Note

Protective Effect of Edaravone against Cationic Lipid-Mediated Oxidative Stress and Apoptosis

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Liposomes containing ionizable cationic lipids have been widely used for the delivery of nucleic acids such as small-interfering RNA and mRNA. The utility of cationic lipids with a permanent positive charge, however, is limited to in vitro transfection of cultured cells due to its dose-limiting toxic side effects observed in animals. Several reports have suggested that the permanently charged cationic lipids induce reactive oxygen species (ROS) and ROS-mediated toxicity in cells. We therefore hypothesized that the concomitant use of ROS inhibitor could reduce toxicity and improve drug efficacy. In this study, suppression of the cationic toxicity was evaluated using an ROS scavenger, edaravone, which is a low-molecular-weight antioxidant drug clinically approved for acute-phase cerebral infarction and amyotrophic lateral sclerosis. Cell viability assay in the mouse macrophage-like cell line RAW264 indicated that the concomitant use of edaravone were not able to suppress the cytotoxicity induced by cationic liposomes comprised of monovalent cationic lipid N-(1-[2,3-dioleyloxypropyl]-N,N,N-trimethylammonium chloride (DOTMA) over a short period of time. Cationic lipids-induced necrosis was assumed to be involved in the cytotoxicity upon short-term exposure to cationic liposomes. On the other hand, the significant improvement of cell viability was observed when the short treatment with cationic liposomes was followed by exposure to edaravone for 24h. It was also confirmed that apoptosis inhibition by ROS elimination might have contributed to this effect. These results suggest the utility of continuous administration with edaravone as concomitant drug for suppression of adverse reactions in therapeutic treatment using cationic liposomes.

Key words liposome; edaravone; cationic lipid; reactive oxygen species

INTRODUCTION

For gene therapy, the development of effective and safe nucleic acid delivery systems is an essential requirement. Non-viral vectors including liposomes are superior platforms than viral vectors because of low immunogenicity, high reproducibility, and availability of established, streamlined manufacturing techniques.1–4 Application of liposome technology to genetic drugs required the development of methods to achieve efficient encapsulation of RNA and DNA polymers.5,6 Since their discovery, they have been widely used to deliver nucleic acids into targeted cells and offered potential utility in the clinic.6–9 Although the benefits brought by cationic lipids in drug delivery have gained much attention and considerable efforts have been devoted to investigating better versions, the issue of toxicity has gained much attention and considerable efforts have been devoted to investigating better versions, the issue of toxicity has always been the main barrier in in vivo application.7 Even the most widely used lipoplexes, which are complexes of mixed cationic lipids with nucleic acid polymers, are limited to in vitro transfection due to issues such as inflammatory toxicity, hepatotoxicity, leukopenia and thrombocyteopenia in vivo.8–11 To address this problem, ionizable cationic lipids with apparent pKs values below 7 have widely been developed, allowing for interaction with nucleic acid polymers below the pKs and the maintenance of a relatively neutral liposome surface charge at physiological pH values.12–14

A cause for the toxicities mediated by cationic lipids is reactive oxygen species (ROS) generation, which induces cytotoxicity and affects intracellular signaling pathways.13,14 The high surface density of positive charges on cationic liposomes is believed to be critical for ROS generation.15 ROS are continuously generated by ROS producers and eliminated through ROS-scavenging systems to maintain redox homeostasis under physiological conditions. Upon disruption of the equilibrium, cell damage occurs.15 Moreover, ROS regulate cell differentiation, proliferation, migration, and apoptosis.

Edaravone (3-methyl-1-phenyl-2-pyrazolin-5-one) is a potent scavenger of free radicals. It is highly efficient in quenching hydroxyl radicals and also prevents oxidative stress-induced cellular damage.17,18 The ROS scavenging ability of edaravone is believed to protect various cells such as endothelial cells, neurons and myocardial cells, against damages caused by oxidative stress conditions.19 In 2001, Radicut® (an aqueous based parenteral preparation of edaravone) developed by Mitsubishi Tanabe Pharma Corporation (Japan), was approved to treat patients of acute-phase cerebral infarction in Japan. Subsequently in 2015, Radicut® was approved in Japan for amyotrophic lateral sclerosis treatment.

We hypothesized that a ROS scavenger such as edaravone could be used as a concomitant drug to suppress toxic effects induced by cationic liposomes. In the present study, we evaluated the protective effect of edaravone by treating...
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RAW264.7 mouse macrophage-like cells with liposomes composed of cationic lipid N-(1-[2,3-dioleyloxy]propyl)-N,N,N-
trimethylammonium chloride (DOTMA), which has been reported to cause ROS-mediated cytotoxicity. 19)

MATERIALS AND METHODS

Materials

DOTMA was purchased from Avanti Polar Lipids (Alabaster, AL, U.S.A.). Cholesterol, edaravone, 2', 7'-dichlorofluorescin diacetate (DCFH-DA) were purchased from Sigma-Aldrich (St. Louis, MO, U.S.A.). Hoechst dye was purchased from Invitrogen (Burlington, ON, Canada). RAW264.7 mouse macrophage-like cell line was obtained from ATCC and maintained in Dulbecco’s modified Eagle’s medium (DMEM) supplemented with 10% heat-inactivated fetal bovine serum (FBS).

Preparation of Cationic Liposomes

Cationic liposomes were prepared as previously described. 20-21 Briefly, lipid components composed of DOTMA/Chol (50/50 mol%) were dissolved in ethanol at 20 mM of total lipid. The lipids ethanol solution was mixed with distilled water through a staggered herringbone micromixer (SHM) at a total flow rate of 2 mL/min, and a flow rate ratio of 3 (v/v) (water/ethanol ratio). The resulting suspension was subsequently dialyzed against at least 1000-fold volume of distilled water overnight to remove the residual ethanol. Cationic liposomes solution was then filtered through a 0.2 µm filter.

Analysis of Cationic Liposomes

Particle size and z-potential analysis was carried out by dynamic light scattering with Malvern Zetasizer (Worcestershire, U.K.). Total lipids were determined by measuring the cholesterol content using the Cholesterol E assay (Wako Pure Chemical Corporation, Richmond, VA, U.S.A.)

Cell Viability Analysis

Cell viability was determined by performing the 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2H-tetrazolium bromide (MTT, Sigma-Aldrich) assay on cultured RAW264.7 cells as described previously. 22 Briefly, 15000 cells/well suspended in 10% FBS/DMEM were seeded 96-well plates, grown overnight. In Fig. 1, cells were preincubated with FBS-free DMEM containing edaravone for 1 h, followed by treatment with edaravone and/or 100 µM cationic liposomes for 3 h (A) and 6 h (B). Results indicate mean ± standard deviation (S.D.) (n = 3).

Fig. 1. Effect of Edaravone on Acute Cytotoxicity Induced by Cationic Liposomes (DOTMA:Chol at 50:50) Treatment in RAW264.7 Cells

Cell viability (% of control) was measured by MTT assay, following the treatment of 100µM cationic liposomes in the presence of edaravone at 0–200 µM for 3 h (A) and 6 h (B). Results indicate mean ± standard deviation (S.D.) (n = 3).

Fig. 2. Effect of 24h Incubation with Edaravone against the Cytotoxicity Induced by Cationic Liposomes (DOTMA:Chol at 50:50) Treatment in RAW264.7 Cells

MTT assay was performed on cells treated with edaravone at 0–100 µM for 24 h, following the treatment with 100 µM cationic liposomes in the presence of edaravone for 0.5 (A), 1 (B), 3 (C), and 5 h (D). Results indicate mean ± S.D. (n = 3). **p < 0.01, ***p < 0.001, compared with cationic liposomes-treated cells in the absence of edaravone.

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by the treatment of 100 µM cationic liposomes in the presence of 0–200 µM edaravone in FBS-free DMEM for 3 and 6 h at 37°C. In Fig. 2, after treatment of 100 µM cationic liposomes with edaravone in FBS-free DMEM for 0.5–5 h, the medium was removed and the cells were incubated with 10% FBS/DMEM in the presence of 0–100 µM edaravone for 24 h at 37°C. After each treatment, cell viability was measured as follows: 30 µL of 5 mg/mL MTT in phosphate buffered saline (PBS) was added to cells in the presence of 125 µL cell culture medium. After 2 h incubation at 37°C, 125 µL of 20% sodium dodecyl sulfate dissolved in dimethylformamide : water (1 : 1) at pH 4.7 was added, and the absorbance at 570 nm was measured after the overnight incubation. Results were expressed as percentages of control.

Fluorescent Analysis of Intracellular ROS RAW264.7 cells suspended in 10% FBS/DMEM were seeded at 15000 cells per well in 96-well plates, grown overnight. Cells were incubated with 10% FBS/DMEM containing 10 µM edaravone and 250 µM cationic liposomes for 24 h at 37°C. After the incubation, the treatment mediums were removed, and cells were incubated with 10 µM DCFH-DA dye (ROS staining) and 0.7 µg/mL Hoechst dye (nuclear staining) in PBS for 30 min in darkness. After being washed 1 time with PBS, fluorescence images were analyzed using a Cellomics ArrayScan VTI HCS Reader (Thermo Scientific, Pittsburgh, PA, U.S.A.).

DNA Fragmentation Analysis RAW264.7 cells suspended in 10% FBS/DMEM were plated on a 60 mm dish at a density of 1 × 10⁶ cells/cm², grown overnight. Briefly, cells were treated with FBS-free DMEM containing 100 µM cationic liposomes (DOTMA:Chol at 50:50) and 10 µM edaravone for 3 h at 37°C. The medium was replaced with 10% FBS/DMEM in absence and presence of 10 µM edaravone. After the incubation for 24 h at 37°C, the supernatant cells and adherent cells were collected. After centrifugation, the cells (5 × 10⁵ cells) were collected, and DNA was extracted according to the method of Wang et al. The extracted DNA was dissolved in TE buffer (10 mM Tris buffer, pH 7.4, containing 1 mM ethylenediaminetetraacetic acid (EDTA)) and subjected to 1.5% agarose gel electrophoresis with 1kb DNA Ladder (Invitrogen, Burlington, ON, Canada).

Statistical Analysis All values were indicated as mean ± standard deviation (S.D.). Statistical comparisons were performed using one-way ANOVA followed Dunnett’s post hoc test for multiple comparisons. Values of p < 0.05 were considered to indicate statistical significance.

RESULTS AND DISCUSSION

Effect of Edaravone on Acute Cytotoxicity Induced by Cationic Liposomes To determine the effect of edaravone on cationic liposomes-mediated cytotoxicity, particles were prepared using the cationic lipid DOTMA and cholesterol at a molar ratio of 50:50. Particles were determined to have a diameter of 45.9 ± 0.9 nm (mean ± S.D.) and a positive z-potential of +51.6 ± 0.4 (mean ± S.D.). Various concentrations of these cationic liposomes were incubated with RAW264.7 cells for 1–6 h. As shown in Fig. S1, cytotoxicity (as measure by cell viability using MTT) in RAW264.7 cells was observed as soon as 1 h post liposomes treatment in a concentration-and time-dependent manner. Indeed, it has been reported that DOTMA-based cationic liposomes rapidly increase ROS generation in treated cells in a concentration-dependent manner, reaching the plateau at 40–60 min. The reaction rates of edaravone to eliminate ROS have been determined to be 10⁷ M⁻¹ s⁻¹ or higher, indicating that edaravone enables rapid ROS elimination. We, therefore, hypothesized that short-term co-administration of edaravone with cationic liposomes could protect cells against cationic lipids-mediated cytotoxicity. In this study, cell viability was measured following the treatment of 100 µM of cationic liposomes in the presence of edaravone at 0–200 µM for 3 and 6 h. As shown in Fig. 1, cationic lipid-mediated cytotoxicity was not suppressed at any edaravone concentration. This is not unexpected as a previous report indicated that HepG2 cell death induced by 100 µM of 1,2-diacyloyl-3-trimethylammonium-propane (DOTAP)-liposome was evident with or without edaravone since high cationic lipid content caused destabilization of the plasma membrane and cell collapse. It is possible that membrane solubilization, poration, and lysis triggers acute cell necrosis before the occurrence of ROS-induced cell apoptosis.

Effect of Incubation with Edaravone against Cationic Liposomes-Induced Cytotoxicity It has been reported that typical cationic carriers such as cationic lipid, chitosan and polyethyleneimine (PEI) can trigger cell apoptosis and apoptotic cells often appear after approximately 24–48 h exposure to the cationic liposomes. Moreover, the protective effect of edaravone against paraquat, hyperosmolarity, and hypoxia-induced ROS production was also observed after 24 h of the treatment. It is therefore possible that long-term exposure to edaravone may be necessary to suppress ROS-induced apoptosis after treatment with cationic liposome.

In order to clarify the protective effect of edaravone against cationic liposomes mediated-cytotoxicity, RAW264.7 cells were incubated with cationic liposomes for 0.5 to 5 h, followed by treatment of edaravone for 24 h, and then measurement of cell viability by MTT assay. As shown in Fig. 2, the cationic liposomes-induced cytotoxicity was markedly alleviated by edaravone at as low as 10 µM (p < 0.01 or p < 0.001, compared with cationic liposomes-treated cells in the absence of edaravone).

Previously, Wei et al. have demonstrated that cathepsin-B (marker of necrosis) was detected in A549 cells incubated with cationic particles for 30 min. In contrast, activation of caspase-3 (a marker of apoptosis) was not detected at 30 min, but at 24 h after incubation with cationic particles. Therefore, our results, which showed that the cationic liposomes-induced cytotoxicity was not affected by short-term exposure to edaravone but was attenuated by long-term exposure, are reasonable in view of the mechanism of this cytotoxicity. However, the short half-life (5.4 min) of edaravone upon intravenous administration is not suitable for clinical use. Some studies are investigating edaravone loaded in alginate-based nanocomposite hydrogel or liposomes for sustained release of edaravone.

Effect of Edaravone against ROS Generation The inhibitory effect of edaravone on cationic liposomes-induced ROS generation was evaluated by dichloro-dihydro-fluorescein diacetate (DCFH-DA) fluorescence assay, a quantitative assessment for oxidative stress in cells. DCFH-DA passively diffuses into cells, where the two acetate groups are cleaved by intracellular esterases to yield cell-impermeable DCFH,
which is subsequently oxidized by ROS to form the highly fluorescent product DCF. RAW264.7 cells were treated with cationic liposomes in the presence or absence of edaravone for 24 h followed by DCFH-DA staining. Our results indicate that ROS fluorescent staining was detected in RAW264.7 cells treated with cationic liposomes alone (Fig. 3), while edaravone co-treatment eliminated the stimulated ROS generation in the cells.

**Effect of Edaravone on Cationic Liposomes-Mediated Apoptosis**

The apoptotic process is intimately connected to orderly DNA fragmentation, in which the key apoptotic proteases (caspases) initiate specific DNA cleavage. To verify the protective effect of edaravone on cationic lipids-mediated apoptosis, we assessed the patterns of DNA fragmentation in RAW264.7 cells following the treatment of cationic liposomes with and without edaravone. As shown in Fig. 4, DNA fragmentation was clearly observed when the cells were treated with cationic liposomes for 3 h followed by incubation without edaravone for 24 h. As expected, the incubation with edaravone for 24 h inhibited the DNA fragmentation, revealing the protective effect of edaravone against cationic lipids-mediated apoptosis. It should be noted that DNA fragmentation was not observed when the cells were treated with cationic liposomes for 3 h without additional incubation for 24 h (Fig. S2) suggesting that ROS-induced apoptosis has minimal contribution to early cytotoxicity, but rather occurs slowly over time.

**CONCLUSION**

In this study, we showed that the long-term treatment of edaravone could suppress the cytotoxicity by cationic liposomes containing DOTMA in vitro. Further, the improvement of cell viability was attributed to the elimination of ROS produced by cationic liposomes-stimulated cells and inhibition of ROS-induced apoptosis, rather than to necrosis due to acute cytotoxicity. Cationic lipid-mediated cytotoxicity has
been reported to vary with physicochemical changes due to the incorporation of nucleic acids in cationic liposomes. 38,39 These factors may affect the protective effect of edaravone. In order to allow a more comprehensive understanding of the mechanism, further studies on the protective effect of edaravone against cationic lipid-mediated toxicities are needed to determine whether edaravone can demonstrate the significant effect in vivo. The present study showed the usefulness of the concomitant administration with edaravone for the therapeutic use of cationic liposomes, and it is expected to become a starting point for the clinical application.

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Conflict of Interest The authors declare no conflict of interest.

Supplementary Materials The online version of this article contains supplementary materials.

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