced senescence morphology in cancer cells could be attributed to the suppression of cell motility. Matrigel invasion assay showed that miR-22 significantly reduced the number of invaded cells in SiHa and MDA-D3 cells (Fig. 7 C), indicating that the invasive potential of cancer cells was severely affected by miR-22. Therefore, the inhibition of cancer cell invasion by miR-22 may be a result of the induction of cellular senescence.

miR-22 inhibits tumor growth and metastatic potential of aggressive breast cancer in vivo

We next asked whether miR-22 overexpression would also induce senescence in vivo and suppress tumor growth and

metastasis in vivo. Using breast cancer tumor models, the cont miR-treated mice showed the apparent presence of primary tumor, whereas those injected with miR-22 complex exhibited no increase in the luminescence of primary tumor during the same observation period (Fig. 8 A, left). Judging from photon count between the cont miR- and miR-22-treated groups at the two points of the experiment, miR-22 treatment resulted in a mean decrease in tumor growth of 41.3% at day 39 ($P = 0.04$; not depicted) and 66% at day 46 ($P = 0.005$; Fig. 8 A, right), suggesting that miR-22 exerted significant tumor growth suppression in vivo. We also compared tumor metastasis with important organs in the two groups and were surprised to find that miR-22 delivery resulted in the inhibition of distant metastasis in the liver, kidney, spleen, stomach, and small intestine (Fig. 8 B). There were significant differences in the whole body of mice between the cont miR- and miR-22-treated groups on day 46 ($P = 0.004$), indicating the inhibition of metastasis by injection with miR-22 in vivo.

We also confirmed that synthetic miR-22 was delivered into primary tumor by quantitation of the miR-22 level in tumor (Fig. 8 C). Furthermore, the number of SA- β -gal-positive cells in miR-22-treated tumor dramatically increased, correlated with the amount of miR-22 in tumor (Fig. 8 D). In addition, we did not observe SA- β -gal-positive cells in nontumor cells such as vascular endothelial cells and other stroma cells of mice. Moreover, we found that the morphologies of the tumors were different; the cells in cont miR-treated groups were densely packed and slightly elongated, whereas those in miR-22-treated groups were larger and more irregularly shaped (Fig. 8 E). Pathologically, vacuolation and nuclear pyknosis associated with degradation of tumor cells were found in miR-22-treated tumor tissues. Therefore, it is possible that induction of cellular senescence in tumor cells may result in these pathological changes.

The progression toward metastasis formation requires proliferation of tumor cells at primary sites and distant sites. Notably, the expression of Ki-67 in miR-22-treated groups was significantly lower than that in cont miR-treated groups and nontreated groups (Fig. 8 F), indicating the inhibition of cell proliferation in tumor tissues treated with miR-22. Together, these findings suggest that miR-22 significantly induced cellular senescence in breast cancer in vivo, consequently inhibiting tumor growth and metastasis in vivo.

Discussion

The present study for the first time reported the functional effect of miR-22 as a novel regulator of cellular senescence in normal human and cancer cells and addressed the inhibitory role of miR-22 in tumor growth and metastasis, suggesting that miR-22-induced senescence acts as a barrier to cancer progression in vitro and in vivo. Our study extends the current understanding

activity in cont miR-transfected groups. PC, positive control. (F) Representative Western blot analysis of SIRT1, Sp1, and CDK6 in SiHa and MDA-D3 cells transfected with cont miR (C) and mature miR-22 (22) at 72 h after transfection. (G) The expression levels of SIRT1, CDK6, and pRb phosphorylation in MRC-5 and HMEC184hTERT cells were analyzed by immunoblotting. β -actin was used as a loading control and the relative density of bands was densitometrically quantified. Y, young; S, senescent; hTERT, 184hTERT. Data in all the panels represent mean \pm SEM ($n = 3$). *, $P < 0.05$; **, $P < 0.01$.

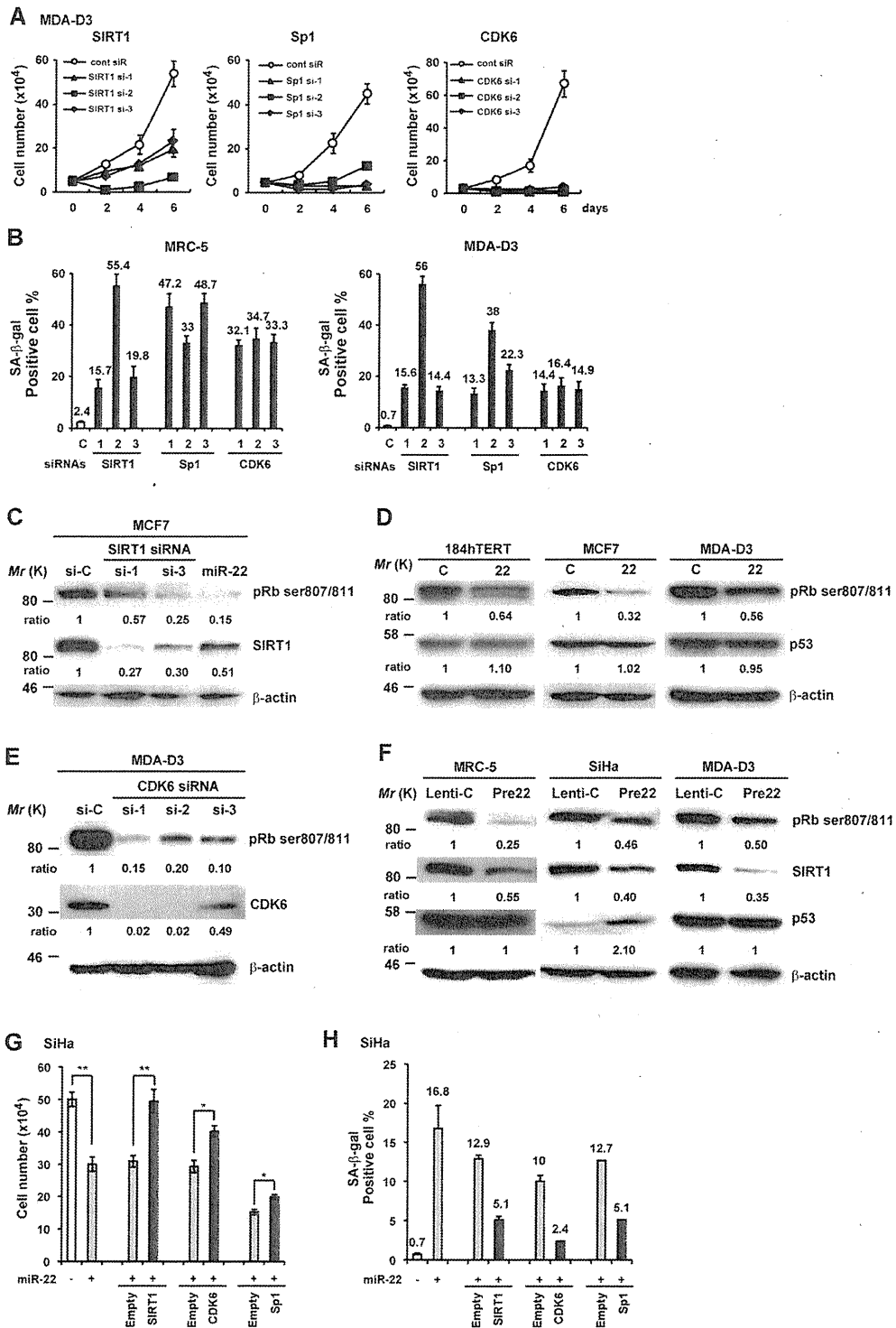


Figure 6. **SIRT1, Sp1, and CDK6 are potentially involved in miR-22-mediated cellular senescence.** (A) Representative growth curves corresponding to MDA-D3 cells transfected with cont siR or siRNAs against SIRT1, Sp1, and CDK6. Each value was determined in triplicate. (B) The histograms display the percentage of SA- β -gal-positive cells in MRC-5 and MDA-D3 cells at day 6 after siRNA transfection. (C–F) Western blot analysis was performed in those cells as indicated in each panel at 72 h after siRNA/miRNA transfection (C–E) or day 6 after infection (F). β -actin was used as a loading control and the relative density of bands was densitometrically quantified. (G and H) SiHa cells were first transfected with miR-22 duplex and, 24 h later, sequentially transfected with expressing plasmids or empty vectors as indicated. Cell proliferation (G) and SA- β -gal (H) activity was evaluated at day 6 after miRNA transfection. Data in all the panels represent mean \pm SEM ($n = 3$). *, $P < 0.05$; **, $P < 0.01$.

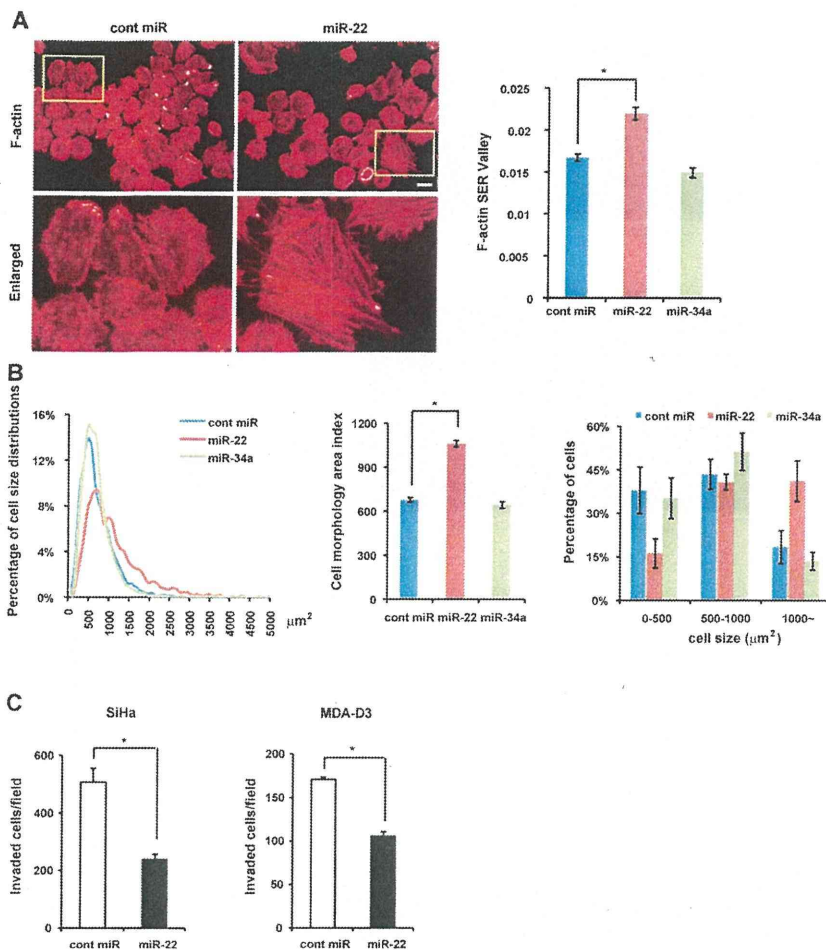


Figure 7. Overexpression of miR-22 induces cell enlargement and inhibits cell invasion in vitro. (A) Cell morphology area and actin stress fiber formation (stained with phalloidin) in miR-22-transfected SiHa cells were examined by confocal microscopy and compared with control cells. Enlarged images of the boxed area from the top are shown in the bottom. Bar, 20 μm (top, left and right). The histogram shows that F-actin formation was quantified using the texture analysis, and F-actin SER Valley represented occurrence of stress fiber structures within cells. (B) Cell size distribution (left), overall morphology area (middle), and percentage of cells in three groups of cell size (right) were calculated and analyzed by automated image analysis in SiHa cells. (C) Effect of miR-22 on SiHa and MDA-D3 cell invasion was measured by Matrigel invasion assay for 48 h, presented by quantitative determination of the number of invaded cells. Data in all the panels represent mean \pm SEM ($n = 3$). *, $P < 0.05$.

of SA-miRNAs in tumorigenesis by unraveling the role of miR-22 in cellular senescence and tumor suppression. miRNAs present a mechanism in which genes involved in a variety of different signaling pathways can be regulated simultaneously (He and Hannon, 2004; Lafferty-Whyte et al., 2009). Not only does miR-22-induced senescence inhibit unlimited tumor cell proliferation, senescence morphological changes also suppress tumor cell motility and invasion, partially because of enhanced actin stress fibers in cancer cells, indicating that the induction of senescence contributes to the suppression of tumor cell growth, invasion, and metastasis in vitro and in vivo.

Our study shows that miR-22 is differentially expressed in normal human and cancer cells. Consistent with our results, miR-22 dysregulation in cancer and human diseases has been documented in several miRNA profiling experiments. miR-22 is down-regulated in intrahepatic cholangiocarcinoma (Kawahigashi et al., 2009) and silenced in acute lymphoblastic leukemia (Li et al., 2010) and hepatocellular carcinoma (Calin et al., 2004) but up-regulated in osteoarthritis (Iliopoulos et al., 2008). These varying levels of miR-22 expression may suggest different requirements for alterations in their target gene pathways. miR-22 regulates a repertoire of cancer-related genes; however, there is no indication of the importance of miR-22 in tumorigenesis

through targeting senescence-associated genes. In the present study, gain-of-function and loss-of-function phenotypes of miR-22 demonstrated the role of miR-22 as a positive regulator of cellular senescence and identified SIRT1, Sp1, and CDK6 as critical targets of miR-22 in the senescence signaling pathway.

Previous studies have documented that SIRT1, Sp1, and CDK6 might act on the p53 and/or pRb pathway. (Ota et al., 2006; Ruas et al., 2007; Tapias et al., 2008; Brooks et al., 2009) SIRT1 plays an important role in the longevity and cellular senescence of most organisms through directly modulating the p16-pRb signaling pathway (Huang et al., 2008) as well as p53 and other proteins (Solomon et al., 2006; Brooks and Gu, 2009). The Sp1 transcription factor regulates the expression of multiple cell cycle genes, including the p53 and Sp1 gene itself (Koutsodontis et al., 2001; Tapias et al., 2008). CDK6 protein has been understood to phosphorylate pRb and delay senescence (Ruas et al., 2007; Ohtani et al., 2009). Our study demonstrated that miR-22 induced the dephosphorylation of pRb by targeting SIRT1 and CDK6. Collectively, we suppose that miR-22 regulates cellular senescence through connecting SIRT1, Sp1, and CDK6 to affect the pRb pathway and might coordinate p53 and other signaling pathways of cellular senescence in a cell type- and genetic context-dependent manner.