Inhibition of SIRT1 Signaling Sensitizes the Antitumor Activity of Silybin against Human Lung Adenocarcinoma Cells In Vitro and In Vivo

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Abstract

Although silybin, a natural flavonolignan, has been shown to exhibit potent antitumor activities against various types of cancers, including lung cancer, the molecular mechanisms behind these activities remain unclear. Silent information regulator 1 (SIRT1) is a conserved NAD+-dependent deacetylase that has been implicated in the modulation of transcriptional silencing and cell survival. Furthermore, it plays a key role in carcinogenesis through the deacetylation of important regulatory proteins, including p53. In this study, we investigated the antitumor activity of silybin towards human lung adenocarcinoma cells in vitro and in vivo and explored the role of the SIRT1 signaling pathway in this process. Silybin treatment resulted in a dose- and time-dependent decrease in lung adenocarcinoma A549 cell viability. In addition, silybin exhibited strong antitumor activity illustrated by reductions in tumor cell adhesion, migratory capability, and glutathione levels and by increased apoptotic indices and reactive oxygen species levels. Silybin treatment also downregulated SIRT1 and upregulated p53 acetylation. SIRT1 siRNA (in vitro) or cambinol (a known SIRT1 inhibitor used for in vivo studies) further enhanced the antitumor activity of silybin. In summary, silybin is a potent inhibitor of lung adenocarcinoma cell growth that interferes with SIRT1 signaling, and this inhibition is a novel mechanism of silybin action that may be used for therapeutic intervention in lung adenocarcinoma treatment. Mol Cancer Ther; 13(7); 1860–72. ©2014 AACR.

Introduction

Lung cancer is the leading cause of cancer burden worldwide with more than 3 million cases and 1 million deaths occurring annually (1). Non–small cell lung cancer (NSCLC) subtypes (adenocarcinoma, squamous cell carcinoma, and large cell carcinoma) account for 80% to 85% of all lung cancers. The majority of patients with NSCLC are diagnosed during advanced stages and exhibit inoperable local or distant metastases (2). Despite extensive research, the overall 5-year survival rate of patients with lung cancer is only 8% to 14%, and this rate has improved only marginally over the past 30 years (1, 3). These alarming statistics suggest that additional strategies are needed to control this disease.

An essential requirement for any successful long-term cancer chemoprevention strategy is that the chemopreventive agent exhibits little or no toxicity (4). An example of such an agent is silybin (the chemical structure of which is shown in Fig. 1A), a flavanone present in milk thistle (Silybum marianum L.) that is used as a hepatoprotective agent and has been marketed as a dietary supplement (5). Silybin exhibits strong chemopreventive and anticancer properties towards various models of colon (6), liver (7), kidney (8), brain (9), prostate, and breast cancer (10), among others. Moreover, no median lethal dose (lethal dose, 50%; LD₅₀) for silybin has been reported in laboratory animals, and it has also been considered exceptionally safe due to its extremely low toxicity in both animals and humans during acute or chronic administration; these findings emphasize the importance of utilizing this effective biologic agent in cancer chemoprevention studies (1, 11). With respect to lung cancer, silybin has been shown to cause significant growth inhibition and apoptosis in both small cell lung cancers and NSCLCs (1, 3, 11). However, the mechanisms responsible for the antitumor effects of silybin in lung adenocarcinoma have not yet been fully elucidated.
Sirtuins are NAD\(^+\)-dependent class III histone deacetylases that are conserved from bacteria to eukaryotes (12). Silent information regulator 1 (SIRT1) is the most well-studied family member due to its purported ability to prolong the lifespan of several species including Drosophila melanogaster, Caenorhabditis elegans, and mammals (12, 13). SIRT1 deacetylates histone proteins and other key transcriptional regulators such as p53, the forkhead box O (FoxO) transcription factors, NF-\(\kappa\)B, liver X receptor (LXR), PPAR\(\gamma\), and the hypoxia-inducible transcription factors (12–14). SIRT1 reportedly performs a wide variety of functions in various biologic systems including obesity-associated metabolic diseases, aging, cellular senescence, stress, and inflammation (15). Over the past decade, a controversial view of the role of SIRT1 in tumorigenesis has emerged. SIRT1 was found to be overexpressed in many cancers including prostate, colon, acute myeloid leukemia, and lung cancers (16, 17). In addition, SIRT1 overexpression in tumor cells correlated with the silencing of tumor suppressor genes (TSG) and resistance to chemotherapy and ionizing radiation (16, 18). The inhibition of SIRT1 by small-molecule inhibitors, dominant negative expression vectors, and siRNA not only rescues TSG expression but also affects key phenotypic aspects of cancer cells (19, 20). Moreover, the pharmacologic effects of silybin can be achieved through the regulation of SIRT1 signaling (12, 21–23). In this study, we assess the antitumor activity of silybin towards human lung adenocarcinoma cells and explore the role of SIRT1 in silybin activity.

**Materials and Methods**

**Materials**

Silybin, SIRT1 siRNA and antibodies against SIRT1 and p53 were obtained from Santa Cruz Biotechnology. Cambinol (a SIRT1 inhibitor), dithiothreitol (DTT), MTT,
dimethyl sulfoxide (DMSO), and 2',7'-dichlorofluorescein diacetate (2',7'-DCFH-DA) were purchased from Sigma-Aldrich. Antibodies against acetylated-p53 (Lys382), cytochrome c, Bcl2, Bax, and β-actin were purchased from Cell Signaling Technology. The FITC-Annexin V (AV)/propidium iodide (PI) staining kit and Bradford protein assay kit were purchased from the Beyotime Institute of Biotechnology (Nanjing, Jiangsu, China). The glutathione (GSH) kit was obtained from Cayman Chemical. Rabbit anti-goat, goat anti-rabbit, and goat anti-mouse secondary antibodies were purchased from the Zhongshan Company.

**Cell culture and treatment**

Human A549 lung adenocarcinoma cells were obtained from the Cell Culture Center at the Chinese Academy of Medical Sciences (Shanghai, China). A quality control including short tandem repeat (STR) analysis was conducted by the provider, and the results of the STR analysis corresponded to the data in ATCC cell banks. The cells were grown in Dulbecco’s modified Eagle medium (Gibco) supplemented with 10% FBS (Gibco), L-glutamine (2 mmol/L), penicillin (100 U/mL), streptomycin (100 U/mL), and HEPES (25 mmol/L). The cells were maintained in the presence of 5% CO2 at 37°C. The cells were treated with different concentrations of silybin (originally dissolved in DMSO) for the indicated time periods. An equal amount of DMSO (vehicle) was added to each treatment including the control. The DMSO concentration did not exceed 0.1% (v/v) for any treatment.

**Cell viability assay**

A549 cell viability was assessed via the MTT assay. After treatment, the cells were washed with PBS, and 100 μL of a 0.5 mg/mL MTT solution dissolved in phenol red-free DMEM was added to the cell cultures. The samples were incubated for 4 hours at 37°C. Next, 100 μL of DMSO were added to each well, and the samples were shaken for 15 minutes at 37°C. The absorbance of each well was measured at 490 nm on a SpectraMax 190 spectrophotometer (Molecular Devices), and cell viability was expressed as an optical density (OD) value.

**Analysis of cell apoptosis**

A549 cell apoptosis was detected using the FITC-AV/PI staining kit. Cells were treated with silybin in 6-well culture plates (1 × 10^6 cells/well), trypsinized, counted, washed twice in ice-cold PBS, and resuspended in 1× binding buffer (10 mmol/L HEPES/NaOH, 140 mmol/L NaCl, and 2.5 mmol/L CaCl_2, pH 7.4). First, 5 μL of AV (20 μg/mL) and 10 μL of PI (25 μg/mL) were added to 100 μL of the cell suspension followed by incubation for 15 minutes at room temperature in the dark. Finally, 400 μL of binding buffer were added to each sample, and the samples were kept on ice before analysis with a FACScan flow cytometer equipped with the FACScan data management system and Cell Quest software (all from Becton Dickinson).

**Analysis of intracellular ROS generation**

DCFH-DA passes through cell membranes and is cleaved by esterases to yield DCFH. ROS oxidize DCFH to generate the fluorescent compound dichlorofluorescein which can then be used for quantification of ROS. After treatment with silybin, cells were trypsinized and subsequently incubated with DCFH-DA (20 μmol/L) in PBS at 37°C for 2 hours. After incubation, the DCFH fluorescence of the cells in each well was measured using an FLX 800 microplate fluorescence reader at an excitation wavelength of 485 nm and an emission wavelength of 530 nm (Bioitex Instruments Inc.). The background was determined by measuring wells that did not contain cells. The fluorescence intensity of the control group was defined as 100%.

**Analysis of GSH levels**

GSH levels in the cells were determined using a commercial kit as described previously (19). Briefly, after treatment with silybin, the cells were scraped, collected, and washed with PBS. The resulting cell suspensions were used to determine the GSH levels using the previously mentioned kit according to the manufacturer’s instructions. GSH levels were evaluated by comparing samples with the standards and normalizing these values to the total protein content. The results were expressed as total GSH (% of control), and the reduced form of GSH was used as the standard.

**Analysis of caspase-3 activity**

Caspase-3 activity was measured with a colorimetric assay kit (MBL International Corporation) according to the manufacturer’s instructions as described previously (24). The cells were washed in ice-cold PBS, and protein was extracted and stored at −80°C. Cell lysates (20 μL) were added to a buffer containing a p-nitroaniline (pNA)-conjugated substrate for caspase-3 (Ac-DEVD-pNA) in a total reaction volume of 100 μL. Incubations were performed at 37°C. The released pNA concentrations were calculated from the absorbance values obtained at 405 nm and the calibration curve of the defined pNA solutions. The caspase-3 activity in the control group was set to 100%.

**Analysis of cell adhesion**

In our preliminary experiments, we found that silybin (less than 40 μmol/L) treatment for 24 hours had no effect on A549 cell proliferation; therefore, we performed adhesion and migration assays after 24 hours of silybin treatment (10, 20, and 40 μmol/L). This assay was performed as described previously (19). After treatment with silybin, cells were centrifuged and resuspended in basal medium with 10% FBS. The treated cells (1 × 10^4 cells/well) were placed in a 96-well plate and incubated for 30 minutes at 37°C. After the cells were allowed to adhere for 30 minutes, they were gently washed 3 times with PBS. The adherent cells were stained with MTT and observed under an inverted/
phase contrast microscope. Pictures were taken with an Olympus BX61 camera. Finally, 100 μL of DMSO were added to each well, and the samples were incubated for 15 minutes at 37°C with constant shaking. The wells were measured by a SpectraMax 190 spectrophotometer at a wavelength of 490 nm (Molecular Devices), and the OD value of the control group was set to 100%.

Analysis of wound healing
A cell culture wound-healing assay was performed according to well-established methods (25). The cells were grown to confluence, and a linear wound was created in the confluent monolayer with a 200 μL micropipette tip. The cells were then washed with PBS to eliminate detached cells. After treatment with silybin for 24 hours, wound edge movement was monitored under a microscope. The results are expressed as the distance between the cells on each side of the scratch wound.

SiRNA transfection
A549 cells were plated into 6-, 24-, or 96-well plates at a subconfluent density. The cells were transiently transfected with negative control siRNA or SIRT1 siRNA at a concentration of 50 pmol/L for 48 hours with the Lipofectamine RNAiMAX reagent (Invitrogen) in OPTI-MEM media (Gibco). The cells were subsequently prepared for further experiments.

Extraction of cytosolic cytochrome c
Extraction of cytosolic cytochrome c was performed as described previously (25). After treatment, the cells were harvested by centrifugation at 1,000 rpm for 5 minutes. The pellets were washed twice with ice-cold PBS, resuspended in a 5-fold volume of ice-cold cell extract buffer (20 mmol/L HEPES-KOH, pH 7.5; 10 mmol/L KCl, 1.5 mmol/L MgCl₂, 1 mmol/L ethylene diamine tetraacetic acid, 1 mmol/L ethylene glycol tetraacetic acid, 1 mmol/L DTT, 250 mmol/L sucrose, 0.1 mmol/L phenylmethylsulfonyl fluoride, and 0.02 mmol/L aprotinin), and incubated for 40 minutes at 4°C. Then, the cells were centrifuged at 1,200 rpm for 10 minutes at 4°C, and the final supernatant containing the cytosolic fraction of cytochrome c was used for Western blot analyses.

Antitumor activity in a xenograft model
Male athymic nude mice were purchased from the Laboratory Animal Centre of the Fourth Military Medical University (Xi’an, China). The mice were housed and maintained under specific pathogen-free conditions in facilities approved by the American Association for the Accreditation of Laboratory Animal Care and in accordance with the current regulations and standards of the United States Department of Agriculture, United States Department of Health and Human Services. The present study was performed according to the Guide for the Care and Use of Laboratory Animals, published by the U.S. NIH (NIH Publication No. 85-23, revised 1996) and was approved by the Ethics Committee of the Fourth Military Medical University. All surgeries were performed under sodium pentobarbital anesthesia and all efforts were made to minimize animal suffering. As described in our previous study (2), A549 cell xenografts were established by subcutaneously injecting 1 × 10⁶ cells into the right flanks of 4- to 6-week-old male athymic nude mice. On the basis of the data obtained from a pilot study, we initiated treatment when the tumor volumes reached approximately 100 mm³. The tumor volumes (V) were calculated using the following formula: V = A × B²/2 (A = largest diameter; B = smallest diameter). First, the mice were randomly divided into 3 groups (n = 6 per group): control (saline) and silybin suspended in saline at either 250 or 500 mg/kg body weight; silybin was administered 5 days per week by oral gavage. Next, the mice were randomly divided into control, silybin, cambinol+silybin, and cambinol groups (n = 6). Silybin was orally administered to the mice at doses of 500 mg/kg body weight per day (5 days/week), cambinol (50 mg/kg), or control (0.05% DMSO), all of which were diluted with saline and administered intraperitoneally (5 days/week). The body weight and tumor sizes were measured every 3 days with calipers (days 2, 5, 8, 11, 14, 17, and 20). On day 20, the tumors were excised from the euthanized mice for Western blot analysis.

Analysis of experimental lung metastasis in vivo
Male NOD/SCID mice (5 weeks) were purchased from the Vital River Company and treated similar to the athymic nude mice before experiments were performed. A549 cells (1 × 10⁶ cells in 0.2 mL PBS) were injected into the tail veins of the mice. Then, the mice were randomly divided into 4 groups upon induction of metastasis including control, silybin, cambinol+silybin, and cambinol groups (n = 6). The concentrations and administration of silybin and cambinol were the same as those used in the xenograft experiments described above. The mice were sacrificed 6 weeks after injection and the lungs were dissected out and photographed. Visible A549 colonies on the surface of the lungs were counted.

Western blot analyses
The cell, cell cytosolic fraction, and tumor tissue samples were homogenized in lysis buffer containing a 1% protease inhibitor cocktail. The lysates were centrifuged for 15 minutes at 12,000 rpm and the resulting supernatants were transferred to new tubes and stored at −70°C. The protein concentrations were determined with a Bradford protein assay kit. Proteins were separated by electrophoresis and transferred to nitrocellulose membranes. The membranes were blocked for 1 hour in Tris-buffered saline and Tween-20 (TBST, pH 7.6) containing 5% non-fat dry milk and were then incubated overnight at 4°C with antibodies against SIRT1, p53 (1:500 dilution), acetylated-p53, cytochrome c, Bcl2, Bax, and β-actin (1:1,000 dilution) followed by several TBST washes. The membranes were then probed with the...
appropriate secondary antibodies (1:5,000 dilution) at room temperature for 90 minutes and washed with TBST. The protein bands were detected with a Bio-Rad Imaging System (Bio-Rad) and quantified with the Quantity One software package.

**Statistical analysis**

All values are presented as the mean ± SD. Group comparisons were performed by ANOVA (SPSS 13.0). All of the groups were analyzed simultaneously with an LSD t test. A difference of *P* < 0.05 was considered statistically significant.

**Results**

**Effects of silybin on lung adenocarcinoma cell viability and apoptosis**

The viability of silybin-treated A549 cells was determined by the MTT assay, and the data are presented in Fig. 1B. The treatment of A549 cells for 12, 24, or 36 hours with 100, 200, or 400 μmol/L of silybin demonstrated inhibition of cell growth in a dose- and time-dependent manner. The microscopy images (Fig. 1C) show that silybin treatment resulted in significant cell shrinkage and a decrease in the rate of cellular attachment when compared with the control treatment. After treatment with 100, 200, or 400 μmol/L of silybin for 24 hours, the apoptotic index increased in a dose-dependent manner (*P* < 0.01 when compared with the control group). These results provide convincing data indicating that silybin can induce A549 cell apoptosis (Fig. 1D).

**Effects of silybin on ROS generation, GSH levels, and caspase-3 activity in lung adenocarcinoma cells**

To determine whether silybin causes intracellular oxidation, we used the specific oxidation-sensitive fluorescent dye DCFH-DA, which exhibits enhanced fluorescence intensity following the generation of intracellular reactive metabolites. Silybin treatment for 24 hours induced dose-dependent ROS generation in A549 cells (*P* < 0.01 when compared with the control group; Fig. 2A). Reduced GSH is the major non-protein thiol present in cells, and it is essential for the maintenance of cellular redox status. Because silybin-induced apoptosis in A549 cells correlated with ROS generation, we hypothesized that silybin treatment may disturb the cellular redox status. To address this issue, we determined the effects of silybin treatment on intracellular GSH levels. After treatment with silybin (24 hours), we observed a dose-dependent decrease in intracellular GSH levels in A549 cells (*P* < 0.01 when compared with the control group; Fig. 2B). Furthermore, we also found that silybin treatment led to higher levels of caspase-3 activity (Fig. 2C).

**Effects of silybin on lung adenocarcinoma cell migration and adhesion**

After 24-hour incubation with silybin, the cell adhesion ratio decreased significantly (*P* < 0.01 when compared with the control group; Fig. 3A), and the effects of silybin on cell adhesion and migratory capability were dose-dependent. In addition, the distances between the scratch wounds were longer in the silybin-treated group, and the migratory distance of the cells was reduced by silybin treatment (*P* < 0.01 when compared with the control group; Fig. 3B). These results indicate that silybin reduces cell adhesion and the migratory capability of A549 cells.

**Effects of silybin on SIRT1 pathway and mitochondrial apoptotic pathway-related proteins in lung adenocarcinoma cells**

Silybin treatment for 24 hours induced a dose-dependent downregulation of SIRT1 and an upregulation of acetylated p53 (*P* < 0.01 when compared with the control group; Fig. 3C).

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**Figure 2.** The effects of silybin on ROS generation, GSH levels, and caspase-3 activity in lung adenocarcinoma cells (24 hours). A, the ROS concentrations are shown, and the fluorescence intensity of the control group was defined as 100%. B, the intracellular GSH levels are shown, and the GSH levels of the control group were defined as 100%. C, the intracellular caspase-3 activity levels are shown, and the caspase-3 activity level of the control group was defined as 100%. The results are expressed as the means ± SD, *n* = 6. **, *P* < 0.01 when compared with the control group; **, *P* < 0.01 when compared with the 100 μmol/L silybin group; and ###, *P* < 0.01 when compared to the 200 μmol/L silybin group. SIL, silybin.
group; Fig. 4). In addition, the mitochondrial apoptotic pathway-related proteins Bax and cytosolic cytochrome c were upregulated by silybin treatment; in contrast, Bcl2 was downregulated ($P < 0.01$ when compared with the control group; Fig. 4).

**Effects of silybin combined with SIRT1 siRNA on cell viability and SIRT1 signaling in lung adenocarcinoma cells**

SIRT1 siRNA significantly decreased SIRT1 levels and increased acetylated p53 expression in A549 cells ($P < 0.01$ when compared with the control siRNA group; Fig. 5B). SIRT1 siRNA also slightly decreased the viability of A549 cells; however, this difference was not significant ($P > 0.05$ when compared with the control siRNA group; Fig. 5A). The combination of SIRT1 siRNA and silybin (200 μmol/L) significantly decreased cell viability ($P < 0.01$ when compared with both the silybin and SIRT1 siRNA groups; Fig. 5A). In addition, Bax and cytosolic cytochrome c were further upregulated by silybin and SIRT1 siRNA cotreatment, whereas Bcl2 was further downregulated ($P < 0.01$ when compared with the silybin and SIRT1 siRNA groups; Fig. 5B).

**Effects of silybin on tumor xenografts in vivo**

To determine whether silybin could inhibit tumor growth in animals, we established A549 xenografts in athymic nude mice. We found that the mice in all treatment groups developed subcutaneous tumors. As shown in Fig. 6A and B, silybin treatment (250 or 500 mg/kg) significantly inhibited tumor growth ($P < 0.01$ when compared with the control group). Silybin treatment (250 or 500 mg/kg) did not cause death or abnormal behavior and did not affect body weight gain ($P > 0.05$ when compared with the control group; Fig. 6C). Western blot analysis showed that silybin treatment induced a dose-dependent downregulation of SIRT1 and upregulated the acetylation of p53 ($P < 0.01$ when compared with the control group; Fig. 6D). In addition, the mitochondrial apoptotic pathway-related protein Bax was upregulated by silybin treatment, whereas Bcl2 was downregulated ($P < 0.01$ when compared with the control group; Fig. 6D).

**Effects of silybin combined with cambinol on tumor xenografts in vivo**

As shown in Fig. 7A and B, treatment with silybin or cambinol alone significantly inhibited tumor growth ($P < 0.01$ when compared with the control group). Silybin treatment (250 or 500 mg/kg) did not cause death or abnormal behavior and did not affect body weight gain ($P > 0.05$ when compared with the control group; Fig. 6C). Western blot analysis showed that silybin treatment induced a dose-dependent downregulation of SIRT1 and upregulated the acetylation of p53 ($P < 0.01$ when compared with the control group; Fig. 6D). In addition, the mitochondrial apoptotic pathway-related protein Bax was upregulated by silybin treatment, whereas Bcl2 was downregulated ($P < 0.01$ when compared with the control group; Fig. 6D).
0.01 or \( P < 0.05 \) when compared with the control group, respectively). The combination of silybin and cambinol further inhibited tumor growth \( (P < 0.01 \) when compared with the silybin or cambinol groups). Silybin or cambinol treatment did not affect animal body weight \( (P > 0.05 \) when compared with the control group; Fig. 7C). Western blot analysis showed that silybin and cambinol cotreatment further decreased SIRT1 levels and increased acetylated p53 expression \( (P < 0.01 \) when compared with the silybin and cambinol groups; Fig. 7C). In addition, Bax was further upregulated by silybin and cambinol cotreatment, whereas Bcl2 was further downregulated \( (P < 0.01 \) when compared with the silybin and cambinol groups; Fig. 7C).

Effects of combination silybin and cambinol treatment on tumor pulmonary metastasis in vivo

NOD/SCID mice were used to explore the effects of combined silybin and cambinol treatment on tumor pulmonary metastasis. As shown in Fig. 8A and B, treatment with silybin alone significantly decreased pulmonary metastatic colonies \( (P < 0.01 \) when compared with the...
The combination of silybin and cambinol further decreased pulmonary metastatic colonies ($P < 0.01$ when compared with the silybin or cambinol groups). Treatment with cambinol alone slightly decreased pulmonary metastatic colonies ($P < 0.05$ when compared with the control group).

Discussion

There is increasing evidence that nutraceutical agents are important for cancer prevention and intervention (1, 11, 26) because dietary and nondietary agents and lifestyle determine cancer incidence and may also affect the growth, progression, or aggressiveness of cancer cells (26). Silybin is a flavonolignan and the major active constituent of silymarin, which is a complex mixture of flavonolignans and polyphenols that are extracted from milk thistle seeds. The German Commission E has recommended its use for dyspeptic complaints and liver conditions including toxin-induced liver damage and hepatic cirrhosis. It has also been recommended as a supportive therapy for chronic inflammatory liver conditions (27). Neither milk thistle extract nor silybin is currently approved for any medical use in the United States; however, it is sold as a dietary supplement and is one of the most frequently sold herbal products in the United States (27). The anticancer efficacy of silybin is

Figure 5. Effects of combined silybin and SIRT1 siRNA on cell viability and SIRT1 signaling in lung adenocarcinoma cells (24 hours). A, viability is expressed as OD values. The combination of silybin and SIRT1 siRNA further inhibited the viability of A549 cells. B, representative Western blot analysis results are shown. The results are expressed as the means $\pm SD$, $n = 6$. **, $P < 0.01$ when compared with the control group; $##$, $P < 0.01$ when compared with the 200 $\mu$mol/L silybin group; and $$, $P < 0.01$ when compared with the SIRT1 siRNA + 200 $\mu$mol/L silybin group. SIL, silybin.
clearly evident in the published reports of its effects against various cancers generated over the last two decades; these effects mainly target proliferation, apoptosis, inflammation, angiogenesis, and cancer cell metabolism (6–10). Various molecules and signaling pathways are involved in the antitumor effects of silybin including VEGF, VEGF receptors, inducible nitric oxide synthase, STAT, PI3K/Akt, β-catenin, IGF-IGFBP3, NF-κB, and MAPK (3–12, 26). However, the effects of silybin on human lung adenocarcinoma and the mechanisms responsible for these effects are not fully understood. In our study, silybin treatment resulted in a dose- and time-dependent inhibition of cell viability and the induction of apoptosis in A549 lung adenocarcinoma cells. Silybin also significantly blocked lung adenocarcinoma cell adhesion and migration, both of which are major events that determine the metastatic potential of tumors. In addition, silybin treatment significantly inhibited tumor growth in A549 xenografts in athymic nude mice and decreased the number of pulmonary metastatic colonies found in NOD/SCID mice.

SIRT1 is a conserved NAD⁺-dependent deacetylase that has been implicated in the modulation of transcriptional silencing and cell survival. It also plays a key role in carcinogenesis through the deacetylation of important regulatory proteins (19). SIRT1 is highly expressed in several human cancers including lung, colon, breast, liver, and prostate cancers (28–30). Studies have also shown that the inhibition of SIRT1 expression and/or activity by siRNA or small-molecule inhibitors promoted cell-cycle regulation, which is essential for cancer cell survival and proliferation.

**Figure 6.** Effects of silybin on A549 tumor xenografts in vivo. A, photographs showing the tumor xenograft morphologies of the various groups. B, the tumor growth curve was drawn from the tumor volumes and the treatment duration. C, the body weight curve graph is shown for the treatment duration. D, representative Western blot analysis results are shown. The results are expressed as the means ± SD, n = 6; ***, P < 0.01 when compared with the control group; ***, P < 0.01 when compared with the 250 mg/kg silybin group. SIL, silybin.
The effects of combination silybin and cambinol treatment on A549 tumor xenografts in vivo. A, photographs showing the tumor xenograft morphologies for the different groups. B, the tumor growth curve was drawn from the tumor volumes and the treatment duration. C, the body weight curve graph is shown for the treatment duration. D, representative Western blot analysis results are shown. The results are expressed as the mean ± SD, n = 6. **P < 0.01 when compared with the control group; ##P < 0.01 when compared with the 500 mg/kg silybin group; **##P < 0.01 when compared with the cambinol + 500 mg/kg silybin group; ##P < 0.01 when compared with the cambinol group.

The vital importance of the tumor suppressor gene p53 in the prevention of human cancer development and progression is demonstrated by the fact that p53 mutations are detected in 50% of all human cancers and is also emphasized by accumulating evidence that p53 protein function and stability are often abrogated via posttranslational mechanisms in the remaining human cancers that express wild-type p53 (28). Cancers must frequently disarm p53; once p53 is activated, it triggers cell growth arrest, apoptosis, autophagy, or senescence, all of which are detrimental to cancer cells. Furthermore, p53 impedes cell migration, metabolism, and angiogenesis, which are favorable conditions for cancer cell progression and metastasis (28, 32). A variety of posttranslational modifications can regulate p53 activity including phosphorylation, acetylation, methylation, and sumoylation, and these modifications have been previously described (33, 34). Acetylation reportedly plays an important role in p53 stabilization, nuclear localization, and transcriptional activation and can lead to p53 activation in a manner independent of its phosphorylation status (33, 35). SIRT1 can deacetylate several lysine residues in the p53 protein...
Camolinol is a cell permeable naphthol compound that inhibits the NAD+-dependent deacetylase activities of SIRT1 and SIRT2 ($IC_{50} = 56$ and $59 \text{ mmol/L}$, respectively) and does not inhibit class I or II histone deacetylase activity (36, 37). Unlike sirtinol (a known SIRT1 inhibitor), cambolnol can be used in vivo and was shown to effectively inhibit Bcl6-expressing Burkitt lymphoma xenograft growth in mice (37). A previous study has verified that the use of a 100 mg/kg cambolnol dose had no toxic effects on the animals which displayed no weight loss or increases in serum transaminase levels (36). In this study, we found that silybin treatment inhibited SIRT1 and activated acetylated p53 in A549 cells. When combined with SIRT1 siRNA in vitro or cambolnol in vivo, silybin further decreased the viability of lung adenocarcinoma cells, inhibited tumor growth, and decreased the number of pulmonary metastatic colonies. As expected, we observed that A549 cells treated with SIRT1 siRNA or cambolnol exhibited increased p53 acetylation when also treated with silybin. These results suggest that SIRT1 downregulation enhances the effects of silybin in part by increasing p53 acetylation.

GSH is a major cellular nonprotein antioxidant that eliminates $O_2^-$ and provides electrons for enzymes such as GSH peroxidase which reduces $H_2O_2$ to $H_2O$. Reports have indicated that the intracellular GSH content exhibits a decisive effect on anticancer drug-induced apoptosis suggesting that apoptotic effects are inversely correlated with GSH content. Reduced GSH is the major nonprotein thiol present in cells and is essential for the maintenance of cellular redox status (19). A majority of chemotherapeutic drugs inhibit cancer cell viability and induce apoptosis through the intrinsic mitochondrial apoptotic pathway; important members of this pathway include Bcl2, Bax, and cytochrome c (38). Release of cytochrome c from mitochondria is a hallmark of apoptosis (26). Studies have provided novel evidence that SIRT1 may be involved in the intrinsic mitochondrial apoptotic pathway (39). During apoptosis, mitochondria serve as a source of ROS, and enhanced ROS production is related to the apoptotic responses induced by antitumor agents (38). Our results show that silybin treatment depletes intracellular GSH levels and increases ROS production in A549 cells. Moreover, in addition to downregulating SIRT1 signaling, silybin also increased intracellular caspase-3 activity, upregulated Bax and cytosolic cytochrome c protein levels, and downregulated Bcl2 protein levels. These findings verify previous work in which the inhibition of SIRT1 signaling was associated with the induction of the mitochondrial apoptotic pathway in human cancer cells (40).

In conclusion, these experiments provide mechanistic evidence that silybin treatment inhibits lung adenocarcinoma cell growth and metastasis via the downregulation of SIRT1 signaling. Furthermore, the downregulation of SIRT1 signaling sensitizes lung adenocarcinoma cells to silybin treatment. Therefore, silybin has multiple advantages that make it a strong candidate for therapeutic applications in lung adenocarcinoma, and SIRT1 downregulation appears to be an effective gene therapy strategy for the treatment of cancer.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

Authors’ Contributions
Conception and design: W. Duan, W. Chen
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Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): Z. Liang, H. Wang, W. Yi, Y. Li, Y. Feng, S. Yu, Z. Jin
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): Z. Liang, W. Yi, X. Yan, J. Yan, Y. Li, Y. Feng, J. Yang, Z. Jin
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