Ultrasound-Induced Cell Death of Nasopharyngeal Carcinoma Cells in the Presence of Curcumin

Xinna Wang, MD1, Xinshu Xia, MD2, Chuanshan Xu, PhD1,3, Jing Xu, MD1, Ping Wang, MD1, Junyan Xiang BSc1, Dingqun Bai, PhD2, and Albert Wingnang Leung, PhD3

Abstract

Objectives. Curcumin, a natural pigment from a traditional Chinese herb, has been attracting extensive attention. The present study aims to investigate cell death of nasopharyngeal carcinoma (NPC) cells induced by ultrasound sonication in the presence of curcumin in vitro.

Methods. The NPC cell line CNE2 was chosen as a tumor model, and curcumin concentration was kept constant at 10 µM while the cells were subjected to ultrasound exposure for 8 s at an intensity of 0.46 W/cm². Cell death was evaluated using flow cytometry with annexinV-FITC and propidium iodine staining, and nuclear staining with Hoechst 33258. Mitochondrial membrane potential and intracellular reactive oxygen species (ROS) were analyzed using flow cytometry with rhodamine 123 and dichlorodihydrofluorecein diacetate staining.

Results. Flow cytometry showed that the combination of ultrasound and curcumin significantly increased the necrotic or late apoptotic rate by up to 31.37% compared with the controls. Nuclear condensation was observed in the nuclear staining, and collapse of ∆Ψm and ROS increase were found in the CNE2 cells after the treatment with curcumin and ultrasound.

Conclusions. The findings demonstrate that the presence of curcumin significantly enhances the ultrasound-induced cell death and ROS level, and induces the collapse of ∆Ψm, suggesting that ultrasound sonication can increase the cell death of NPC cells in the presence of curcumin and that the treatment using curcumin and ultrasound together is a potential therapeutic modality in the management of malignant tumors.

Keywords

curcumin, ultrasound sonication, cell death, nasopharyngeal carcinoma

Introduction

Nasopharyngeal carcinoma (NPC) remains one of the most common cancers in Southern China, especially Hong Kong. Although recent therapeutic modalities for NPC, such as surgery, radiotherapy, and chemotherapy, are initially successful in the majority of cases, the 5-year survival rate is about 25% in NPC patients.1 Therefore, novel and more efficient therapeutic strategies and drugs are currently being pursued in the management of NPC.

Hematoporphyrin derivative (HpD)–mediated photodynamic therapy (PDT) has been introduced as an alternative for NPC, but prolonged skin photosensitivity and poor penetration in biological tissues limit the clinical application of HpD-PDT.2-4 To overcome the shortcomings of HpD, new and efficient photosensitizers are being explored. Our previous studies have also investigated the effect of PDT with the use of some second-generation photosensitizers on NPC. Our findings suggested that photosensitization of MPPa and temoporfin (mTHPC) could effectively kill NPC cells.5,6 In view of their relatively nontoxic and inexpensive characteristics, natural products or herbs have been attracting extensive interest for screening as novel and efficient sensitizers. Recently, curcumin, a natural pigment of perylquinone derivatives (Figure 1), has been found to be a naturally occurring photosensitizer, and light irradiation significantly enhanced curcumin-induced cell death of CNE2 cells.6,7 However, the poor penetration of light in biological tissues is still a limitation on effective activation of curcumin in solid tumor tissues.

1Chongqing Medical University, Chongqing, China
2Department of Rehabilitation Medicine, The First Affiliated Hospital, Chongqing Medical University, Chongqing, China.
3School of Chinese Medicine, The Chinese University of Hong Kong, Hong Kong, China

Corresponding Author:
Chuanshan Xu, 74 Linjiangmen, Yuzhong district, Chongqing, 400010, China
Email: xcshan@163.com
Recent studies showed that ultrasound could efficiently activate some sensitizers to produce cytotoxic reactive oxygen, directly or indirectly killing tumor cells. The fact that ultrasound is a more efficient activating source because it has a better penetration power than light has drawn our interest to this area of study. In our previous studies, we have investigated the combined effect of ultrasound and several sensitizers on tumor cells. Our findings showed that hematoporphyrin monomethyl ether and hypocrellin B could enhance the “sonokilling” action of ultrasound in tumor cells. In the present study, we have explored whether curcumin could enhance the effect of ultrasound on the cell death of CNE2 cells in vitro in order to provide a novel technology for treating malignancies.

**Materials and Methods**

**Sensitizer**

Curcumin was purchased from Sigma (USA). A stock solution was made in dimethyl sulfoxide at a concentration of 100 mM and kept in the dark at −20°C.

**Cell Culture**

NPC cell line CNE2 was provided by the Shanghai Biology Institute under approval from the ethics committee of Chongqing Medical University. The cells were grown in Roswell Park Memorial Institute 1640 medium supplemented with 10% fetal calf serum (Gibco), 50 µg/mL penicillin, 50 µg/mL streptomycin, and 10 µg/mL neomycin. The cells were incubated at 37°C in a humidified CO₂ (5%) incubator.

**Ultrasound Treatment**

The CNE2 cells were exposed to ultrasound 1 hour after the incubation with curcumin (10 µM). A 1-cm diameter transducer with a central frequency of 1.7 MHz and intensity of 0.46 W/cm² was used to generate continuous ultrasound energy at 8 s. The plane transducer was placed in a water tank filled with degassed water, and the temperature was kept at 37°C during ultrasonic exposure. All experiments were randomly divided into 4 groups: Curcumin–ultrasound treatment, ultrasound sonication alone, and the controls, including curcumin treatment alone and sham sonication. For the curcumin–ultrasound treatment, the cells were pretreated with curcumin incubation before the ultrasound exposure. The cells in the ultrasound sonication alone group were only exposed to ultrasound but not incubated with curcumin. Those in the curcumin treatment alone group were only pretreated with curcumin incubation with no ultrasound sonication. The cells in the sham sonication group were not treated with ultrasound or curcumin.

**Cell Death Detection**

After ultrasound treatment, the CNE2 cells were incubated in culture flasks at 37°C for 6 hours. Cell death was analyzed by flow cytometry with annexin V-FITC Apoptosis Detection Kit (Beyotime, Jiangshu, China). Briefly, the cells from each sample were suspended in 195 µL of 1× annexin V-FITC binding buffer and 5 µL annexin V-FITC. The cells were incubated at room temperature for 10 minutes. Then, each sample was centrifuged at 1000 g for 5 minutes, suspended again in 190 µL of binding buffer, to which was added 10 µL of propidium iodide (PI) working solution. Then, the samples were analyzed by the flow cytometric method (FCM). The population was separated into 3 groups: live cells with a low level of fluorescence, apoptotic cells in the earlier period with green fluorescence, and necrotic and advanced-stage apoptotic cells with both red and green fluorescence.

**Nuclear Staining**

The CNE2 cells (2 × 10⁵ cells/well) were incubated in a 24-well microplate at 37°C for 6 hours after ultrasonically induced cell damage in the presence and absence of curcumin. The cells were washed with phosphate buffered saline (PBS), and nuclear staining was performed. Briefly, the treated and the control cells were stained with Hoechst 33258 (5 µg/mL; stock solution 1 mg/ml in sterile water) for 5 minutes at 37°C. Stained cells were washed twice with PBS and then observed immediately under a fluorescence microscope. A filter set of Ex/Em of BP330-380/LP420 nm was used, and the images were recorded by a color charge-coupled device camera.

**Mitochondrial Membrane Potential (ΔΨm) Measurement**

Mitochondrial membrane potential (ΔΨm) was monitored using FCM with rhodamine 123 staining. Briefly, the CNE2 cells were sensitized with curcumin (10 µM) for 1 hour. The

![Chemical structure of curcumin](image)
cells were then sonificated by ultrasound at an intensity of 0.46 W/cm² for an exposure of 8 s and further incubated for 3 hours. The rhodamine 123 (5 µg/mL) was added 30 minutes before cell harvesting. The washed cells were resuspended in PBS and analyzed using a flow cytometer FACS Vantage (SE, Becton Dickinson) with the excitation setting at 488 nm, and signals were acquired at the FL-2 channel. At least 10 000 cells per sample were acquired in histograms, and data were analyzed using CellQuest software.

**Intracellular Reactive Oxygen Species (ROS)**

Intracellular ROS were detected using the FCM with 2,7-dichlorodihydrofluoresein diacetate (DCFH-DA) staining. The DCFH-DA was supplied by Sigma and dissolved in ethanol to produce a 1 mmol/L stock solution. The DCFH-DA (10 µM) was added 3 hours after cells were treated by ultrasound. The washed cells were resuspended in PBS and analyzed using a flow cytometer FACS Vantage (SE, Becton Dickinson) with the excitation setting at 488 nm, and signals were acquired at the FL-2 channel. At least 10 000 cells per sample were acquired in histograms, and data were analyzed by CellQuest software.

**Statistical Analysis**

All data were processed using analysis of variance (ANOVA). A P value of less than .05 was considered a significant difference.

**Results**

*Cell Death of the CNE2 Cells Induced by Curcumin and Ultrasound*

Flow cytometry with annexin V (annexin V-FITC) and PI staining can identify early and late apoptotic cells by annexin V-FITC binding to PS exposed on the outer leaflet in early apoptotic cells. This can also distinguish early apoptosis from late apoptosis or necrosis because PI is impermeable to living cells and early apoptotic cells are impermeable to PI. The results from our studies showed that ultrasound exposure in the presence of curcumin increased the necrotic or late apoptotic rates of the CNE2 cells. Figure 2A shows that the early apoptotic and necrotic (late apoptotic) rates of the CNE2 cells 6 hours after treatment with sham sonication were 0.96% and 3.18%, respectively. Figure 2B shows that the early apoptotic and necrotic (late apoptotic) rates of the CNE2 cells treated with ultrasound and curcumin together were 2.12% and 4.79%. Figure 2C shows that the early apoptotic and necrotic (late apoptotic) rates of the CNE2 cells after the treatment with ultrasound sonication in the absence of curcumin were 1.57% and 4.55%. Figure 2D shows that the apoptotic and necrotic (late apoptotic) rates after ultrasound sonication and curcumin together significantly increased to 2.91% and 31.37%, respectively, under the intensity of 0.46 W/cm² for 8 s. These findings suggest that ultrasound sonication and curcumin together could obviously enhance necrosis or late apoptosis of the CNE2 cells. To further verify curcumin-sonodynamic therapy induced cell death of the CNE2 cells, the cells were stained using Hoechst 33258 after the treatment with ultrasound and curcumin together. The CNE2 cells in the sham control, curcumin treatment alone, and ultrasound sonication alone groups displayed a weak fluorescence, whereas nuclear condensation was found 6 hours after ultrasound sonication in the presence of curcumin (Figure 3).

**Mitochondrial Membrane Potential (ΔΨm)**

The fluorescent intensity value of rhodamine 123 reflects the mitochondrial membrane potential (ΔΨm) and the functioning of mitochondria. FCM with rhodamine 123 staining was used to measure the change of mean fluorescent intensity in Ψm. CNE2 cells were sensitized with curcumin (10 µM) and then treated with ultrasound (1.7 M) at an intensity of 0.46 W/cm² for an exposure time of 8 s. Figure 4 shows the significant changes in mean fluorescent intensity in ΔΨm in the CNE2 cells after ultrasound sonication in the presence of curcumin. A collapse of ΔΨm was observed in the CNE2 cells treated with ultrasound and curcumin together.

**Intracellular Reactive Oxygen Species**

The fluorescent intensity of cells was detected by flow cytometry with DCFH-DA staining, showing that the spectral shift of the fluorescence curve to the right after the combination of sonication and curcumin was more significant than that after ultrasound treatment alone and curcumin treatment alone (Figure 5). This indicated that ultrasound sonication in the presence of curcumin significantly enhanced the intracellular ROS in the CNE2 cells.

**Discussion**

Curcumin, a natural pigment of diferuloylmethane, is obtained from the rhizome of the plant *Curcuma longa*. In India and China, curcumin has been consumed as a dietary supplement and extensively used to treat body aches, rheumatic disease, skin diseases, urinary diseases, and digestive and inflammatory disorders. In view of its various important pharmacological properties, including antioxidative, antiviral, anti-inflammatory, and antitumoral effects, curcumin has been extensively studied as an important chemopreventive and chemotherapeutic drugs. Recent evidence showed that curcumin was a potent photosensitive drug and curcumin on its own could increase its cytotoxicity in cancer cells. However, its absorption wavelength is...
cell death, the poorly differentiated CNE2 cells were chosen as a tumor model for cell death testing in the present study. Cells die through 2 major modes—namely, necrosis and apoptosis. Necrosis is a passive event usually ensuing from rigorous inflammation, directly resulting in cell death. Apoptosis is a programmed cell death with an active self-destruction of a single cell characterized by specific nuclear and cytoplasmic features.\textsuperscript{21,22} In this

located in the range of 450 nm to 550 nm. Its low penetration in biological tissues limits the clinical application of light-activated curcumin. Because of the ability of ultrasound to noninvasively target specific regions of interest at depth without affecting the intermediate tissue,\textsuperscript{20} ultrasound-activated curcumin may be developed as a novel noninvasive approach for combating malignancies. To investigate the effect of curcumin on ultrasound-induced

Figure 2. Cell death of the CNE2 cells was analyzed 6 hours after ultrasound sonication in the presence of curcumin (10 \(\mu\)M) under ultrasound sonication (1.7 MHz) with an intensity of 0.46 W/cm\(^2\) for 8 s. Flow cytometry with annexin V-FITC and propidium iodide (PI) staining: annexin V-FITC in conjunction with PI staining could distinguish early apoptotic (annexin V-FITC positive, PI negative; bottom right quadrant of each panel) from late apoptotic or necrotic (annexin V positive, PI positive; top right quadrant of each panel) cells. Fluorescence intensity for annexin V-FITC is plotted on the x axis, and PI is plotted on the y axis. A. Sham sonication. B. Curcumin alone. C. Ultrasound sonication alone. D. ultrasound sonication with curcumin

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Figure 3. Observation of nuclear features in the CNE2 cells 6 hours after ultrasound sonication in the presence of curcumin (10 µM) was analyzed by the Hoechst33258 staining method. A: Sham sonication. B: Curcumin alone. C: Ultrasound sonication alone. D: Ultrasound sonication with curcumin.

Figure 4. Collapse of ∆Ψm in the CNE2 cells was analyzed using flow cytometry with rhodamine 123 staining 3 hours after ultrasound sonication in the presence of curcumin (10 µM). A: Sham sonication. B: Curcumin alone. C: Ultrasound sonication alone. D: Ultrasound sonication with curcumin.

Figure 5. Measurement of reactive oxygen species level in the CNE2 cells using flow cytometry with 2,7-dichlorodihydrofluorecein diacetate staining 3 hours after ultrasound sonication in the presence of curcumin (10 µM). A: Sham sonication. B: Curcumin alone. C: Ultrasound sonication alone. D: Ultrasound sonication with curcumin.

In the study, the apoptosis and necrosis of the CNE2 cells induced by ultrasound sonication and curcumin together (10 µM) were analyzed 6 hours after ultrasound exposure using nuclear staining and flow cytometry with annexin V and PI staining. Nuclear staining indicated that the treatment with curcumin and ultrasound sonication together significantly induced nuclear condensation in the CNE2 cells. Flow cytometry with annexin V and PI staining showed...
that the necrotic or late apoptotic rate of the CNE2 cells after ultrasound sonication significantly increased to 31.37% and the early apoptotic rate only up to 2.91% in the presence of curcumin. Our findings suggest that necrosis or late apoptosis might be a main mode of cell death induced by the combined treatment with curcumin and ultrasound.

Mitochondria are known to be a regulatory center in the process of cell death. The alterations of mitochondrial structure and function directly or indirectly interfere with cellular respiration and energy metabolism; the permeability transition pore opens and mitochondria membrane potential (MMP/ΔΨm) collapses, causing cell death.23,24 Thus, mitochondrial integrity and function is a decisive factor in cellular fate between life and death.23 Our present study shows that after ultrasound sonication alone, ΔΨm began to decline but significantly decreased to its lowest after the combined treatment of curcumin and ultrasound sonication, demonstrating that ultrasound sonication in the presence of curcumin significantly resulted in the collapse of ΔΨm. The collapse of ΔΨm is a standard indicator of mitochondrial damage.25 Our results demonstrated that the combined effect of curcumin and ultrasound sonication seriously damaged the mitochondria of the CNE2 cells. When ΔΨm collapses, the mitochondria generate morphological and functional changes, resulting in cell death. Therefore, combined treatment of curcumin and ultrasound sonication induced cell death probably through the mitochondrial pathway.

Oxidative stress is an important event in ultrasound-induced cell damage. Ultrasound sonication can increase the level of ROS in ultrasound-treated cells.26 The highly reactive oxygen can initiate further oxidative modification of lipid and protein molecules causing damage to the target cells/tissues.27 Our flow cytometry results also showed that ROS was significantly retained in the CNE2 cells after ultrasound sonication in the presence of curcumin. Previous studies reported that curcumin possessed an inhibitory effect on the generation of ROS. Our findings demonstrate that the production of ROS induced by ultrasound sonication in the presence of curcumin exceed the inhibitory effect of curcumin treatment alone, causing the excessive accumulation of ROS in the CNE2 cells. The high level of ROS resulted in the mitochondrial damage and cell death of the CNE2 cells. It is well known that ROS are a group of reactive, short-lived species, including free radicals and singlet oxygen (\(^{1}\)(O\(_2\))). However, it was unclear whether the combined treatment of ultrasound sonication and curcumin increased cell death of the CNE2 cells mainly through producing free radicals or through producing singlet oxygen. The exact mechanisms should be determined by further investigations.

In summary, the present study manifested that ultrasound sonication could effectively enhance the CNE2 cell death in the presence of curcumin. Our results highlight the importance of ROS production and MMP collapse in the process of cell death induced by combined treatment of curcumin and ultrasound sonication. Considering that photosensitizers have the feature of preferential retention in tumor tissues,28 and ultrasound has the advantage of better tissue penetration and targeted focus, our present results indicate that ultrasound sonication in the presence of curcumin might be a potential modality for the treatment of cancer. As there may be differences between in vitro and in vivo studies, further investigation will be focused on the efficiency in vivo.

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