Emerging evidence has demonstrated the antitumor activity of allicin in various tumors. However, little study has been carried out on the functional role of allicin in cervical cancer. Our data showed that allicin suppressed cervical cancer cell viability in a time- and dose-dependent manner. Allicin treatment could reverse H$_2$O$_2$-induced reactive oxygen species accumulation. Meanwhile, levels of glutathione and superoxide dismutase were increased, but malondialdehyde was decreased after allicin incubation for 48 h. Furthermore, TUNEL staining showed that H$_2$O$_2$ treatment induced cell apoptosis, but allicin treatment could decrease cell apoptosis. Western blot assay showed that allicin could suppress the expression of nuclear factor erythroid 2-related factor 2 (NRF2) and heme oxygenase 1. We also showed that NRF2 prompted SiHa cell proliferation and reduced SiHa cell apoptosis. More importantly, allicin-inactivated phosphoinositide 3-kinase/protein kinase B (PI3K/AKT) signaling could be partially reversed by overexpressing of NRF2. We also showed that NRF2 in the eukaryotic expression vector pcDNA3.1, and NRF2 siRNA, and the scrambled sequence (CCA ACC AGU UGA CAG UGA ACU CAUU / CAA ACU GAC AGA AGU UGA CAA UUAU) were constructed by GenePharma (Shanghai, China).

In the present study, we found that allicin significantly suppressed cervical cancer proliferation and migration mainly by inhibiting the expression of NRF2, thereby maintaining the intracellular oxidative homeostasis.

**Materials and methods**

Cell culture and transfections. SiHa cells (ATCC; Manassas, VA, USA), a human cervical squamous cell carcinoma cell line, were cultured in RPMI-1640 plus 10% calf serum and 1% penicillin/streptomycin in a 5% CO$_2$ humidified incubator at 37°C.

Transient transfection. NRF2 in the eukaryotic expression vector pcDNA3.1, and NRF2 siRNA, and the scrambled sequence (CCAACCAGUGACAGUGAACAUUU/CAA ACUGACAGAGUUGACAAUU) were constructed by GenePharma (Shanghai, China).
In brief, SiHa cells were seeded in 6-well plates and grown to 60-80% confluence overnight. Transfection complexes were formed with Lipofectamine RNAiMAX (Invitrogen, CA, USA) in Opti-MEMI (Invitrogen; Thermo Fisher Scientific, Inc., Waltham, MA, USA) according to manufacturer guidelines. All transfections were performed in triplicate. Cell proliferation was determined by counting cells 24, 48, and 72 h after transfection.

RNA isolation and qRT-PCR. Total RNA was isolated from SiHa cells using Trizol reagent (Invitrogen; Thermo Fisher Scientific, Inc.) according to the manufacturer's instructions. RNA was reverse transcribed into cDNA using the Prime-Script one-step RT-PCR kit (C28025-032, Invitrogen; Thermo Fisher Scientific, Inc.). Detailed RT-PCR procedure was described as follows: 95˚C for 10 min followed by 50 cycles of 95˚C for 10 sec, 55˚C for 10 sec, 72˚C for 5 sec; 99˚C for 1 sec; 59˚C for 15 sec; 95˚C for 1 sec; then cooling to 40˚C. The relative expression levels were calculated with the 2- ΔΔCq method and experiments were repeated in triplicate. The primers used were listed as follows: NRF2-forward primer: 5'-TCA GCG ACG GAA AGA GTA TGA-3' and reverse primer: 5'-CCACTGGTTTCTGACTGGATG-3'.

Protein isolation and western blotting. Firstly, protease inhibitors (Sigma-Aldrich; Merck KGaA, Darmstadt, Germany) were added to cell lysates and maintained on ice for 15 min. Then, cell lysates were centrifuged at 12,000 x g for 10 min at 4˚C. And the supernatant was collected and separated by SDS-PAGE and transferred to polyvinylidene fluoride membranes (EMD Millipore, Billerica, MA, USA). Then, the membranes were blocked in 10% skim milk for 40 min at 37˚C. A primary antibody against NRF2 (Abcam, Cambridge, MA, USA) or β-Actin (Sangon, Shanghai, China) was added overnight to blots at 4˚C. Blots were washed in PBS Tween three times, after which the secondary antibody (horseradish peroxidase-conjugated goat anti-rabbit immunoglobulin G; Zhongshan Gold Bridge, Beijing, China) was added at room temperature for 2 h. Chemiluminescent substrate (Thermo Fisher Scientific, Inc.) was added to visualize bands. Quantity One software was used to quantify the intensity of each band and was normalized to the intensity of the internal control β-actin.

Detection of reactive oxygen species. Cells were seeded at 1x10^4 cells per well into 96-well plates and treated with 40 nM allicin. The cells were incubated for 48 h at 37˚C and 5% CO₂. At the end of the incubation period, cells were washed twice in PBS and incubated in 200 µM ROS Fluorescent Probe-DHE (Vigorous, Beijing, China) for 15 min (Sigma-Aldrich; Merck KGaA).

Analyses of cell cycle and apoptotic changes by flow cytometry. SiHa cells were seeded in 6-well culture plates at a density of 5x10^4 cells/well in RPMI 1640 supplemented with 10% calf serum and 1% penicillin/streptomycin. After allicin treatment for 48 h, cell cycle distributions were examined by measuring PI-fluorescence with a BD FACS Calibur flow cytometer (BD Biosciences, San Jose, CA, USA) through an FL-2 filter (585 nm).

Annexin V staining was performed to evaluate apoptosis. Control and treated SiHa cells were added at 5x10⁴ cells/ml in binding buffer (10 mM HEPES (4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid) [Ph 7.4], 140 mM NaCl, 2.5 mM CaCl2). FITC-Annexin V (10 µl) in 190 µl of cell suspension was incubated for 10 min at room temperature. Cell mixtures were centrifuged and resuspended in 190 µl binding buffer, and 10 µl PI (1 mg/ml) solution was added. Then, the cells were washed with cold PBS and resuspended at a final concentration of 1x10⁴ cells/ml. FITC-Annexin V (5 µl) and propidium iodide were gently mixed and incubated with the cells for 15 min at a room temperature. After incubation, the samples were analyzed by flow cytometry within 1 h. The Annexin V and PI+ represented necrotic cells, the Annexin V+ and PI+ represented late apoptotic cell, the Annexin V- and PI+ represented early apoptotic cell, and the Annexin V- and PI- represented normal cells.

Transwell migration and invasion assays. Migration and invasion assays were performed as previously described. Migration was evaluated in Transwell cell culture chambers with 6.5-mm-diameter polycarbonate membrane filters containing 8-µm pores (Corning Incorporated, Corning, NY, USA). Cells were added in 100 ml serum-free media to the upper chamber. The lower chamber contained 600 ml culture media with 10% calf serum. After 10 h at 37˚C, cells were removed from the upper surface of the membrane with a cotton swab. Filters were fixed in methanol for 20 min and stained with Giemsa solution for 30 min. The number of cells that had migrated were counted. Five random fields (Nikon ECLIPSE TS100; Nikon Corporation, Tokyo, Japan) were counted per well, and the mean was calculated. The membrane of the upper chamber of the transwell was pre-coated with 100 ml of a 1 mg/ml solution of Matrigel (BD Biosciences, Franklin Lakes, NJ, USA).

TUNEL assay. Cells were stained by terminal deoxy-nucleotidyl transferase-mediated dUTP nick-end labeling (TUNEL; In situ Cell Death Detection kit; Roche Diagnostics, Basel, Switzerland). In brief, cells were fixed in 4% paraformaldehyde, added permeabilisation solution, and incubated with TUNEL reaction mixture. TUNEL positive cells and total cells were counted and percent apoptotic cells calculated.

Statistical analysis. The data are represented as the mean ± standard error of the mean (SEM). The two-tailed unpaired Student's t-tests were used for comparisons of two groups. The ANOVA multiple comparison test (SPSS 13.0; SPSS, Inc., Chicago, IL, USA) followed by Turkey post hoc test were used for comparisons of two more groups. P<0.05 was considered to indicate a statistically significant difference.

Results

Allicin suppressed SiHa cell viability in time- and dose-dependent manner. Firstly, we analyzed the effects of allicin on SiHa cell viability. As shown in Fig. 1A, treatment with 5, 20 and 50 nM allicin significantly decreased cell viability by 10.2, 27.8 and 43.1%, respectively. Furthermore,
incubation of 20 nM allicin reduced SiHa cell viability by 12.3, 24.3 and 38.9 at 24, 48 and 72 h (Fig. 1B). Allicin‑induced accumulation of reactive oxygen species and SiHa cell apoptosis. Next, we evaluated the role of allicin in the accumulation of ROS. Compared with blank control, H₂O₂ treatment markedly increased the fluorescence density of DHE, but allicin treatment could reverse H₂O₂‑induced ROS accumulation (Fig. 2A). We also quantified the contents of glutathione (GSH), superoxide dismutase (SOD) and malondialdehyde (MDA) contents. Our data showed that H₂O₂ treatment decreased GSH and SOD contents, but increased MDA content (Fig. 2B-D). In contrast, GSH and SOD contents were increased, but MDA was decreased after allicin incubation for 48 h (Fig. 2B-D). Furthermore, TUNEL staining showed H₂O₂ treatment induced cell apoptosis, but allicin treatment could decrease cell apoptosis (Fig. 2E).

Allicin inhibited the expression of NRF2 in SiHa cells. NRF2 is a key transcription factor that is widely involved in the regulation of antioxidant genes. Thus, we evaluated the expression of NRF2 after allicin treatment. As shown in Fig. 3, treatment with allicin significantly suppressed the level of NRF2. Furthermore, heme oxygenase 1 (HO-1), an antioxidant enzyme regulated by NRF2, was decreased by allicin incubation (Fig. 3).

NRF2 prompted SiHa cell proliferation and reduced SiHa cell apoptosis. Furthermore, we explored the effects of NRF2 in SiHa cell proliferation and apoptosis. Our data showed that overexpressing NRF2 significantly enhanced SiHa cell migration and invasion capacity (Fig. 4A and B). Furthermore, overexpressing NRF2 could largely reverse H₂O₂‑induced cell apoptosis (Fig. 4C).

Allicin suppressed the malignant phenotype of SiHa cells by inhibiting NRF2. We further evaluated whether allicin inhibits SiHa cell proliferation through suppressing NRF2. Thus, a full‑length human NRF2 was successfully transfected into SiHa cells in the presence or absence of allicin. Compared with normal control, transfection of NRF2 significantly enhanced the activation of PI3K/AKT signaling (Fig. 5A). However, pre‑incubation of allicin could decrease the phosphorylation levels of PI3K/AKT and the protein level of Bcl-2 (Fig. 5A). In contrast, allicin‑inactivated PI3K/AKT signaling and Bcl-2 expression could partially reversed by overexpressing of NRF2 (Fig. 5A). We also evaluated cell apoptosis in SiHa cells transfected with pNRF2. Our data showed that overexpressing of NRF2 decreased cell apoptosis rate by 3.1±0.54% (Fig. 5B). More importantly, allicin‑induced cell apoptosis (43.5±3.8%) could largely be abolished by upregulation of NRF2 (12.3±2.08%). These data indicated that allicin induced SiHa cell apoptosis mainly by suppressing the expression of NRF2.

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Discussion

Cervical cancer is ranked as the second most common cancer in women worldwide (18,19). A most important feature of cervical cancer is the high mortality rate, which is mainly attributed to the lack of effective therapies for women with high-grade cervical cancer (20). It is reported that high-risk human papillomaviruses (HPVs) is a key causal factor for cervical cancer (21). And HPV infection is also suggested to correlate with other anogenital cancers as well as a small
fraction of head & neck cancer (22). Therefore, it is important to identify effective prevention methods of human cervical cancers.

Allicin is characterized by antitumor effect in multiple cancers through suppressing cancer cell growth and increasing cell apoptosis (23,24). For example, allicin is reported to sensitize hepatocellular carcinoma (HCC) cells to 5-FU induced apoptosis mainly by modulating ROS-mediated mitochondrial pathway, showing the application of allicin as a novel chemotherapy regimen in HCC (25). In addition, allicin is reported to enhance MGC-803 human gastric carcinoma cell apoptosis by activating the p38 mitogen-activated protein kinase/caspase-3 signaling pathway (26). In the current study, we mainly evaluated the role of allicin in the malignant proliferation of cervical cancer cells. Our data showed that allicin suppressed cervical cancer viability in a time- and dose-dependent manner. Further study revealed that allicin inhibited cervical cancer cell proliferation and migration. These data showed an antitumor role of allicin in cervical cancer cells.

These above findings prompts us to further explore the underlying mechanism in which allicin modulates the progression of cervical cancer. Here, we mainly focused on NRF2, an anti-oxidant enzyme. It is reported that abnormal activation of NRF2 enhances the expression of enzymes for the detoxification of chemical carcinogens, thereby leading to the protection against carcinogenicity, mutagenicity and various toxicity (27,28). Increasing evidence has showed the protective role of NRF2 in intracellular oxidative stress, chemotherapeutic agents and radiotherapy (29,30). However, disruption of NRF2 also enables the cells towards carcinogens, which resulting in the development of inflammation and cancer formation (31,32). Therefore, it is important to maintain the expression of NRF2 in normal status, or else the excessive NRF2 expression confers to the aberrant survival of cancer cells.

Here, we found that treatment with allicin could significantly suppress the expression of NRF2 and the downstream enzyme, HO-1. Meanwhile, we also evaluated the functional role of NRF2 on cervical cancer cell proliferation. We found that overexpressing of NRF2 enhanced cervical cancer cell invasion and migration, indicating an oncogenic role of NRF2 in cervical cancer cells. More importantly, allicin-induced cell apoptosis could largely be abolished by overexpressing...


