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Golgi Phosphoprotein 3 Confers Radioresistance via Stabilizing EGFR in Lung Adenocarcinoma

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Purpose: Radioresistance is a major cause of treatment failure in tumor radiation therapy, and the underlying mechanisms of radioresistance are still elusive. Golgi phosphoprotein 3 (GOLPH3) has been reported to associate tightly with cancer progression and chemoresistance. Herein, we explored whether GOLPH3 mediated radioresistance of lung adenocarcinoma (LUAD) and whether targeted suppression of GOLPH3 sensitized LUAD to radiation therapy.

Methods and Materials: The aberrant expression of GOLPH3 was evaluated by immunohistochemistry in LUAD clinical samples. To evaluate the association between GOLPH3 and radioresistance, colony formation and apoptosis were assessed in control and GOLPH3 knockdown cells. γ-H2AX foci and level determination and micronucleus test were used to analyze DNA damage production and repair. The rescue of GOLPH3 knockdown was then performed by exogenous expression of small interfering RNA-resistant mutant GOLPH3 to confirm the role of GOLPH3 in DNA damage repair. Mechanistically, the effect of GOLPH3 on regulating stability and nuclear accumulation of epidermal growth factor receptor (EGFR) and the activation of DNA-dependent protein kinase (DNA-PK) were investigated by quantitative real-time polymerase chain reaction, western blot, immunofluorescence, and coimmunoprecipitation. The role of GOLPH3 in vivo in radioresistance was determined in a xenograft model.

Results: In tumor tissues of 33 patients with LUAD, the expression of GOLPH3 showed significant increases compared with those in matched normal tissues. Knocking down GOLPH3 reduced the clonogenic capacity, impaired double-strand break (DSB) repair, and enhanced apoptosis after irradiation. In contrast, reversal of GOLPH3 depletion rescued the impaired repair of radiation-induced DSBs. Mechanistically, loss of GOLPH3 accelerated the degradation of EGFR in lysosome, causing the reduction in EGFR levels, thereby weakening nuclear accumulation of EGFR and attenuating the activation of DNA-PK.

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Disclosures: none

Research data are stored in an institutional repository and will be shared upon request to the corresponding author.

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Furthermore, adenovirus-mediated GOLPH3 knockdown could enhance the ionizing radiation response in the LUAD xenograft model.

Conclusions: GOLPH3 conferred resistance of LUAD to ionizing radiation via stabilizing EGFR, and targeted suppression of GOLPH3 might be considered as a potential therapeutic strategy for sensitizing LUAD to radiation therapy.

Introduction

Lung cancer, the leading cause of cancer mortality in the world, has been estimated at 1.8 million deaths worldwide in 2020.[1] Based on histology, lung cancer can be classified either as small cell lung cancer (SCLC) or non-SCLC (NSCLC), and the latter accounts for approximately 80% of all lung cancers. Radiation therapy is increasingly used because of its advantages for lung cancer patients, especially inoperable cases, besides surgery and chemotherapy. Optimization of radiation therapy is necessary for treating NSCLC because of a relatively higher radioresistance, especially with lung adenocarcinoma (LUAD), which is the most frequently encountered among NSCLC cases.[2]

Tumor cell radioresistance, one of the most important determinants in therapy planning and prognosis, is tightly associated with its genetic background.[3] Previous studies have revealed various radiorsistance-associated genes such as P53,[4] STAT3,[5] and epidermal growth factor receptor (EGFR).[6,7] Highly expressed EGFRs were present in most cases of NSCLC[8] and associated with chemotherapy resistance.[9] Furthermore, it is known that abnormal activity or overexpression of EGFR usually causes radioresistance in NSCLC,[10] and targeting EGFR to increase ionizing radiation (IR) sensitivity has been preclinically tested.[11] Nuclear EGFR has been found to play a key role in preventing tumor cell death via activating DNA-dependent protein kinase catalytic subunit (DNA-PKcs)-dependent DNA double-strand break (DSB) repair after treatment with cisplatin or IR.[12]

The Golgi phosphoprotein 3 (GOLPH3) protein, also known as GPP34, GMx33, MIDAS, or Vps74p, is a component of the trans-Golgi network, which functions as a late secretory-sorting station. Recently, GOLPH3 has also been identified as a new oncoprotein, which is commonly overexpressed in human cancers including breast cancer,[13] hepatocellular carcinoma,[14] prostate cancer,[15] and NSCLC.[16,17] In addiation, clinical data demonstrate that GOLPH3 functions as an independent prognostic marker for early-stage NSCLC patients after surgery,[16] and overexpression of GOLPH3 is associated with poor survival in NSCLC patients.[17] Oncogenes frequently play an important role in determining drug resistance, and there is no exception for GOLPH3. It is confirmed that GOLPH3 overexpression and the decreased level of microRNA 34a promote enrichment of cancer stem cells and chemoresistance.[18] Indeed, depletion of GOLPH3 causes a significant increase in cellular apoptosis in response to doxorubicin and camptothecin depending on the Golgi dispersal regulated by the DNA-PK/GOLPH3/MYO18A signaling pathway.[19] Due to modulation of mammalian target of rapamycin signaling by regulating receptor recycling of the upstream key molecules, GOLPH3 confers increased sensitivity to rapamycin in cancer.[20] Therefore, the expression level and gene copy number status of GOLPH3 may be useful predictors of cellular sensitivity to mammalian target of rapamycin inhibitors. Although some evidence suggested that GOLPH3 may be a predictive marker of the clinical response to DNA-damaging chemotherapy, whether GOLPH3 plays an important role in resistance of NSCLC to IR, which also causes DNA damage, is still unknown.

In the present study, overexpression of GOLPH3 was observed in collected LUAD clinical tissue samples, and knocking down GOLPH3 sensitized LUAD cells to x-ray irradiaition via impairing DSB repair. Furthermore, a novel signaling pathway GOLPH3/EGFR/DNA-PK, in which GOLPH3 stablized EGFR, enhanced the nuclear accumulation of EGFR, and activated DNA-PK after IR, was found to be involved in radioresistance. An in vivo study also confirmed that GOLPH3-knockdown (KD) enhanced the growth delay of the LUAD xenograft after IR exposure. These results suggested that the expression level of GOLPH3 in LUAD was tightly correlated with the radioresistance, and targeting GOLPH3 might be considered as a therapeutic strategy for sensitizing LUAD cells to radiation therapy.

Methods and Materials

Cell culture

The LUAD cell lines A549 and NCI-H1299 were purchased from the Cell Bank of Type Culture Collection of Chinese Academy of Sciences (Shanghai, China). The NCI-H522, NCI-H1975, NCI-H322, and NCI-H1793 cell lines were purchased from the American Type Culture Collection (Manassas, VA). The PC9 line was purchased from Sigma-Aldrich (St Louis, MO). The A549, NCI-H1299, NCI-H522, NCI-H1975, NCI-H322, as well as PC9 cell lines were cultured in Roswell Park Memorial Institute-1640 medium (HyClone; GE Healthcare Life Sciences, Logan, UT), supplemented with 10% fetal bovine serum (FBS; HyClone), 100 μg/mL streptomycin (Gibco, Carlsbad, CA), and 100 U/mL penicillin (Gibco). NCI-H1793 was cultured in Dulbecco's modified Eagle's medium:F12 medium (HyClone), supplemented with 0.005 mg/mL insulin (Sigma-Aldrich), 0.1 mg/mL transferrin (Sigma-Aldrich), 30 nM sodium selenite (Sigma-Aldrich), 10 nM hydrocortisone (Sigma-Aldrich), 10 nM beta-estradiol (Sigma-Aldrich), 2 mM L-

glutamine (Sigma-Aldrich), and 5% FBS (HyClone). All cell lines were maintained at 37°C in a humidified 5% CO_2 incubator, and all cell lines were free of mycoplasma.

Irradiation

The cells were irradiated with a series of doses (0−6 Gy) by using an XHA600D x-ray irradiator (Shinva, Zibo, Shandong, China) at a dose rate of 0.189 Gy/min. The culture medium was replaced with fresh medium before irradiation.

Retroviral and adenovirus infection

The plasmids, phU6-GOLPH3-RNA interference (RNAi)-puro and phU6-EGFR-RNAi-puro, were generated by subcloning human GOLPH3- and EGFR-targeting short hairpin RNA (shRNA) oligonucleotide sequences into the lentiviral vector GV248 or GV112 (Shanghai GeneChem Co, Ltd, Shanghai, China). The shRNA target sequences of GOLPH3 were RNAi#1, GCATGTTAAGGAAACTCAGCC, and RNAi#2, GCAGCGCCTCATCAAGAAAGT. The shRNA target sequences of EGFR were RNAi#1, CACAAAG-CAGTGAATTTAT, and RNAi#2, CAAGCCAA ATGG-CATCTTT. Lentiviruses were prepared by cotransfecting HEK293T cells with a phU6-RNAi-puro vector containing shRNAs against GOLPH3 or EGFR and the packaging plasmids psPAX2 and pMD2.G as described previously.[21] A549 and H1299 cells were infected with the lentiviruses, and the stable cell lines expressing GOLPH3 or EGFR shRNA were selected for 10 days with puromycin (2 μg/mL) from 48 hours after infection.

For the rescue experiments, the wild-type GOLPH3 expression plasmid was mutagenized by polymerase chain reaction (PCR) to generate an RNAi-resistant isoform ($GOLPH3^{Res}$) that contained 5 silent mutations (aCAaCGgCTaATCAAGAAgGT) introduced into the region targeted by GOLPH3-RNAi#2. The isoform was subcloned into the shuttle vector pHBAd-MCMV-IRES-EGFP (fused with an N-terminal 3 × FLAGs tag), and the adenovirus with a titer of 5×10^{10} plaque-forming units (PFU)/mL was prepared by Hanbio Co, Ltd (Shanghai, China). After adenovirus infection, western blot and the immunofluorescence assay were administrated to detect varied protein expressions and the level of DSBs induced by IR.

Colony formation assay

Cells of A549 (300 cells) and H1299 (200 cells) were seeded in 60 mm dishes after irradiation and then incubated for 8 days to form colonies. Survival curves were constructed by using Origin 8.0 software. The survival curve parameters, D0 and Dq, were calculated by fitting the data with the single-hit, multitarget model.[22]

Flow cytometric analysis

Cells were harvested at 72 hours after irradiation, and apoptotic cells were stained with the Annexin V-APC/PI kit, according to the manufacturer's instructions (BD Biosciences, San Jose, CA), and then analyzed with a BD Accuri C6 analyzer (BD Biosciences).

Micronucleus test

The frequency of micronucleus formation was determined according to the in vitro micronucleus technique.[23] Cells were trypsinized, and 5×10^4 cells were seeded in 35 mm dishes. Cytochalasin B (Sigma-Aldrich) was added into the culture medium with a final concentration of 1 μg/mL at 2 hours after irradiation. After 2 doubling-time incubation, the cells were fixed with 4% paraformaldehyde (Sigma-Aldrich) for 30 minutes, stained with 0.1% acridine orange (Sigma-Aldrich) for 3 minutes, washed with phosphate-buffered saline (PBS), and then viewed under a DMI4000B microscope (Leica, Wetzlar, Germany). The number of micronucleated (MN) cells in at least 1000 binucleate (BN) cells was scored, and the frequencies of MN per 1000 BN cells were calculated.

Immunofluorescence

Cells were fixed with 4% paraformaldehyde for 30 minutes and permeabilized with TNBS solution (PBS supplemented with 0.5% Triton X-100 and 1% FBS) for 1 hour. The cells were then incubated for 2 hours with specific primary antibodies for different proteins as follows: anti-γ-H2AX (phospho S139) antibody (1:200; Abcam, Cambridge, MA) or anti-EGFR antibody (1:200; Abcam) at 37°C. After rinsing in TNBS solution 3 times, the cells were incubated for 1 hour with Goat Anti-Rabbit IgG H&L (tetramethylrhodamine isothiocyanate) (1:1000; Abcam) at 37°C. 4′,6-Diamidino-2-phenylindole (5 mg/mL; Sigma-Aldrich) was used to stain the nuclei. The cells were visualized with a DMI4000B microscope (Leica). At least 200 cells were counted for each group to calculate the number of γ-H2AX foci per cell. To further detect the subcellular localization of EGFR, the images of EGFR staining were captured using an LSM710 confocal laser-scanning microscope (Zeiss, Oberkochen, Germany).

Immunohistochemistry

Tumor specimens of human LUAD were collected from patients registered at the Fourth Affiliated Hospital of Anhui Medical University during 2012 to 2017. The age of patients ranged from 41 to 78 years with the median age as 60 years. The use of human tissues was approved by the Ethics Committee of the hospital. The tumor specimens or excised xenografts were fixed with 10% buffered formalin and embedded in paraffin. Tumor sections were cut into

sections (3 μm), and then slices were deparaffinized and rehydrated. These prepared slides were incubated at 4°C overnight with primary antibodies as follows: anti-GOLPH3 (1:100; Abcam), anti-EGFR (1:100; Abcam), or anti-Ki67 (1:1000; Protein Tech Group, Wuhan, China), followed by a 30-minute incubation in horseradish peroxidase-conjugated Goat Anti-Rabbit IgG H&L (1:200; Abcam). After washing, slices were incubated with streptavidin peroxidase and visualized using diaminobenzidine tetrahydrochloride substrate (Beyotime Biotechnology, Shanghai, China). The expression of GOLPH3 and EGFR was quantified by using ImagePro Plus (Media Cybernetics). The mean optical density (MOD) of the selected area (integrated optical density/unit area) represented the expression level of the indicated protein.

Subcellular fractionation, western blot, and coimmunoprecipitation (co-IP)

Cytoplasmic and nuclear extracts were acquired using the NE-PER nuclear and cytoplasmic extraction kit (Pierce, Rockford, IL). Whole-cell protein was extracted with immunoprecipitation assay lysis buffer (Beyotime Biotechnology), and the protein concentration was determined with a bicinchoninic acid protein assay kit (Beyotime Biotechnology). Briefly, proteins were separated by 6% to 15% sodium dodecyl sulfate-polyacrylamide gel electrophoresis and transferred to polyvinylidene fluoride membranes (Merck Millipore, Darmstadt, Germany). Membranes were blocked in 5% skim milk (BD Difco, Sparks, MD) for 1 hour and then incubated with different primary antibodies at 4°C overnight. The primary antibodies used were anti-GOLPH3 (1:1000; Abcam), anti-EGFR (1:1000; Protein Tech Group), anti-γ-H2AX (phospho S139) (1:1000; Abcam), anti-ubiquitin (1:1000; Protein Tech Group), anti-DNA-PK (1:1000; Santa Cruz Biotechnology, Santa Cruz, CA), anti-DNA-PK pT2609 (1:1000; Rockland, Limerick, PA), anti-β-actin (anti-ACTB) (1:1000; Protein Tech Group), anti-β-tublin (1:1000; Protein Tech Group), or anti-lamin B (1:1000; Protein Tech Group). After extensive washing with Tris-buffered saline with Tween 20, blots were incubated with IRDye-conjugated secondary antibodies (1:10,000; Li-COR Biosciences, Lincoln, NE) for 1 hour at room temperature. Immunoreactive bands were imaged using the Odyssey CLx Infrared Imaging system (Li-COR Biosciences).

For co-IP, 2 μg of anti-DNA-PK, anti-EGFR, or control IgG antibody was incubated with 4 mg of cell lysate, followed by capturing with protein-A/G agarose. The beads were then washed extensively and suspended in sodium dodecyl sulfate loading buffer for western blot analysis.

Quantitative real-time (RT)-PCR

RT-PCR was performed with One Step SYBR PrimeScript RT-PCR Kits (Takara Bio, Otsu, Japan) on a Roche 480 Light Cycler (Roche, Basel, Switzerland). The primers used for PCR amplification are shown as follows: 5′-TGTA AGTCAGATGCTCCAACAGG-3′ and 5′-TCACCCATT TGTCAAGAACGG-3′ (GOLPH3); 5′-TTTCGATACCCAG GACCAAGCCACAGCAGG-3′ and 5′-AATATTCTTG CTGGATG CGTTTCTGTA-3′ (EGFR); and 5′-CTGGGAC GACATGGAGAAA A-3′ and 5′-AAGGAAGGCTG GAAGAGTGC-3′ (ACTB). ACTB was used as a normalizing control, and data analysis was performed as previously described,[24] through calculating fold change by the $2^{-\Delta\Delta Ct}$ method.

Adenovirus production

To knock down GOLPH3 in xenografts and overexpress EGFR in LUAD cells, the shuttle plasmids, pDC311-U6-GOLPH3-shRNA and pDC315-EGFR, were generated by subcloning human GOLPH3-targeting shRNA oligonucleotide sequences and EGFR cDNA into the shuttle vector pDC311-U6 and pDC315 with ClonExpress II (Vazyme Biotech Co, Ltd, Nanjing, China), respectively. The shRNA targeting sequences of GOLPH3 were the same as those mentioned previously. The adenovirus was then produced by cotransfecting 293A cells with the shuttle plasmids and genomic plasmid (pBHGlox△E1, 3Cre). Adenovirus was harvested, amplified, and purified by 2 rounds of cesium chloride ultracentrifugation. After dialysis, purified adenovirus was aliquoted and stored at −80°C until use. Viral titer was determined by plaque assay.

Xenograft model and treatments

Six-week-old male Balb/c nude mice were obtained from Model Animal Research Center of Nanjing University (Nanjing, China). All animal studies were conducted according to protocols approved by the Ethical Committee of Experimental Animals of Hefei Institutes of Physical Science, Chinese Academy of Sciences. Mice were grafted with 1×10^7 A549 cells by subcutaneous injection into the right flank. When tumors reached a size of ~100 mm^3, the tumors were treated with intratumoral injection of 1×10^{10} PFU adenovirus one time per week for 2 cycles (2 times total). Two days after each intratumoral injection, tumors were exposed to 6 Gy x-ray with the rest of the body shielded with a lead block. Mice were weighed, and tumors were measured every 2 days. The calculation of tumor volume was as follows: $(L \times S^2)/2$ (where L was the longest length, and S was the shortest length). The mice were sacrificed 42 days after the first intratumoral injection of adenovirus, and all tumors were excised.

Statistical analysis

All experiments were performed at least 3 times. The data were presented as mean ± standard deviation of a sample.

Differences were calculated by Student *t* test with SPSS version 21.0 software (SPSS), and $P < .05$ was considered a statistically significant difference.

Results

GOLPH3 overexpresses in human LUAD

To investigate the aberrant expression of GOLPH3 in LUAD, we first analyzed the mRNA level of *GOLPH3* in 515 primary tumors and 59 normal tissues based on TCGA (The Cancer Genome Atlas) database by using the online tool UALCAN (http://ualcan.path.uab.edu./analysis.html). As shown in Figure 1A, significantly elevated *GOLPH3* expression at the mRNA levels was observed in LUAD samples. Further analyses of GOLPH3 protein level with immunohistochemistry in 33 LUAD tissues and 33 adjacent nontumorous tissues, collected from the Fourth Affiliated Hospital of Anhui Medical University, showed a high level of GOLPH3 protein expression (brown staining) in LUAD tissues but a low level in adjacent nontumorous tissues (Fig. 1B). The quantitative analysis indicated that the MODs of GOLPH3 in LUAD tissues (MOD = 0.046 ± 0.027) were significantly higher than those in adjacent nontumorous tissues (MOD = 0.004 ± 0.003) ($P < .001$; Fig. 1C). These results indicated that GOLPH3 overexpressed in human LUAD.

Downregulating GOLPH3 sensitizes LUAD cells to IR

Usually, aberrant expression of some genes, especially oncogenes, might cause resistance to radiation therapy. To investigate the role of GOLPH3 in the radioresistance of LUAD, we, respectively, established stable GOLPH3-KD A549 and H1299 cell lines. The loss of GOLPH3 protein in GOLPH3-KD cells was confirmed using western blots (Fig. 2A). Survival fractions of GOLPH3-KD A549 and H1299 cells were lower than the respective control (RNAi-negative control [NC]) after exposure to the same dose of x-ray irradiation (1-6 Gy) (Fig. 2B and 2C). The sensitization enhancement ratio for D_q ($SERD_q$) in Table E1 showed an increase to 1.40 (GOLPH3-RNAi#1) and 2.25 (GOLPH3-RNAi#2) in A549 after GOLPH3 silencing. Similarly, the $SERD_q$ of H1299 after GOLPH3 silencing also increased to 1.36 (GOLPH3-RNAi#1) and 1.59 (GOLPH3-RNAi#2) (Fig. 2B and 2C). Furthermore, the role of GOLPH3 in IR-induced cell death, especially apoptosis, was assessed. The apoptosis rate of GOLPH3-KD cells was significantly higher than RNAi-NC cells at 72 hours after 6 Gy IR (32.43% ± 5.52%, 29.40% ± 2.61% vs 17.10% ± 2.69%) (Fig. 2D and 2E). The level of cleaved poly-ADP-ribose polymerase in GOLPH3-KD cells was also higher than that in RNAi-NC cells after IR (Fig. 2F). Taken together, these results indicated that downregulating GOPLH3 enhanced the sensitivities of A549 and H1299 cells to IR and revealed the important role of GOLPH3 in radioresistance in LUAD cells.

GOLPH3 promotes the repair of IR-induced DNA damages

For a further study, MN was assessed after IR as a consequence of accumulated DNA damages. The results in Figure 3A showed that BN MN yields of GOLPH3-KD cells were distinctly higher than those of the RNAi-NC, which indicated production of more DNA damages or lower efficiency of damage repair after GOLPH3 silencing or both. To analyze the dynamics of DSBs, the most lethal DNA damage after IR, they were assessed by quantifying their marker γ-H2AX. No significant difference in γ-H2AX foci numbers per cell between GOLPH3-KD and RNAi-NC A549 cells was observed at 0.5 hour after 4 Gy IR (Fig. 3B and 3C), which indicated that silencing GOLPH3 did not influence the production of DSBs after IR. However, the γ-H2AX foci numbers per cell in GOLPH3-KD cells were still kept at a high level at 24 hours after IR compared with those of the

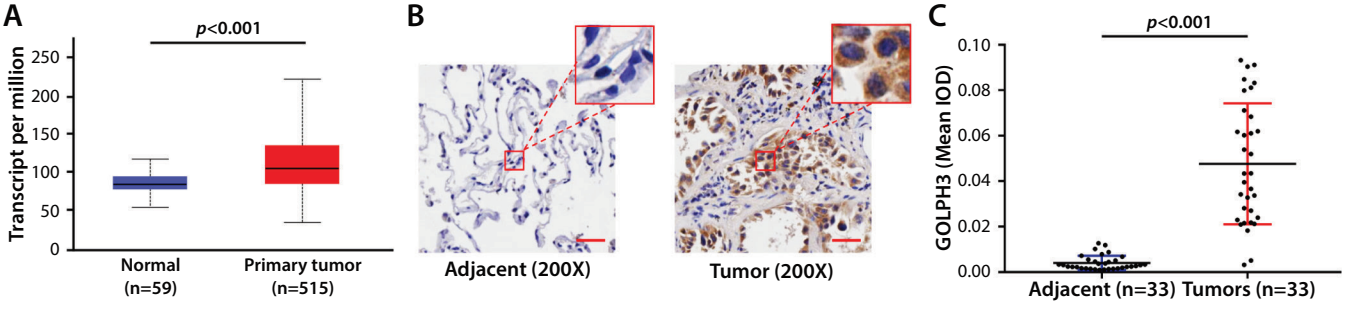

Fig. 1. Golgi phosphoprotein 3 (GOLPH3) overexpressed in lung adenocarcinoma (LUAD) clinical tissue samples. (A) GOLPH3 mRNA levels in normal and LUAD tissues (based on The Cancer Genome Atlas [TCGA] database). (B) Representative images of GOLPH3 immunohistochemistry in adjacent nontumorous and LUAD tissues. Scale bar, 40 μm. (C) Statistical quantification of the average mean optical density (MOD) of GOLPH3 staining in adjacent nontumorous (n = 33) and LUAD (n = 33) tissues.

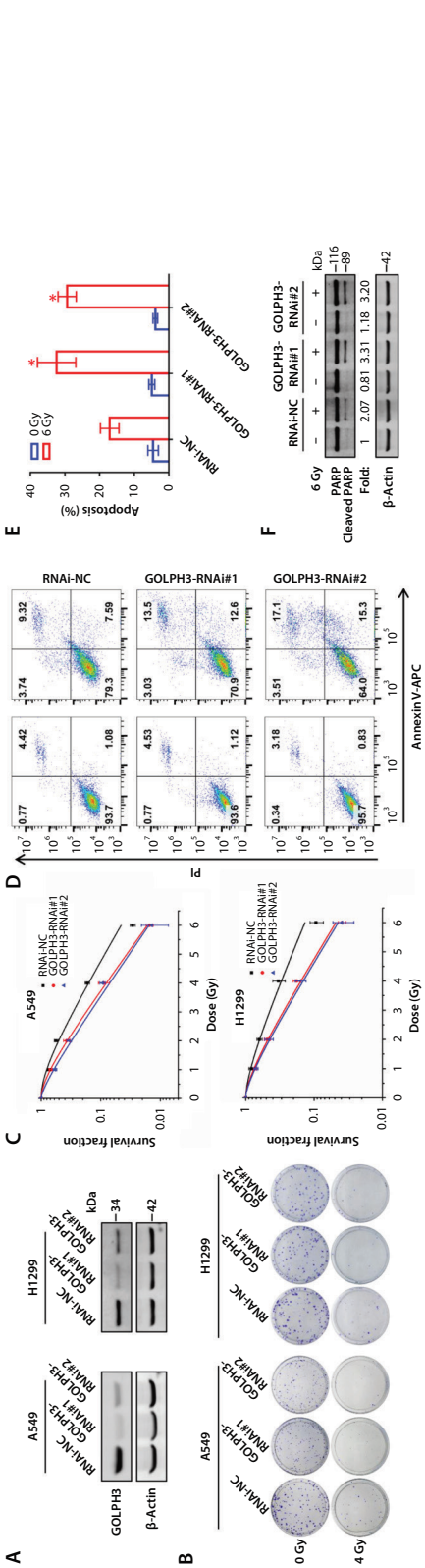

Fig. 2. Loss of Golgi phosphoprotein 3 (GOLPH3) sensitizes lung adenocarcinoma (LUAD) cells to ionizing radiation (IR). (A) Determination of GOLPH3 knockdown in A549 and H1299 cells. (B) Representative images of the colonies from RNA interference-negative control (RNAi-NC) and GOLPH3-RNAi A549 and H1299 cells after IR. (C) The survival curves of RNAi-NC and GOLPH3-RNAi A549 and H1299 cells after IR. (D) Representative results of flow cytometry depicting apoptosis of RNAi-NC and GOLPH3-RNAi H1299 cells at 72 hours after IR (6 Gy). (E) Quantification of apoptosis ratio in RNAi-NC and GOLPH3-RNAi H1299 cells (*$P < .05$). (F) Western blot of cleaved poly-ADP-ribose polymerase (PARP) in RNAi-NC and GOLPH3-RNAi H1299 cells at 72 hours after IR (6 Gy). The number under each band represents the relative level of cleaved PARP and PARP.

RNAi-NC (Fig. 3B and 3D). The dynamics of DSBs after IR were similar in NC and GOLPH3-KD H1299 cells (Fig. 3E and 3F), suggesting that silencing GOLPH3 impaired the capacity of DSB repair. Moreover, the capacity of DSB repair was effectively rescued after re-expressing GOLPH3^{Res} in GOLPH3-RNAi#2 cells (Fig. 3G and 3H), confirming the involvement of GOLPH3 in DSB repair after IR. Residual γ-H2AX protein levels detected at various time points after IR revealed slower kinetics of DSB repair in GOLPH3-KD cells but almost the same after re-expressing GOLPH3 in GOLPH3-KD cells compared with the RNAi-NC (Fig. 3I and 3J), further supporting the key role of GOLPH3 in DSB repair.

GOLPH3 stabilizes EGFR protein to mediate radioresistance

Both Golgi phosphoprotein 2 (GOLPH2) and GOLPH3 belong to the Golgi phosphoprotein family and have some similar functions.[25,26] Ye et al[27] reported that GOLPH2 is involved in the regulation of the EGFR protein level. In addition, we found that the expression of EGFR was correlated with the GOLPH3 level in various LUAD cell lines (Fig. 4A). Therefore, we hypothesized that GOLPH3 also could regulate EGFR protein in LUAD cells. Direct evidence was that expression of EGFR markedly decreased after GOLPH3-KD in A549, H1299, and NCI-H1975 cells (Fig. 4B and Fig. E1A). Along with increasing the adenovirus (GOLPH3-RNAi) amount to gradually knock down GOLPH3, the EGFR protein level showed the same trend with GOLPH3 (Fig. E1B). Moreover, EGFR protein level was distinctly restored after the re-expression of GOLPH3^{Res} in GOLPH3-RNAi#2 cells, which confirmed the key role of GOLPH3 in regulating the EGFR protein (Fig. 4C). However, no changes in mRNA expression of EGFR, quantified with RT-PCR, were detected in GOLPH3-KD cells (Fig. 4D), which suggested that the loss of EGFR along with GOLPH3-KD was not attributed to transcriptional regulation. Considering that the level of EGFR protein was also determined by its stability, we measured the turnover rate of EGFR protein by cycloheximide (CHX) chase in GOLPH3-KD and control LUAD (A549 and H1299) cells. CHX (100 μg/mL) was used to block total cellular protein synthesis, and chase was performed at 4, 8, and 12 hours. As shown in Figure 4E, only small amounts of EGFR protein, which quickly degraded within 12 hours after CHX treatment, were observed in GOLPH3-KD cells. In contrast, EGFR protein was relatively more abundant and highly stable in GOLPH3-NC cells. To investigate how GOLPH3 loss promoted EGFR degradation, we treated cells with MG132 and NH_4Cl to inhibit proteasome and lysosomal activity, respectively. Results showed that NH_4Cl but not MG132 treatment promoted the accumulation of EGFR protein, and the accumulation was faster in GOLPH3-KD cells than in

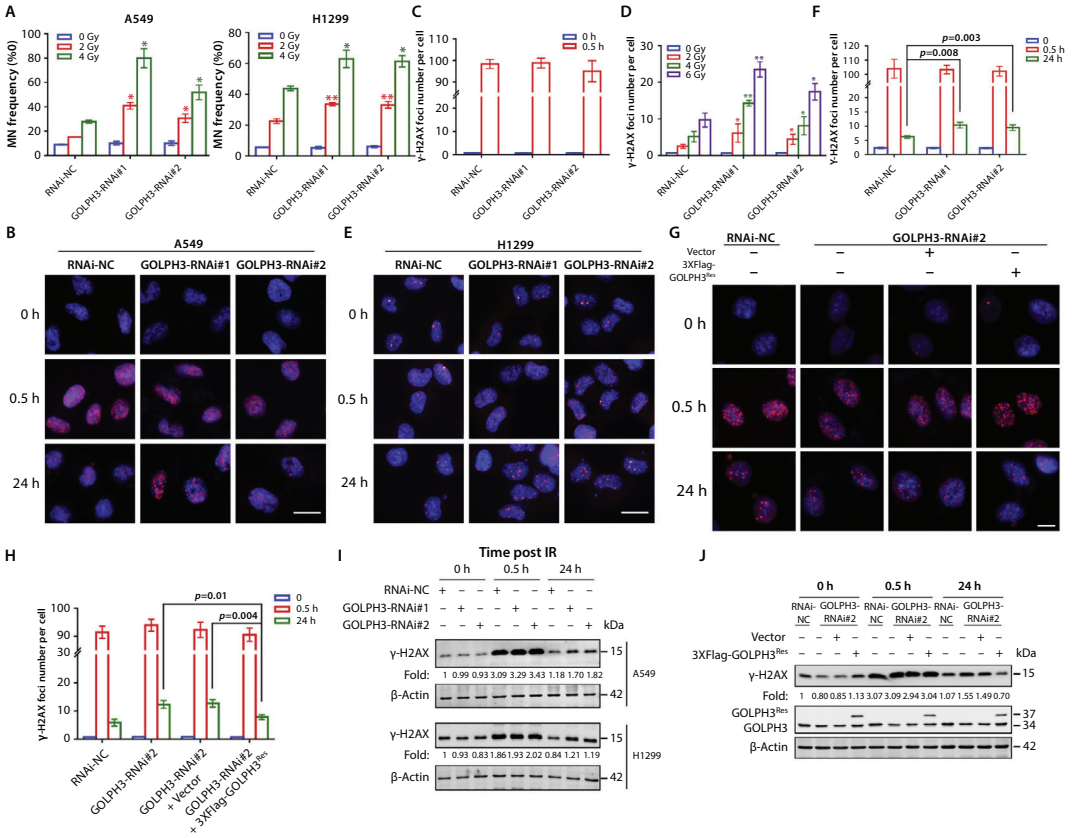

Fig. 3. Golgi phosphoprotein 3 (GOLPH3) participates in the repair of ionizing radiation (IR)-induced double-strand breaks (DSBs). (A) Micronucleate (MN) yields in RNA interference-negative control (RNAi-NC) and GOLPH3-RNAi cells after IR (*$P < .05$). (B) Representative immunofluorescence images of γ-H2AX foci (red) in nucleus (blue) of RNAi-NC and GOLPH3-RNAi A549 cells at 0.5 hour and 24 hours after IR (4 Gy). Scale bar, 20 μm. (C) Quantification of γ-H2AX foci at 0.5 hour to evaluate DSB production after IR (4 Gy) in RNAi-NC and GOLPH3-RNAi A549 cells. (D) Quantification of γ-H2AX foci at 24 hours after IR to evaluate the residual DSBs in RNAi-NC and GOLPH3-RNAi A549 cells (*$P < .05$; **$P < .01$). (E) Representative immunofluorescence images of γ-H2AX foci (red) in nucleus (blue) of RNAi-NC and GOLPH3-RNAi H1299 cells at 0.5 hour and 24 hours after IR (4 Gy). Scale bar, 20 μm. (F) Quantitative data are depicted. (G) Representative immunofluorescence images of γ-H2AX foci at 0.5 hour and 24 hours post-IR (4 Gy) after GOLPH3 re-expression in GOLPH3-knockdown (KD) A549 cells. Scale bar, 10 μm. (H) Quantitative data are depicted. (I) Western blot of γ-H2AX protein level at multiple time points after IR (4 Gy). The number under each band represents the relative expression level of γ-H2AX. (J) Western blot of γ-H2AX protein level at multiple time points after IR (4 Gy) after GOLPH3 re-expression in GOLPH3-KD A549 cells. The number under each band represents the relative expression level of γ-H2AX.

GOLPH3-NC cells (Fig. 4F). Because ubiquitination of EGFR was reported to play a key role in the subsequent lysosome-mediated degradation,[28] we next detected the ubiquitylation levels of immunoprecipitated EGFR in GOLPH3-NC and GOLPH3-KD A549 cells. As shown in Figure 4G, the level of ubiquitinated EGFR in GOLPH3-KD cells was higher than that in GOLPH3-NC cells. These results indicate that loss of GOLPH3 promotes the ubiquitination of EGFR, which is beneficial to the subsequent lysosome-mediated degradation of EGFR. Considering the important role of EGFR in resistance to IR,[29] we hypothesized that radiosensitization mediated by knocking down GOLPH3 benefited from the accompanying and profound decrease of EGFR.

To test this hypothesis, EGFR stable KD A549 cells (EGFR-RNAi#1 and EGFR-RNAi#2) were established (Fig. 4H). A lower survival fraction of EGFR-KD cells was observed compared with that for EGFR-NC cells after the same irradiation dose (Fig. 4H). The $SERD_q$ values were 2.27 and 1.97 for EGFR-RNAi#1 and EGFR-RNAi#2 cells, respectively (Fig. 4H and Table E2). These results suggested that loss of EGFR protein significantly increased the radiosensitivity of A549 cells. To further test whether GOLPH3 mediated radioresistance via regulating EGFR protein, we overexpressed EGFR in GOLPH3-KD A549 cells by adenovirus (Fig. 4I). The survival fraction of GOLPH3-KD cells after IR was increased after EGFR overexpression (Fig. 4J and Table E3), providing reliable evidence that GOLPH3

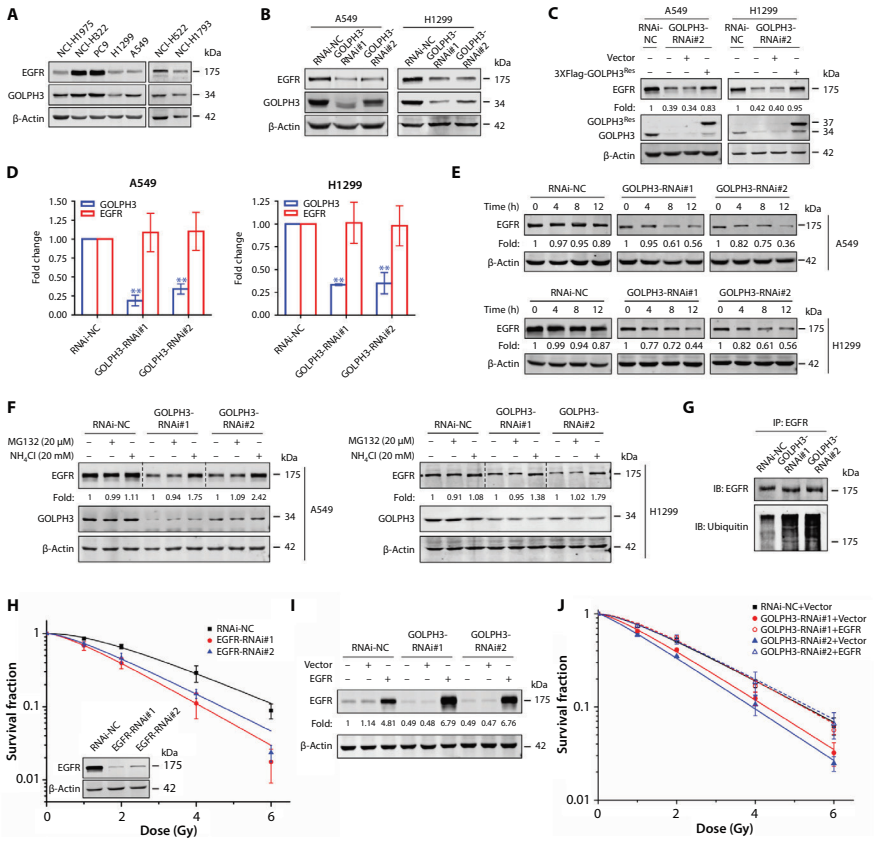

Fig. 4. Golgi phosphoprotein 3 (GOLPH3) confers radioresistance by regulating the stability of epidermal growth factor receptor (EGFR). (A) Western blot of GOLPH3 and EGFR expression in 7 lung adenocarcinoma (LUAD) cell lines. (B) Western blot of EGFR protein expression in RNA interference-negative control (RNAi-NC) and GOLPH3-RNAi A549 and H1299 cells. (C) Western blot of EGFR, GOLPH3, and GOLPH3 RNAi-resistant isoform ($GOLPH3^{Res}$) protein expression after the re-expression of GOLPH3 in GOLPH3-RNAi#2 A549 and H1299 cells. The number under each band represents the relative expression level of EGFR. (D) Quantitative real-time polymerase chain reaction (RT-PCR) detection of the relative expression of GOLPH3 and EGFR transcripts in RNAi-NC and GOLPH3-RNAi A549 and H1299 cells. (E) RNAi-NC and GOLPH3-RNAi A549 and H1299 cells were treated with cycloheximide (CHX) (100 μg/mL) for the indicated time. Then, cells were lysed and EGFR protein expression analyzed by western blot. The number under each band represents the relative expression level of EGFR. (F) RNAi-NC and GOLPH3-RNAi A549 and H1299 cells were treated with MG132 (20 μM) or NH_4Cl (20 mM) for 48 hours. Then, cells were lysed and EGFR protein expression analyzed by western blot. The number under each band represents the relative expression level of EGFR. (G) Western blot detection of the ubiquitination levels of EGFR immunoprecipitated from RNAi-NC and GOLPH3-RNAi A549 cells. (H) The survival curves of RNAi-NC and EGFR-RNAi A549 cells after ionizing radiation (IR). (I) Western blot of EGFR protein level in indicated cells after EGFR overexpression mediated by adenovirus. The number under each band represents the relative expression level of EGFR. (J) The survival curves of RNAi-NC and GOLPH3-RNAi A549 cells after EGFR overexpression after IR.

mediated the radioresistance via maintaining the EGFR protein stability.

GOLPH3 facilitates IR-induced nuclear EGFR accumulation and subsequent activation of DNA-PK

It has been reported that EGFR nuclear translocation modulates DNA damage repair after IR treatment and that inhibition of IR-induced nuclear EGFR accumulation suppressed DNA-PK activity and sensitized cancer cells to IR.[30] Therefore, we wondered whether the level of nuclear EGFR accumulation was impaired after the downregulation of GOLPH3. As shown in Figure 5A, the immunofluorescence signal of EGFR (red) was dramatically weaker in nonirradiated GOLPH3-KD cells compared with GOLPH3-NC. IR (4 Gy) induced the accumulation of EGFR within the nucleus (red and blue) of GOLPH3-NC cells at 20 and 40 minutes but not in GOLPH3-KD cells (Fig. 5A). To further confirm this result, proteins from cell cytoplasm or nucleus were separated. Similar to the results of immunofluorescence, in RNAi-NC cells, the EGFR protein level in the nuclear fraction significantly increased after IR, but no changes were observed in GOLPH3-KD A549 and H1299 cells (Fig. 5B and 5C). Taken together, these results suggested that

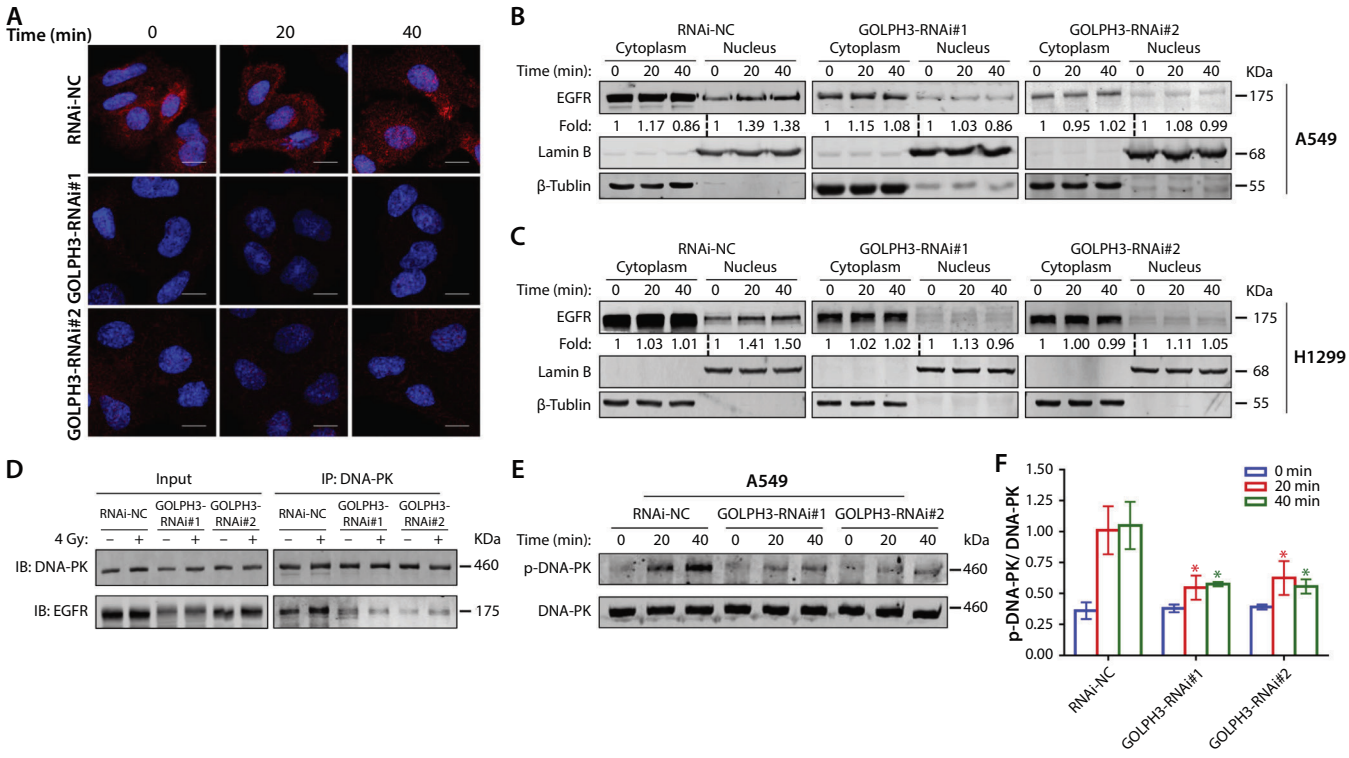

Fig. 5. Golgi phosphoprotein 3 (GOLPH3) knockdown impairs the ionizing radiation (IR)-induced epidermal growth factor receptor (EGFR) nuclear import and activation of DNA-dependent protein kinase (PK). (A) Representative immunofluorescence images of EGFR (red) in RNA interference-negative control (RNAi-NC) and GOLPH3-RNAi A549 cells at 20 and 40 minutes post-IR (4 Gy). Nucleus (blue) was stained with 4′,6-diamidino-2-phenylindole (DAPI). Scale bar, 10 μm. Western blot of EGFR in the cytoplasmic and nuclear fractions of RNAi-NC and GOLPH3-RNAi (B) A549 and (C) H1299 cells treated with IR (4 Gy). The cytoplasmic and nuclear proteins were separated at 20 and 40 minutes after IR. β-Tublin and lamin B were used as loading controls of cytoplasmic and nuclear proteins, respectively. The number under each band represents the relative expression level of EGFR. (D) Western blot of anti-DNA-PK immunoprecipitates from RNAi-NC and GOLPH3-RNAi A549 cells after IR (4 Gy). The number under each band represents the relative level of EGFR and DNA-PK. (E) Western blot of DNA-PK phosphorylation induced by IR (4 Gy) in RNAi-NC and GOLPH3-RNAi A549 cells. (F) Quantitative data are depicted (*$P < .05$).

decreased IR-induced nuclear EGFR accumulation by silencing GOLPH3 could be an explanation for the enhancement of radiosensitivity.

Considering that the EGFR is complexed with DNA-PK when transported into the nucleus,[31] co-IP was performed to identify the binding of DNA-PK and EGFR. EGFR coimmunoprecipitated with DNA-PK (Fig. 5D), confirming the physiological relevance of the interaction. However, the basal and IR-triggered EGFR binding on DNA-PK markedly decreased after GOLPH3-KD (Fig. 5D), which was also further confirmed by an immunoprecipitation assay with anti-EGFR antibody (Fig. E2). Because activation of DNA-PK linked with IR-induced EGFR nuclear translocation has been reported to be mainly mediated by autophosphorylation at the Thr2609 site,[31,32] activation of DNA-PK was examined in the present work. The results in Figure 5E and 5F showed that downregulation of GOLPH3 significantly suppressed IR-induced autophosphorylation of DNA-PK, which meant weaker activation of DNA-PK post-irradiation.

Taken together, knocking down GOLPH3 attenuated the nuclear accumulation of EGFR after IR, which in turn suppressed the activation of DNA-PK and ultimately inhibited DNA repair to increase the radiosensitivity.

Targeting GOLPH3 enhances IR-induced tumor growth suppression in vivo

In vivo studies were performed subsequently. Adenovirus was constructed with a high titer ($\sim 1.5 \times 10^{11}$ PFU/mL) to mediate the expression of either empty vector (adenovirus-RNAi-NC) or GOLPH3 shRNA (adenovirus-GOLPH3-RNAi#1 and #2) in tumor xenografts. Tumor xenografts were established by subcutaneous injecting A549 cells ($\sim 1 \times 10^7$) into the right flank area of Balb/c nude mice. When the tumors reached a size of $\sim$100 mm^3, the mice were randomly divided into 6 groups (5 mice/group) as follows: RNAi-NC, RNAi-NC + IR, GOLPH3-RNAi#1, GOLPH3-RNAi#1 + IR, GOLPH3-RNAi#2, and GOLPH3-RNAi#2 + IR. The treatment of mice was administrated

according to the schematic in Figure 6A. Adenovirus (1×10^{10} PFU/tumor) was injected intratumorally (day 0) followed by IR (6 Gy) at 48 hours after injection with 2 cycles. The tumor volume was measured every 2 days. At the endpoint of measurement (day 42), the tumor volumes for GOLPH3-RNAi#1 + IR and GOLPH3-RNAi#2 + IR (305.7 ± 102.8 mm^3 and 313.0 ± 105.6 mm^3) were significantly smaller than RNAi-NC + IR (586.9 mm^3 $\pm$ 129.3 mm^3) (Fig. 6B and 6C). The tumor growth curves showed that tumor growth slowed upon IR or GOLPH3-KD treatment, but mice treated with IR plus GOLPH3-KD showed more significant tumor regression. Moreover, tumors in GOLPH3-RNAi + IR groups nearly stopped growing from day 12 to day 32 (Fig. 6C).

The mice were sacrificed on day 42, and the images of tumors were acquired (Fig. 6D). Results of Ki67 immunohistochemistry revealed a dramatically reduced proliferation index in tumors generated from the treatment with IR plus GOLPH3-KD (Fig. 6E). Consistent with the above results, GOLPH3 shRNA treatment enhanced tumor radiosensitivity. The protein level of both GOLPH3 and EGFR in tumors, detected with western blot and immunohistochemistry, showed marked reduction after injection with adenovirus-mediated GOLPH3 shRNA expression (Fig. 6F-6H). These results suggested that knocking down GOLPH3 effectively enhanced IR-induced tumor xenograft growth suppression.

Discussion

In the present study, we demonstrated that downregulating GOLPH3 expression enhanced the radiosensitivity of LUAD cells both in vitro and in vivo and that GOLPH3 played an important role in radioresistance. GOLPH3, characterized as an oncogene, overexpressed in some types of human cancers, including breast cancer,[13] hepatocellular carcinoma,[14] and prostate cancer.[15] Based on RNA sequencing data (515 LUAD tissues vs 59 normal tissues) from TCGA, we found that mRNA of GOLPH3 significantly overexpressed in tumor tissues compared with normal tissues. Moreover, a coincident result with immunohistochemistry was obtained from 33 tumor and normal pairs of LUAD tissues from the clinic, and this was also confirmed in previous studies.[17] Importantly, unfavorable clinical outcomes were considered to be associated with overexpression of GOLPH3 in glioma, hepatocellular carcinoma, breast cancer, and NSCLC.[13,14,16,33] However, it has been reported that GOLPH3-positive, cancer-associated fibroblasts and tumor-associated macrophages are correlated with the absence of regional or distant metastases of melanoma.[34] Therefore, targeting GOLPH3 needs more comprehensive understanding and needs to be further studied.

In NSCLC patients, GOLPH3 is identified as an oncogene frequently targeted for copy number gain and amplification, and high GOLPH3 expression is a potential prognostic biomarker for poor survival.[17,20] Several previous studies have shown overexpression of GOLPH3 confers resistance to DNA-damaging chemotherapeutic drugs, supported by previous results that knocking down GOLPH3 overcame resistance to doxorubicin and 5-fluorouracil due to increased apoptosis.[19,35] Herein, GOLPH3-associated resistance to radiation therapy, another effective treatment of tumors, was explored. Our results showed that knocking down GOLPH3 impaired DNA damage repair, enhanced cell death, and delayed tumor growth after IR. Furthermore, reversal of GOLPH3 depletion rescued the defect in the repair of IR-induced DSBs. Thus, GOLPH3 might be considered as a potential biomarker to evaluate individual radiosensitivity and progression for radiation therapy. Targeting GOLPH3 will be a novel strategy to enhance the radiosensitivity of LUAD. Notably, identification of small molecules to downregulate GOLPH3 expression will be of particular interest toward applications in radiation therapy.

DNA damages, especially DSBs inflicted by IR, were confirmed as a major factor contributing to IR-induced cell killing.[36] Repair of DSBs exerts powerful influence on radioresistance. An increased capacity for DSB repair confers a survival advantage after IR and shows an enhanced radioresistance.[37] Indeed, DSBs induced by IR can activate complex damage recognition, repair, and other cellular response machinery. Various components of the DSBs response, including ATM, ATR, and DNA-PK, and so on, were also revealed to play important roles in radioresistance, and the corresponding inhibitory small targeting molecules have been developed to serve as potential sensitizers for cancer radiation therapy.[38] Interestingly, Farber-Katz et al[19] reported that the DNA-PK/GOLPH3/MYO18A pathway was required for cell survival after DNA damage. In this pathway, directly phosphorylated GOLPH3 by DNA-PK enhances the interaction of GOLPH3 and MYO18A and causes Golgi dispersal, impairing Golgi trafficking to enable cell survival after DNA damage. Unlike the study by Farber-Katz et al,[19] our findings demonstrated that silencing GOLPH3 blocked the phosphorylation of DNA-PK, thereby reducing the DNA-PK activity after irradiation. Undoubtedly, impairment of DNA-PK activity will enhance the radiosensitivity because DNA-PK was one of 3 major kinases at the "heart" of the DNA damage response.[39] Therefore, a new pathway, GOLPH3/EGFR/DNA-PK, in response to DSBs after irradiation was revealed in the present work. In addition, our results indicated that interaction between DNA-PK and GOLPH3 might be more complex than initially thought, and further studies are warranted to determine the relationship between them.

It is now well appreciated that GOLPH3 is a highly conserved protein enriched at the trans-Golgi network,[20] whereas DNA damage repair mainly takes place in the nucleus. Whether GOLPH3 translocated into the nucleus to participate in the DSB repair is still unclear. However, we did not observe the recruitment of the GOLPH3 protein to DSB sites and even translocation into nucleus after irradiation (Fig. E3A and E3B). Thus, a mediator could be required to link GOLPH3 to DSB repair. In fact, our data suggested that EGFR played a crucial role in DSB repair as a link

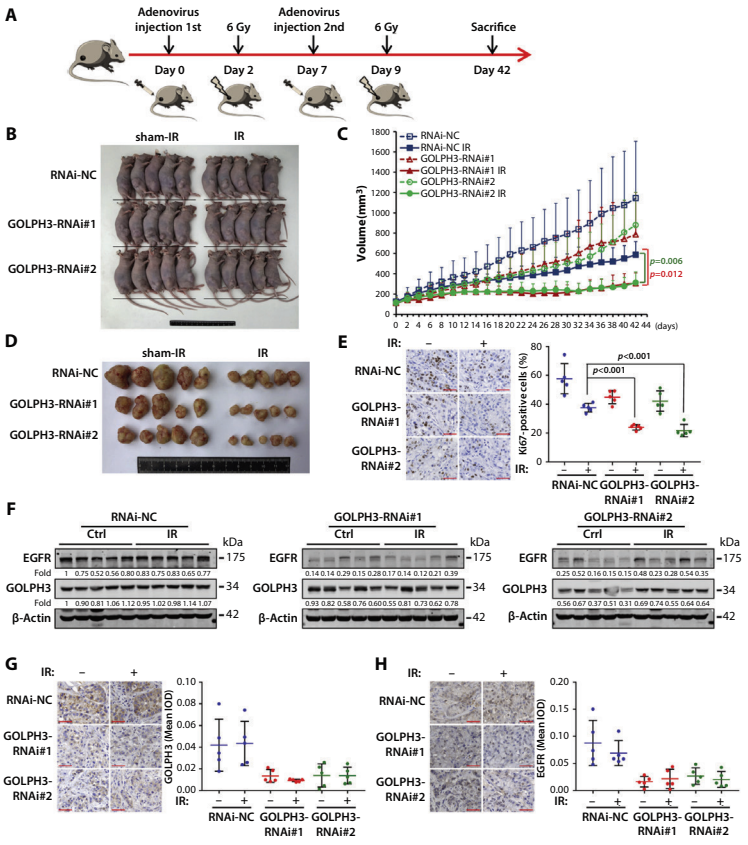

Fig. 6. Silencing of Golgi phosphoprotein 3 (GOLPH3) expression increases radiation-induced tumor xenograft growth delay in vivo. (A) Schematic showing the treatment for Balb/c nude mice bearing the A549 xenograft. Adenovirus was intratumorally injected at day 0 and day 7, respectively. Tumors were irradiated with 6 Gy x-ray at 48 hours after each adenovirus injection. (B) Images of nude mice bearing tumors at day 42. (C) Tumor volume. From day 0, tumors were measured every 2 days. Tumor volumes were calculated, and data were plotted using the geometric mean for each group versus time. Each point represents the mean tumor volume (mean ± standard deviation [SD]) of measurements from each group (n = 5). (D) Images of tumors acquired from nude mice at day 42. (E) Representative immunohistochemistry images and quantification of Ki67 in RNA interference-negative control (RNAi-NC) and GOLPH3-RNAi tumor. Scale bar, 50 μm. (F) Western blot of epidermal growth factor receptor (EGFR) and GOLPH3 in tumor tissues from each group. The number under each band represents the relative expression level of EGFR or GOLPH3. (G) Representative immunohistochemistry images and quantification of GOLPH3 in the RNAi-NC and GOLPH3-RNAi tumor. Scale bar, 50 μm. (H) Representative immunohistochemistry images and quantification of EGFR in the RNAi-NC and GOLPH3-RNAi tumor. Scale bar, 50 μm.

between GOLPH3 and DNA-PK. Previous studies have confirmed that IR initiates internalization and nuclear translocation of EGFR by phosphorylating its residues Thr654 and Tyr845 and then increases the activity of DNA-PK.[32,40] In our study, a positive correlation has been found between EGFR and GOLPH3 proteins in various LUAD cell lines, and knocking down GOLPH3 reduces the radioresistance of LUAD cells via decreasing nuclear EGFR protein level and DNA-PK activity, suggesting the key role of GOLPH3/EGFR/DNA-PKcs signal axis in radioresistance of LUAD cells. Undoubtedly, EGFR mutations may affect the role of the GOLPH3/EGFR/DNA-PKcs signal axis in radioresistance because EGFR with activating mutations, L858R or ΔE746-E750, are defective in radiation-induced translocation into the nucleus and fail to activate the DNA-PK.[41,42] Therefore, the effect of GOLPH3 on the radioresistance of LUAD cells with mutant EGFR needs to be studied further. Moreover, it has been reported that the activation of EGFR after radiation is affected by cell cycle, and EGFR inhibitors may reduce the radiosensitivity in quiescent tumor cells but enhance the radiosensitivity in proliferating cells.[43] With the considering that GOLPH3 regulates EGFR protein levels, whether the effect of GOLPH3 on radiosensitivity is affected by cell cycle is also still a question that needs further studies in the future.

Recent studies report that some members of Golgi phosphoprotein family are involved in the regulation of EGFR stability. GOLPH2 (also named GOLM1), complexed with Rab11 and EGFR, assist the recycling of EGFR back to plasma membrane instead of following the degradation pathway, thereby preventing EGFR degradation.[27] Scott and Chin[44] have reported that GOLPH3 transports to the

endosomal and the plasma and regulates receptor recycling of key molecules. It is noted that GOLPH3 depletion expedites the internalization of EGFR after EGF stimulation and promotes EGFR endocytosis and degradation via activating Rab5.[33] Although our results indicated that knocking down GOLPH3 promoted the ubiquitination and degradation of EGFR without extra EGF stimulation, FBS in cell culture medium also contains EGF. It was possible that GOLPH3 modulated the stability of EGFR by sharing the same molecular mechanisms. Indeed, further studies would be needed to confirm this conjecture. In addition, we also observed that loss of GOLPH3 reduced the level of other receptor tyrosine kinases such as platelet-derived growth factor receptor and vascular endothelial growth factor receptor 2 (Fig. E4A and E4B), which take part in proliferation, migration, and invasion of tumor cells.[45,46] As such, targeting GOLPH3 might have multiple effects in reducing cancer risk and progression by decreasing multiple receptor tyrosine kinases.

Our results demonstrated that GOLPH3 promoted DSB repair after irradiation by sustaining stability of EGFR, which is necessary for DNA-PK activation. Our findings provide strong support that the expression level of GOLPH3 in LUAD was tightly associated with radioresistance, and targeting GOLPH3 might be a therapeutic strategy for sensitization in LUAD radiation therapy.

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