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ORIGINAL RESEARCH

RETRACTED ARTICLE: Gallbladder Cancer Progression Is Reversed by Nanomaterial-Induced Photothermal Therapy in Combination with Chemotherapy and Autophagy Inhibition

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Introduction: Gallbladder cancer (GBC) is the most common malignancy in biliary tract with extremely poor prognosis. Photothermal therapy (PTT) shows great promises for tumor therapy, which causes tumor cell death via selectively directed heating released by nanoparticles under the near-infrared irradiation. Through degrading damaged organelles and misfolded proteins in autophagosomes, autophagy plays a vital role in maintaining the intracellular homeostasis. The present study attempted to combine chemotherapy and autophagy blocking with PTT.

Materials and Methods: We purchased multi-walled carbon nanotubes from Nanostructured and Amorphous Materials and performed PTT using an 808-nm diode laser. The cytotoxic effects of PTT and chemotherapy in vitro were assessed by cell viability analysis. The effects of PTT and chemotherapy on autophagy in vitro were assessed by GFP-LC3 and Western blot. And these results were confirmed by in vivo experiment.

Results: PTT and chemotherapy could trigger cytoprotective autophagy to tolerate the cellular stresses and prolong the survival of GBC cell; therefore, the blocking of autophagy could enhance the efficacy of PTT and chemotherapy in GBC treatment in vitro and in vivo.

Conclusion: Chemotherapeutic drug doxorubicin and autophagy inhibitor chloroquine could enhance the efficacy of nanoparticle-mediated hyperthermia in GBC.

Keywords: gallbladder cancer, photothermal therapy, carbon nanotubes, chemotherapy, autophagy

Introduction

Gallbladder cancer (GBC) is not a common form of cancer in general but is the most common malignancy in biliary tract.[1] The prognosis of GBC is pretty dismal: the 5-year overall survival rate is less than 5%.[2] There are several factors ascribed to the extremely poor prognosis, such as non-specific symptoms at early stage, highly aggressive behaviors and short of effective therapeutic methods. Therefore, it is urgently needed to develop some novel and satisfactory therapies for GBC.

Photothermal therapy (PTT) shows great promises for tumor therapy, which causes tumor cell death via selectively directed heating released by nanoparticles under the near-infrared (NIR) irradiation.[3] With the development of various photothermal nanoparticles, PTT was reported to be effective on treating diverse cancers.[4,5] Compared with other therapeutics such as surgical resection, chemotherapy, radiotherapy, etc.,

PTT is minimally invasive, therapeutically short and relative highly efficient.[6,7] However, there are several factors that impede the applications of PTT, for example, the heterogeneous heat distribution leads to the incomplete eradication of tumor, the hyperthermia damages the healthy tissues.[8,9]

To improve the efficacy and reduce the side effects of PTT, researchers have attempted to combine chemotherapy with PTT and found that nanoparticle-mediated hyperthermia could enhance the efficacy of chemotherapeutic drugs such as doxorubicin (Dox).[10] Dox, an anthracycline antibiotic with broad-spectrum anticancer activity, is one of the mainstay chemotherapeutic drugs for clinical treatment of a wide variety of cancers, including GBC.[11] Nonetheless, the low chemotherapy response rate in GBC (less than 30%) and severe adverse events (particularly cardiotoxicity) limited its clinical use.[12,13]

Autophagy, an evolutionarily conserved self-restructuring process, presents a low constitutive level under physiological conditions.[14–16] However, autophagy is intensely activated by physiological stimuli or stress, including starvation, oxidation, PTT and chemotherapy.[17–19] Through degrading damaged organelles and misfolded proteins in autophagosomes, autophagy plays a vital role in maintaining the intracellular homeostasis.[20] PTT generates local heat and causes stress, metabolite accumulation, by which the autophagy pathway was triggered. In the progress of tumorigenesis, the activation of autophagy may be associated with the resistance to oxidative stress induced by chemotherapeutic drugs and the [illegible] resulting from the relatively defective tumor vascularization. Cytoprotective autophagy may help cancer cells to tolerate the cellular stresses and prolong their survival, therefore, the blocking of autophagy could enhance the efficacy of PTT and chemotherapy in cancer treatment.[17,21,22] In this study, we proposed that thermal damages induced by carbon nanotubes (CNTs) under NIR combined chemotherapy and autophagy inhibition could successfully reverse GBC progression in vitro and in vivo.

Materials and Methods

Cell Lines and Animal Experiments

Human GBC cell line NOZ (purchased from the Health Science Research Resources Bank, Osaka, Japan) was maintained in Williams's Medium E (Genom, China) supplemented with 10% FBS (Gibco, USA) in a humidified incubator at 37°C containing 5% CO_2. Human GBC cell line GBC-SD (purchased from the cell bank of the Chinese Academy of Science, Shanghai, China) was maintained in DMEM high-glucose medium (Gibco, USA) supplemented with 10% FBS (Gibco, USA) in a humidified incubator at 37°C containing 5% CO_2.

Each six-week-old female BALC/c nude mouse was subcutaneously injected with NOZ or GBC-SD cells (100μL, 1×10^6) to establish the animal model. When the volume of tumors attained 80–120 mm^3, mice were randomly assigned for different treatments. To inhibit autophagy, we injected chloroquine (CQ, 60mg/kg, Sigma, USA) intraperitoneally into mice every 3 days. For chemotherapy, we injected Dox (1mg/kg, Meilunbio, China) intraperitoneally into mice every 3 days.

Multi-walled CNTs (20–30 nm diameter, 0.5–2μm length; batch 1240XH; 95% purity) were purchased from Nanostructured and Amorphous Materials.[23] Before the process of PTT, CNTs were oxidized and acidized to shorten the nanotubes and increase their water dispersibility as previously described.[24] Then 50μL of CNT suspension (500μg/mL) was intratumorally injected into mice. After 5 mins, tumors were irradiated using an 808-nm diode laser with the power density in 2W/cm^2 for 5 mins. The surface temperature on the mouse skin was mapped and monitored by an infrared camera (Compact Pro, Seek Thermal, USA). The mice were monitored daily, and the tumor volumes were assessed (0.5 × length × $width^2$) per 2 days. After 2 weeks, mice were sacrificed, and all tumor grafts were excised, photographed. All tumor grafts were subjected to H&E and immunohistochemical staining. The antibodies for immunohistochemical staining were LC3 (1:200, Novus, USA), p62 (1:100, Proteintech, China), PCNA (1:500, Proteintech, China), Ki-67 (1:200, Cell Signaling Technology, China), LOX (1:100, Proteintech, China) and HIF-1α (1:100, Proteintech, China).

Adenovirus Expressing GFP-LC3

The adenovirus vector containing the GFP-LC3 reporter was purchased from Beyotime (Shanghai, China). After different treatments, the cells were fixed and then analyzed using fluorescence microscopy (Olympus BX51, Japan).

Cell Viability Analysis, in vitro Chemosensitivity Assay and Western Blot

Cell viability analysis, in vitro chemosensitivity assay and Western blot were performed as described previously.[25] For cell irradiation, GBC cell was incubated with CNTs at various concentrations for 18 hrs and rinsed twice with PBS. Then, the

cell was exposed to the 808-nm-diode laser at 2W/cm^2 for 3 mins, including dose-effect experiments. The antibodies for Western blot were LC3 (1:1000, Novus, USA), p62 (1:1000, Proteintech, China) and β-actin (1:5000, Proteintech, China).

Statistical Analysis

All experiments were conducted in triplicate independently, the data are presented as mean ± standard deviation. All statistical analyses were performed using GraphPad Prism 5.0. Paired-samples *t*-test or independent-samples *t*-test was used to analyze the difference between groups. $P<0.05$ was determined statistically significant.

Results and Discussion

Evaluation of Photothermal Effect and Cell Toxicity of CNTs

In the context of PTT of tumor, it is not easy to overall evaluate the effects induced by multiscale heat. Previous studies documented that the remotely activated nanoparticles for local hyperthermia could influence tumor growth, autophagy, angiogenesis and microenvironment.[17,24,26,27] However, the therapeutic effect of PTT alone remains not so desirable. The present study aimed to explore whether PTT combined other medical treatments would improve the therapeutic effect in GBC and preliminarily investigate the relevant biological mechanism. To quantitatively evaluate the efficacy of photothermal conversion in vitro and in vivo, we monitored the temperature increase by the infrared camera in the aqueous suspensions and mice under the exposition of 808-nm laser. As shown in Figure 1A, at a fixed laser power density in 2W/cm^2, the temperature of an aqueous suspension containing CNTs increased rapidly in the first 30 s and then started to level off after 60 s, but the temperature of PBS did not increase. Furthermore, with the increase in CNTs concentrations, the temperature went up even faster and higher. Then, PTT was performed in mice after intratumoral administration, we found the tumor temperature was increased to 62°C for 5 mins in "CNTs (500μg/mL) + NIR" group and to 42°C for 5 mins in "PBS + NIR" group (Figure 1B). These results indicated that the CNTs could be used to significantly raise the local temperature in vitro and in vivo.

To evaluate the cell toxicity of CNTs in vitro, we performed the CCK-8 assays. After treatment with CNTs at various concentrations (0, 2.5, 5, 10 and 20μg/mL) in NOZ and GBC-SD cells for 12, 24 and 48 hrs, both NOZ and GBC-SD cells did not show a significant dose- or time-dependent decrease in cell viability (Figure 1C). These results indicated that there is no significant cell toxicity of CNTs at a particle concentration up to 20μg/mL in NOZ and GBC-SD cells.

The Cytotoxic Effect of PTT Could Be Enhanced by Autophagy Blocking in vitro

According to the results of transmission electron microscopy from Iris Marangon's study,[23] CNTs could enter the cell and appear intracellularly as large bundles within endosomes. To evaluate the cytotoxic effect of PTT on GBC cell in vitro, we assessed the cell viability of GBC cell after NIR irradiation at various CNTs concentrations ranging from 0 to 20μg/mL and incubation for 18 hrs. As shown in Figure 2A, both the cell viability of NOZ and GBC-SD cells gradually decreased with the increase of CNTs concentrations under NIR irradiation. These results indicated that PTT could effectively inhibit GBC cell growth. Previous studies reported that PTT could damage proteins and organelles and thus trigger cytoprotective autophagy to tolerate the cellular stresses and prolong the survival of cancer cells.[17,19,28] Here, in the first place, we intended to validate whether the autophagic activity could be enhanced by PTT in GBC in vitro. To our knowledge, LC3 and p62 are important autophagic markers. And we established transient expressing fluorescent protein-tagged LC3 (GFP-LC3) NOZ and GBC-SD cell lines. As shown in Figure 2B, GFP-LC3 was distributed diffusely in the cytoplasm in that without NIR irradiation, but redistributed from the cytosol to autophagosome membrane in that under NIR irradiation and appeared as green punctate dots, which indicated the formation of autophagosomes in NIR irradiation group. Compared with non-NIR irradiation group, NOZ and GBC-SD cells under NIR irradiation both presented enhanced conversion from LC3-I to LC3-II and increased p62 degradation (Figure 2C). While CQ is an established autophagy inhibitor, which raises the intralysosomal pH and suppresses the fusion of autophagosome and lysosome at a late stage. And its inhibitory of autophagy has been confirmed in our previous study.[25] Then, we treated GBC cell with CQ to block its autophagic activity, and the results of cell viability experiments showed that CQ alone could not inhibit cell growth but CQ combined PTT could significantly enhance the cytotoxic effect of PTT in GBC cell (Figure 2D). These results above indicated that PTT could trigger GBC cell autophagy and blocking autophagy could enhance the cytotoxic effect of PTT in vitro.

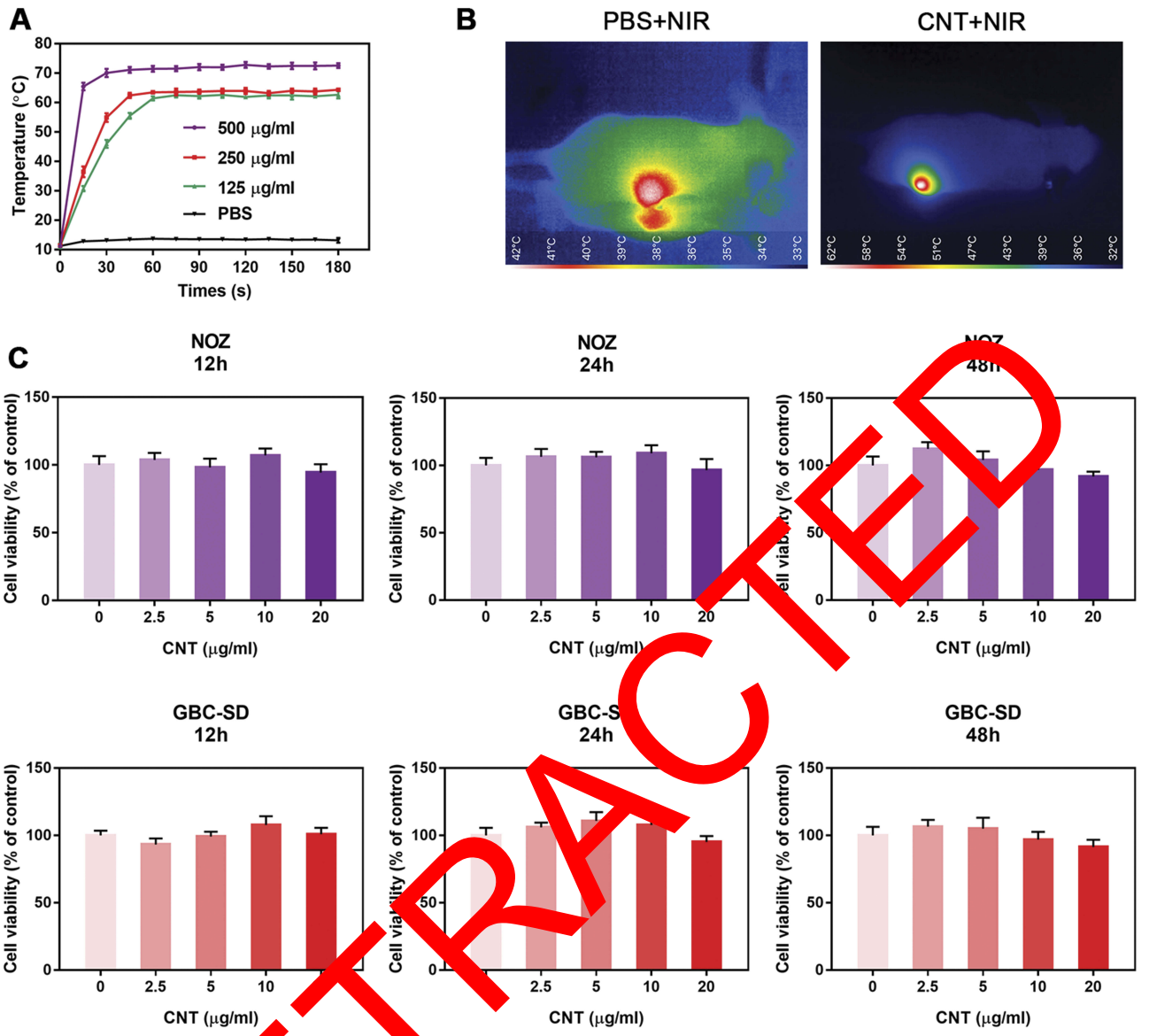

Figure 1 Evaluation of photothermal effect and cell toxicity of CNTs. (**A**) Maximum temperature profiles of PBS, 125 μg/mL CNTs, 250 μg/mL CNTs and 500 μg/mL CNTs as a function of the irradiation time under continuous 808-nm laser irradiation at a power intensity of 2.0W/cm^2. (**B**) In vivo whole-body thermal images of GBC cell xenografted mice injected intratumorally with PBS and 500 μg/mL CNTs after NIR laser irradiation (808 nm, 2.0 W/cm^2) for 5 mins. (**C**) The cell toxicity of CNTs at various concentrations (0, 2.5, 5, 10 and 20 μg/mL) in NOZ and GBC-SD cells for 12, 24 and 48 hrs without NIR were determined by CCK-8 assay.

This study reported that PTT enhanced cell autophagy and autophagy blocking improved the cytotoxic effect of PTT in GBC. Recently, more and more researchers have paid their attention to manipulate autophagy to enhance the efficacy of cancer therapeutic. Autophagy is a dynamic catabolic process, we found that it could be activated by PTT in GBC. CQ, an established drug, has been widely used for malaria prophylaxis. However, its potential use as a tumor chemosensitizer for its inhibitory of autophagy has been focused recently.[29] This study indicated that CQ could enhance the cytotoxic effect of PTT in vitro and in vivo. Moreover, the pharmacological properties of CQ are clearly studied, the cytotoxic of CQ is low, and the price of CQ is cheap.[30] These characteristics made it suitable as a tumor sensitizer for PTT and this study laid the foundation for future clinical trials of CQ in GBC.

The Cytotoxic Effect of PTT Could Be Enhanced by Chemotherapy in vitro

To evaluate the cytotoxic effect of Dox on GBC cell in vitro, we first assessed the cell viability after incubation with various concentrations of Dox for 24 hrs and calculated the IC_{50} values of GBC cell to Dox. As shown in Figure 3A, the IC_{50} values for Dox in NOZ and GBC-SD cells were 0.911 μg/mL and 3.693 μg/mL, respectively, and we used these two

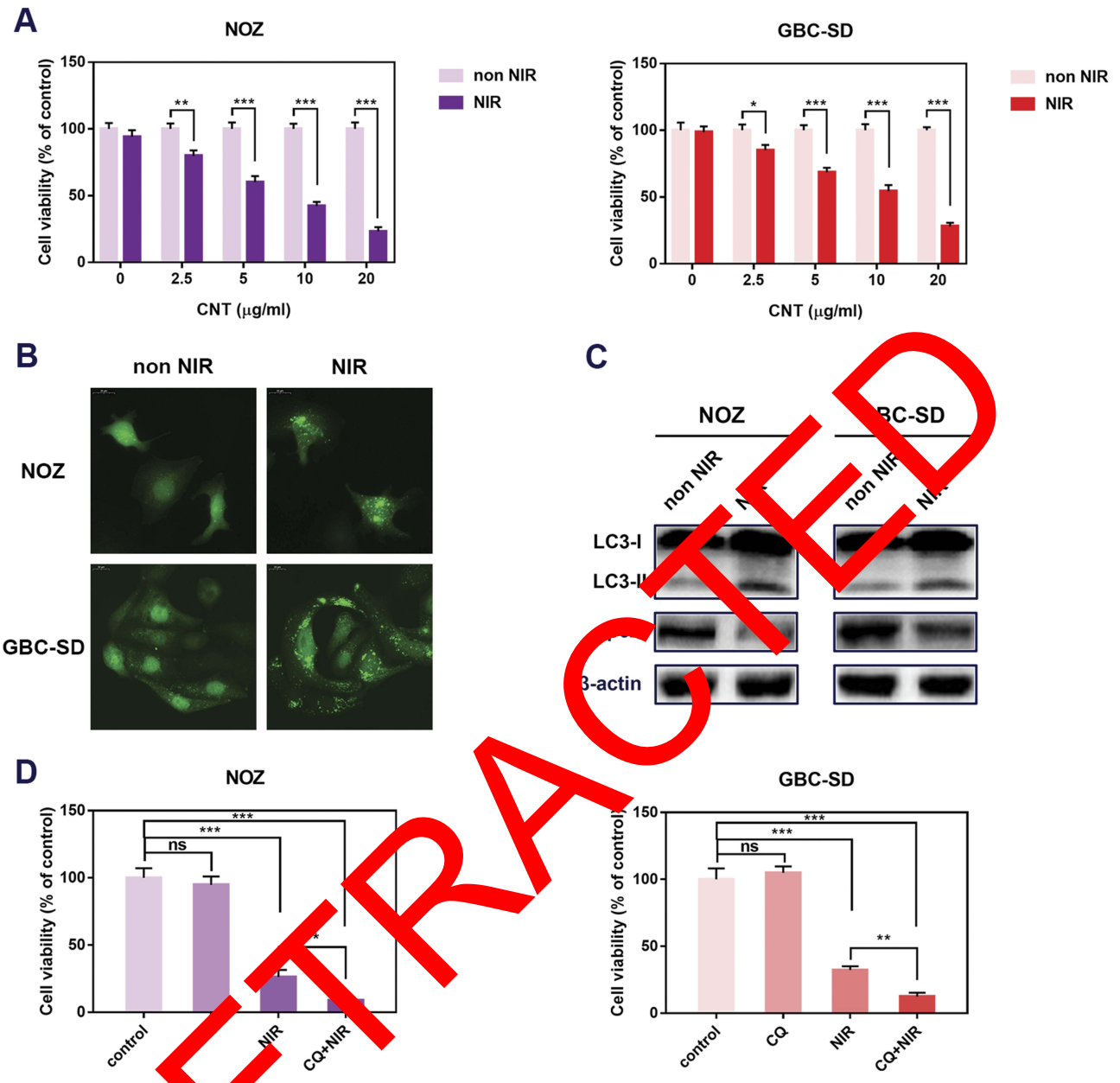

Figure 2 The cytotoxic effect of CNT could be enhanced by autophagy blocking in vitro. (**A**) The cell toxicity of CNTs at various concentrations (0, 2.5, 5, 10 and 20 μg/mL) in NOZ and GBC-SD cells after NIR laser irradiation (808 nm, 2.0 W/cm^2) for 3 mins were determined by CCK-8 assay. (**B**) NOZ and GBC-SD cells that transiently express GFP-LC3 tandem protein under NIR were observed by the fluorescence microscope. Scale bar = 20 μm. (**C**) The protein levels of LC3 and p62 in NOZ and GBC-SD cells under NIR were determined by Western blot assay. (**D**) The cell toxicity of CNTs in NOZ and GBC-SD cells with NIR or CQ (10μM) were determined by CCK-8 assay. The mean ± SD of triplicate experiments were plotted, *P<0.05, **P<0.01, ***P<0.001, n.s., not statistically significant.

concentrations for the subsequent experiments. Then, we performed PTT in GBC cell after incubation with Dox to assess the cell viability. Compared with "Dox" and "NIR" group, the cytotoxic effect of "Dox + NIR" group presented most effective both in NOZ and GBC-SD cells (Figure 3B). However, our previous study suggested that drug-resistant GBC cell presented enhanced autophagic activity and blocking autophagy could successfully reverse the drug-resistant property in GBC in vitro and in vivo.[25] To this end, we also explored whether the autophagic activity would be enhanced by chemotherapy. According to our expectations, the results of GFP-LC3 distribution and Western blot simultaneously suggested that Dox could trigger GBC cell autophagy (Figure 3C and D). Noteworthily, the results of cell viability experiments indicated that the cell-killing effects of "Dox + NIR", "CQ + Dox" and "CQ + NIR" group were approximate and generally better than "Dox" and "NIR" group; however, the most potent cell-killing combination was "CQ + Dox + NIR" group (Figure 3E). In

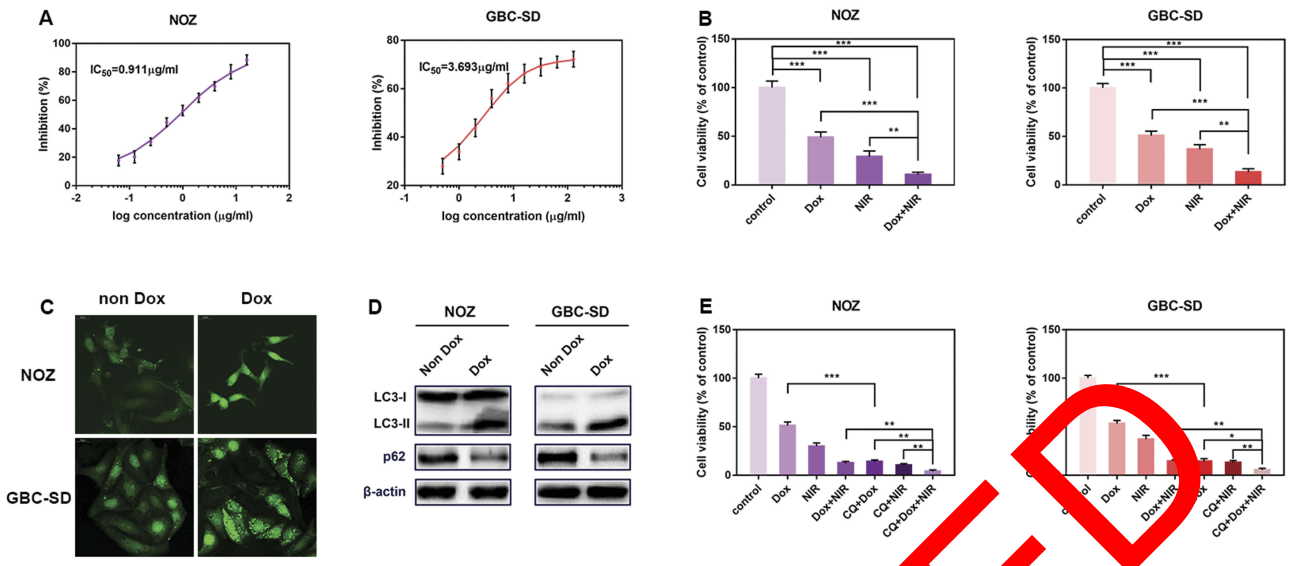

Figure 3 The cytotoxic effect of PTT could be enhanced by autophagy blocking or chemotherapy in vitro. (**A**) The sensitivity of NOZ and GBC-SD cells with Dox were determined by CCK-8 assay. (**B**) The cell toxicity of CNTs in NOZ and GBC-SD cells with NIR or Dox were determined by CCK-8 assay. (**C**) NOZ and GBC-SD cells that transiently express GFP-LC3 tagged protein under Dox were observed by the fluorescence microscope. Scale bar = 20 μm. (**D**) The protein levels of LC3 and p62 in NOZ and GBC-SD cells under Dox were determined by Western blot assay. (**E**) The cell toxicity of CNTs in NOZ and GBC-SD cells with NIR, CQ (10 μM) or Dox were determined by CCK-8 assay. The mean ± SD of triplicate experiments were plotted, **P*<0.05, ***P*<0.01, ****P*<0.001.

a word, this part suggested that the cytotoxic effect of PTT combined Dox could be significantly enhanced by blocking autophagy in vitro.

Because the symptoms and signs of GBC are vague and non-specific, the majority of GBC patients are diagnosed at the advanced stages.[31] And the prognosis of GBC is extremely poor. In those stages, it is difficult to conduct surgical curative resection and acquire benefits. The current notion is that the adjuvant therapy based on chemotherapy would prolong the survival of GBC patients.[32] However, as is well known, GBC is not sensitive to the current chemotherapeutic drugs.[33,34] Chemotherapy resistance is mainly related to the adaptation of cancer cells to the multiple stresses induced by drugs, which is attributed to a variety of mechanisms such as drug efflux, drug metabolism, inactivation of apoptosis, angiogenesis, induction of autophagy, etc.[35,36] Meanwhile, autophagy is constitutively activated in chemotherapy.[37] Our previous study[25] and the current evidence both supported that mediating autophagy might be a useful therapeutic strategy to enhance the therapeutic effect of Dox. Interestingly, PTT combined Dox presented more efficient inhibition of tumor growth than PTT or Dox alone, and PTT combined CQ and Dox could achieve the most efficient inhibition of tumor growth, while a series of studies by Ali Shakeri-Zadeh et al also supported that the combination of PTT and chemotherapy could achieve synergistic therapeutic outcome and be promising in cancer therapy.[38–44] Given this finding, we thought it is promising to change the current situation of the chemoresistance of GBC. In combination with PTT and CQ, it is possible to reduce the dosage of chemotherapeutic drugs while achieving equivalent or even better therapeutic effect. Once the photoresponsive nanoparticles are injected into tumor, it is possible to flow into the bloodstream. So, it is necessary to consider the cell toxicity of photoresponsive nanoparticles. In the present study, we preliminarily assessed to cell toxicity of photoresponsive nanoparticles by CCK-8 and did not find its cytotoxicity to GBC cell. However, we considered it is not enough to fully assess its cytotoxicities such as hepatotoxicity and renal toxicity, and the limitation would be made up in our next study.

PTT Combined Autophagy Blocking and Chemotherapy Could Effectively Inhibit GBC Cell Growth in vivo

As shown in Figure 4, tumor inhibition efficacy was measured by in vivo treatment of tumor-bearing mice that randomly divided into several groups: PBS (control), CQ, Dox, NIR, Dox + NIR, CQ + Dox, CQ + NIR, CQ + Dox + NIR. In general, the results from the two cell lines (NOZ and GBC-SD) showed a similar tendency. Compared to the control group that with a steep rise in tumor growth, no significant tumor inhibition was observed in "CQ" group, indicating that the low drug toxicity of CQ in vivo. Compared to the control group and "CQ" group, the single-mode treatment (Dox, NIR) group showed obvious inhibition of tumor growth. Compared to

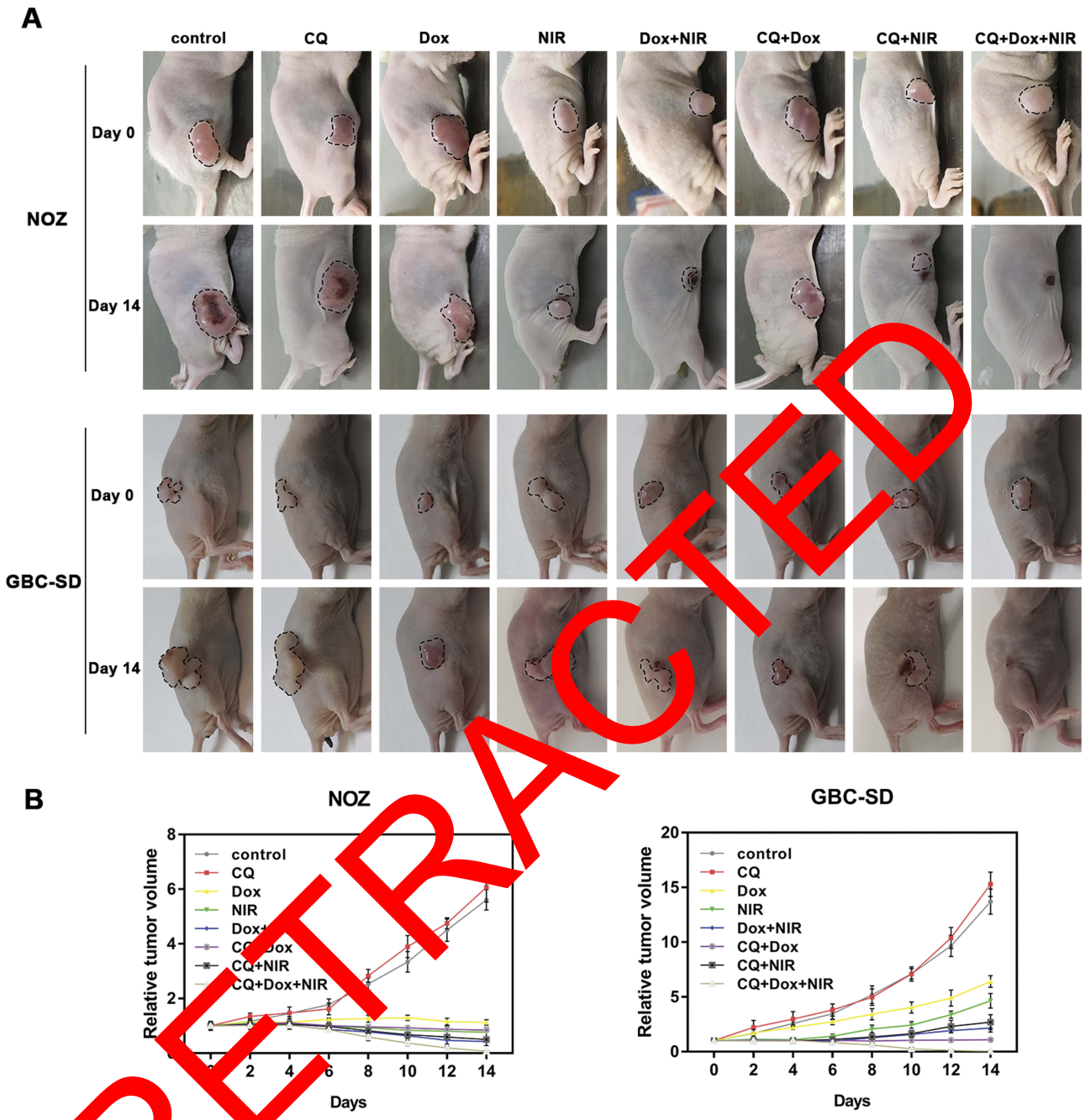

Figure 4 [illegible] combi[illegible] blocking and chemotherapy could effectively inhibit GBC cell growth in vivo. (**A**) Representative pictures of tumor growth evolution for "PBS" (contro[illegible], "Dox", "NIR", "Dox + NIR", "CQ + Dox", "CQ + NIR", "CQ + Dox + NIR" groups. (**B**) Tumor volume plot for "PBS" (control), "CQ", "Dox", "NIR", "Dox + [illegible]", "CQ + Dox", "CQ + NIR", "CQ + Dox + NIR" groups.

the single-mode treatment (Dox, NIR) group, dual-mode treatment (Dox + NIR, CQ + Dox, CQ + NIR) presented more efficient inhibition of tumor growth. Moreover, triple-mode (CQ + Dox + NIR) presented the most efficient inhibition of tumor growth compared with the other groups and even induced tumor regression as tumor volume decreased by 14-fold in NOZ cells and 27-fold in GBC-SD cells considering equivalent time points.

In addition to the monitor of tumor growth, H&E and immunohistochemical staining were performed to assess the histological features of the tumor and antitumor mechanisms of several groups. As shown in Figure 5, H&E staining showed that dense GBC cells were observed in the control group and "CQ" group, suggesting a rapid tumor growth and the low drug toxicity of CQ. However, the groups treated with "Dox" or "CQ + Dox" exhibited

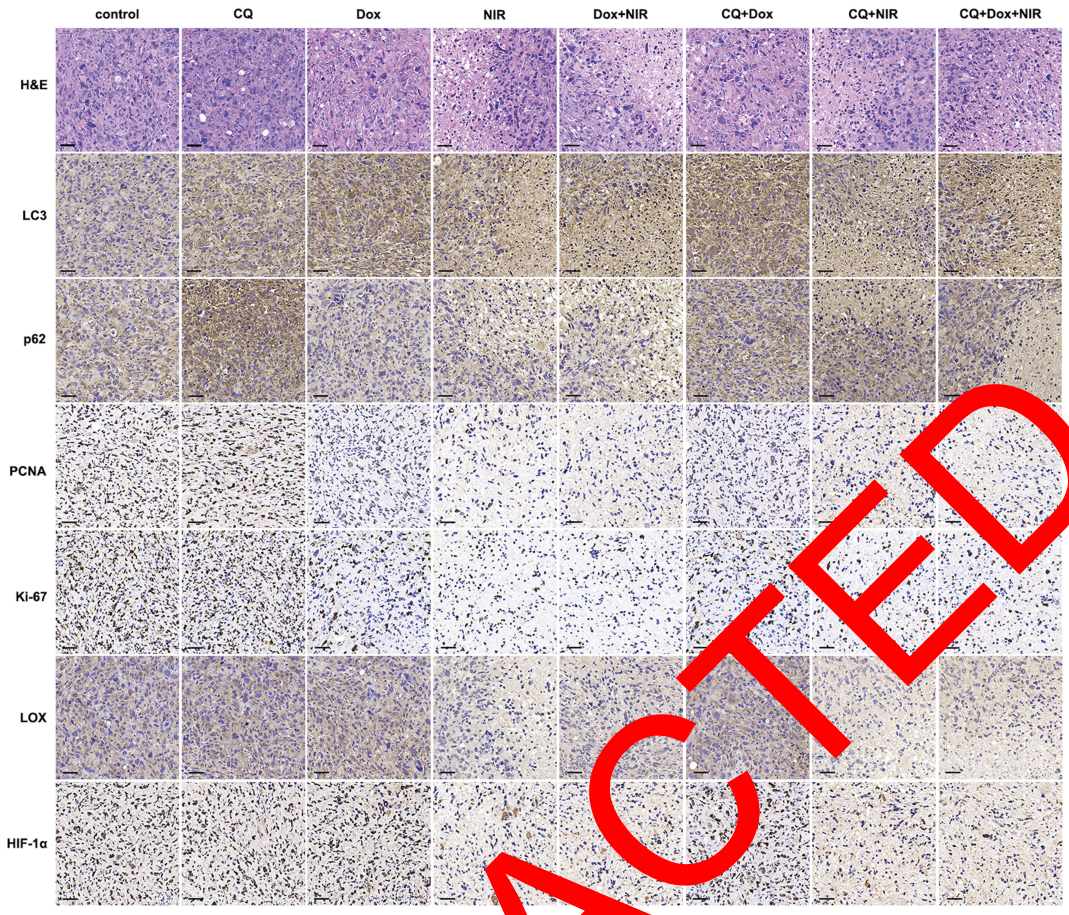

Figure 5 Evaluation of tumor by H&E and immunohistochemical stai[illegible]. The histo[illegible] characteristics were determined by H&E. The LC3, p62, PCNA, Ki-67, Lox and HIF-1α expression and positive cell numbers were determined b[illegible]munohistochem[illegible] staining. Scale bar = 50 μm (NOZ).

relatively higher necrotic levels, wh[illegible]eas [illegible]o[illegible] treated with NIR ("NIR", "Dox + NIR", "[illegible]Q + NIR" [illegible]nd "CQ + Dox + NIR" groups) exhib[illegible]ed h[illegible]her necrosi[illegible] area, which was mostly in line wi[illegible] the previo[illegible]in vivo tumor-suppressing results. F[illegible]thermore, the e[illegible]pression of autophagy-associated [illegible]oteins (LC3 and p62), proliferation-associated proteins ([illegible]NA and [illegible]-67) and microenvironment-ass[illegible]iated [illegible]roteins ([illegible]O[illegible] and HIF-1α) in tumor tissues wer[illegible] determi[illegible]d by immunohistochemical staining. The immuno[illegible]chemical analysis of LC3 and p62 showed that eith[illegible] NIR or Dox could trigger GBC cell autophagy and CQ [illegible]ould block autophagy in vivo, the immunohistochemical analysis of PCNA and Ki-67 showed that either NIR or Dox could inhibit GBC cell proliferation and CQ addition could further strengthen the inhibitory effect, which was consistent with the aforementioned results in vitro. Moreover, the tumor cells of NIR-treated mice ("NIR", "Dox + NIR", "CQ + NIR" and "CQ + Dox + NIR" groups) showed significantly slight positive staining for LOX, indicating that the antitumor effect of NIR might be related to the decrease of tumor tissues density. And the tumor cells of NIR-treated mice also showed positive staining for HIF-1α, indicating that the antitumor effect of NIR might be related to the decrease of tumor tissues blood supply induced by NIR caused vascular collapse.

As reported, PTT could release local heat and affect the microenvironment.[45] And tumor microenvironment could regulate the response of solid tumors to chemotherapy or PTT. LOX is a secreted copper-dependent monoamine oxidase that catalyzes a key enzymatic step in the cross-linking of soluble collagens and elastin in the extracellular matrix, an essential process for the structural integrity of all tissues.[46] And LOX enzymes can also remodel the tumor microenvironment and have been implicated in all stages of tumor initiation and progression of many cancer types.[46] Aberrantly abundant and dense extracellular matrix, high interstitial pressure, chaotic vessel organization, enhanced solid stress are physical features that dramatically restrict the transport of cytotoxic therapeutic

agents. Such physical barriers directly contribute to decreased therapeutic efficacy and the emergence of drug resistance by creating drug-free sanctuaries. Furthermore, a major activator of LOX at the transcriptional level is the transcription factor HIF-1.[47] HIF-1α, a hypoxia-responsive protein, is usually aberrantly abundant in human cancers for the intratumoral hypoxia condition.[48] And our present study confirmed that PTT could decrease the tumor tissues density and change the tumor microenvironment, and these functions might improve the effect of chemotherapy.

In summary, we have demonstrated that PTT mediated by CNTs could effectively damage GBC cell and inhibit tumor growth. Through a local denaturation of tumor, CNTs-generated heat stress or chemotherapeutic drug could trigger cytoprotective autophagy. PTT combined autophagy blocking and chemotherapy could effectively inhibit GBC progression.

Ethics Approval and Consent to Participate

All animal experiments were performed in the animal laboratory center of Xinhua Hospital (Shanghai JiaoTong University School of Medicine, Shanghai, China). The study protocol was approved by the Animal Care and Use committee of Xinhua Hospital. Besides, all procedures followed by international ethics guidelines and the National Institutes of Health Guide concerning the Care and Use of Laboratory Animals.

Availability of Data and Material

The data and material in this paper are available upon request from the corresponding authors.

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Disclosure

The authors report no conflicts of interest in this work.

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