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Novel and simple loading procedure of cisplatin into liposomes and targeting tumor endothelial cells

M. Hirai[a,b], H. Minematsu[a], Y. Hiramatsu[a], H. Kitagawa[a], T. Otani[a,b], S. Iwashita[a], T. Kudoh[b], L. Chen[b], Y. Li[b], M. Okada[b], D.S. Salomon[c], K. Igarashi[a], M. Chikuma[d], M. Seno[b,*]

[a] *R&D Division, Katayama Chemical Industries Co., LTD, Minoh, Osaka 562-0015, Japan*
[b] *Department of Medical and Bioengineering Science, Graduate School of Natural Science and Technology, Okayama University, Okayama 700-8530, Japan*
[c] *Tumor Growth Factor Section, Mammary Biology and Tumorigenesis Laboratory, Center for Cancer Research, National Cancer Institute, Bethesda, MD 20892, USA*
[d] *Osaka University of Pharmaceutical Sciences, Takatsuki, Osaka 569-109, Japan*

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ABSTRACT

Although intravenous administration of high levels of cisplatin (CDDP) are limited due to its severe side effects, efficient delivery of CDDP directly to the tumor should improve the therapeutic response while potentially by-passing significant side effects.

High loading of CDDP into liposomes is one technique that could be used as a potential drug delivery system. Since *cis*-diamminedinitratoplatinum (CDDP3) is highly soluble in water and converts to CDDP in the presence of chloride ions, we encapsulated CDDP3 into liposomes in the absence of chloride ions and supplemented chloride ions to prepare CDDP-encapsulated liposomes (CDDP-Lip) resulting in a significantly improved loading efficiency of CDDP. We further conjugated the CDDP-Lip with Sialyl Lewis^X (CDDP-SLX-Lip) because we previously demonstrated Sialyl Lewis^X enhanced efficient accumulation of liposomes into tumors in vivo. CDDP-SLX-Lip treated mice showed a survival rate of 75% at 14 days even if a lethal level of CDDP was injected into mice. Loss of body weight was negligible and no histological abnormality was found in a variety of normal tissues. Accumulation of CDDP-SLX-Lip was about 6 times more than that of CDDP-Lip or CDDP. As the result, there was better antitumor activity of CDDP-SLX-Lip than that of CDDP-Lip with significantly less toxic effects in normal tissues.

1. Introduction

Cisplatin (*cis*-diamminedichloroplatinum, CDDP) is one of the most widely used chemotherapeutic drugs in the clinical treatment of a variety of tumors, such as lung, ovarian and gastric carcinomas (Comis, 1994). However, administration of escalating doses of CDDP is limited because of severe side effects such as nephrotoxicity, hematopoietic injury, and deafness (Cvitkovic et al., 1977; Hayes et al., 1977; Von Hoff et al., 1979; Goldstein et al., 1981). Efforts to decrease these deleterious side effects by screening various CDDP derivatives and by developing improved forms of dosage or methods of medication have been unsuccessful (Borch and Markman, 1989; Ogilvie et al., 1992; Legha et al., 1992; Navari et al., 1994). Practical drug delivery systems, which specifically recognize tumors to efficiently deliver drugs at high doses *in vivo*, have also been undertaken. However, as yet no efficient carriers to efficiently deliver CDDP to tumors have been developed (Bandak et al., 1999; Newman et al., 1999; Vaage et al., 1999). Among the several liposomal formulations of CDDP, the latest is SPI-077, in which CDDP is encapsulated in pegylated stealth liposomes (Newman et al., 1999). Although preclinical studies showed that compared with the free drug, SPI-077 exhibited improved stability, prolonged circulation time, increased antitumor effect, and reduced side effects (Newman et al., 1999; Vaage et al., 1999), little antitumor activity of SPI-077 was observed in Phase I/II studies (Harrington et al., 2001; Kim et al., 2001; Veal et al., 2001). The major problem of conventional liposomal formulations involving CDDP, such as in SPI-077, was the extremely low drug to lipid weight ratio due to water insolubility and low lipophilicity of CDDP, which resulted in failure to adequately deliver the drug to the tumor (Bandak et al., 1999; Meerum Terwogt et al., 2002).

In contrast with CDDP, *cis*-diamminedinitratoplatinum (II) (CDDP3), one of the various CDDP derivatives, is highly water soluble and is readily converted into CDDP in the presence of chloride

Abbreviations: SLX, Sialyl Lewis^X; CDDP, *cis*-diamminedichloroplatinum (II) or cisplatin; CDDP3, *cis*-diamminedinitratoplatinum (II); SLX-Lip, liposomes modified with SLX; CDDP-Lip, liposomes containing CDDP; CDDP-SLX-Lip, liposomes modified with SLX containing CDDP; LEL, *lycopersicon esculentum* lectin.

* Corresponding author at: Room 361, Bldg. ENG-6, Laboratory of Nano-Biotechnology, Department of Medical and Bioengineering Science, Graduate School of Natural Science and Technology, Okayama University, 3.1.1 Tsushima-Naka, Kita-ku, Okayama 700-8530, Japan. Tel.: +81 86 251 8216; fax: +81 86 251 8216.
E-mail address: mseno@cc.okayama-u.ac.jp (M. Seno).

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ions (Dhara, 1970). In this study we exploited this character of CDDP3, to establish an efficient procedure of CDDP encapsulation into liposomes at a high concentration.

As for the precedent targeting delivery of CDDP, cationic liposomes conjugated with 3,5-dipentadecycloxybenzamidine hydrochloride (TRX-20) encapsulating CDDP were shown to be significantly effective to suppress tumor growth and liver metastasis targeting chondroitin sulfate proteoglycans on the malignant cell surface (Lee et al., 2002). Here in this study, we employed a new formula for anionic liposomes conjugated with Sialyl Lewis^X (SLX), which specifically and efficiently targeted E-selectin and accumulated in tumors *in vivo* (Hirai et al., 2007a,b). Liposomes with SLX showed affinity to E-selectin expressed on tumor vascular endothelial cells and exhibited rolling action on the vascular endothelial cells. The SLX-coated liposomes then entered the gaps of the vascular walls, where permeability is augmented by tumor angiogenesis (Bevilacqua et al., 1989; Vestweber and Blanks, 1999; Mayer et al., 1998; Liu and Rabinovich, 2005).

2. Materials and methods

2.1. Materials

CDDP, potassium tetrachloroplatinate (II), potassium iodide, ammonia aqueous solution (28%), silver nitrate, dipalmitoylphosphatidyl choline (DPPC), cholesterol (Chol), dicetylphosphate (DCP), sodium cholatehydrate (cholic acid) human serum albumin (HSA), sodium periodate, deuterium oxide (D_2O) sodium hexachloroplatinate, tris(hydroxymethyl)aminomethane (Tris), DMEM, RPMI-1640, gelatin, fetal bovine serum (FBS) and penicillin–streptomycin solution were purchased from Sigma (St. Louis, MO). Ganglioside was purchased from Avanti Polar Lipids (Alabaster, AL, USA). Dipalmitoylphosphatidylethanolamine (DPPE) was purchased from Alexis (Plymouth Meeting, PA). N-tris(hydroxymethyl)methyl-3-amino-propane sulfonic acid (TAPS) and *n*-(2-hydroxyethyl) piperazine-*n*′-(2-ethanesulfonic) acid were purchased from Dojin Chemical (Kumamoto, Japan). Sodium cyanoborohydrate was purchased from Aldrich (Milwaukee, WI). Sialyl Lewis^X (SLX) was purchased from EMD Chemicals (Gibbstown, NJ). Bis(sulfosuccinimidyl)suberate (BS_3) and 3,3-dithiobis(sulfosuccinimidylpropionate) (DTSSP) were purchased from Pierce Biotechnology (Rockford, IL, USA). Determiner TC555 kit was purchased from Kyowa Medics (Tokyo, Japan). Potassium dichloroplatinum was purchased from Nacalai Tesque (Kyoto, Japan). In situ apoptosis detection kit was purchased from Takara BIO (Kyoto, Japan). TNF-α was purchased from R&D Systems (Minneapolis, MN). FITC labeled anti-mouse IgG antibody was purchased from Santa Cruz (Santa Cruz, CA). Collagen was purchased from Roche (Basel, Switzerland). Female BALB/c mice were purchased from Japan SLC (Shizuoka, Japan). Ehrlich's ascites tumor (EAT) cells were purchased from RIKEN Bio Resource Center (Ibaragi, Japan). Human lung cancer A549 cells and Hybridoma (CCL-3) were obtained from the ATCC (Manassas, VA). Human umbilical vein endothelial cells (HUVEC) and human endothelial cell medium were purchased from DS Pharma Biomedical (Osaka, Japan).

2.2. Preparation of CDDP3

CDDP3 was synthesized by the method of Dhara (1970). Briefly, potassium tetrachloroplatinate (II) (4.15 g, 10 mmol) was dissolved in distilled water. Potassium iodide (6.64 g, 40 mmol) was then added and stirred on ice for 5 min under a nitrogen atmosphere and light shielding. Ammonia aqueous solution (28%, 1.35 mL) was added to this reaction solution, and stirred on ice for 3 h. The yellow crystals formed were washed with distilled water and ethanol, and dried at 40 °C for 10 h under decompression. At this stage, 4.49 g of *cis*-diamminediiodeplatinum (II) (CDDP2) was obtained. CDDP2 (2.41 g, 5 mmol) was suspended in distilled water. Silver nitrate (1.68 g, 9.9 mmol) was then added and stirred on ice for 24 h under light shielding. The reaction solution was passed through a paper filter to remove any silver iodide. The filtrate was then concentrated using a rotating evaporator and white crystals were obtained. These crystals were washed with iced distilled water and ethanol, and then dried at 40 °C for 10 h under decompression. The final yield of CDDP3 was 1.0 g.

2.3. Measurement of absorption spectrum

The absorption spectra were measured using a UV spectrophotometer (Model UV-2500PC, Shimazu, Japan) at 5, 10, 15, 30, 60, 120 and 180 min after dissolving 5 mg of CDDP3 in 1 mL of 150 mM NaCl. In contrast, 2 mg of CDDP was dissolved in 1 mL of 150 mM NaCl and 24 h after dissolution, the absorption spectrum was measured. The absorption spectrum of 150 mM NaCl was deducted from each absorption spectrum.

2.4. Preparation of CDDP-encapsulated liposomes

The liposomes were prepared using an improved cholate dialysis method (Yamazaki, 1989; Yamazaki et al., 1994). DPPC, Chol, ganglioside, DCP and DPPE were mixed at the molar ratio 35:40:5:15:5 (total lipid 456 mg) and then cholic acid (469 mg) was added to facilitate micelle formation. The mixture was dissolved in 30 mL of methanol/chloroform (1:1, v/v) solution. The solvent was evaporated using a rotating evaporator at 37 °C to produce a lipid film, which was dried under vacuum. This lipid film was dissolved in 30 mL of 10 mM TAPS buffer without NaCl at pH 8.4, followed by sonication to obtain a suspension of uniform micelles. One gram of CDDP3 was completely dissolved in 70 mL of 10 mM TAPS (pH 8.4), without NaCl and the pH was readjusted to 8.4 with 1 M NaOH. The CDDP3 solution was then added to the micelle suspension described above. To subsequently remove cholic acid and free CDDP3, the micelle solution was ultrafiltrated with 10 mM TAPS (pH 8.4) using an ultrafiltration cell holder (Amicon model 8200, Millipore, Billerica, MA) fitted with an ultrafiltration disc membrane (molecular cut off 10,000) (Amicon PM10, Millipore, Billerica, MA). One hundred milliliter of the liposome encapsulated CDDP3 was obtained. To convert CDDP3 in the liposomes into CDDP, the buffer was exchanged to 10 mM TAPS, pH 8.4, containing 150 mM NaCl by ultrafiltration through an ultrafiltration disc membrane (molecular cut off: 300,000) (Amicon XM300, Millipore, Billerica, MA). Hydrophilization treatment and SLX conjugation on the surface of liposomes were carried out as described previously (Hirai et al., 2007a). To exchange buffer, the solution was ultrafiltrated with sodium 5 mM hydrogencarbonate buffer (CBS, pH 8.5) through Amicon XM300 membrane. One hundred milligram of the crosslinking agent BS_3 was added to 100 mL of the liposome solution, and stirred at 25 °C for 2 h. The suspension was then further stirred overnight at 4 °C after which BS_3 was conjugated to the liposome surface. Four hundred milligram of Tris was then added, and stirred at 25 °C for 2 h and further stirred overnight at 4 °C to bind Tris to BS_3. The suspension was ultrafiltrated with 10 mM TAPS (pH 8.4) through an Amicon XM300 membrane to remove any residual Tris. Human serum albumin (HSA) was coupled to the liposome surface as previously described (Yamazaki, 1989; Yamazaki et al., 1994). To oxidize the liposome surface, 108 mg of sodium periodate was added to 100 mL of the liposome solution and stirred at 4 °C overnight. To remove residual sodium periodate, the suspension was ultrafiltrated with 10 mM phosphate saline buffer (PBS, pH 8.0) through an Amicon XM300 membrane. Two hundred mil-

ligram of HSA was then added to the suspension and stirred at 25 °C for 2 h. Then 31.3 mg of sodium cyanoborohydrate was added, and stirred at 25 °C for 2 h and further overnight at 4 °C. To remove any residual sodium cyanoborohydrate, the solution was ultrafiltered with CBS buffer (pH 8.5) through an Amicon XM300 membrane. SLX was conjugated to the liposome surface through DTSSP. One hundred milligram of DTSSP, a crosslinking agent, was added to 100 mL of liposomes solution, and stirred at 25 °C for 2 h, and further overnight at 4 °C. To remove residual DTSSP, the solution was ultrafiltrated with CBS buffer (pH 8.5) through an Amicon XM300 membrane. The amination of the reducing group terminal of SLX was accomplished through the glycosyl amination reaction. Eight milligram of SLX was dissolved in 2 mL of distilled water. One gram of ammonium hydrogencarbonate was added and stirred at 37 °C for 3 days. Aminated SLX was added to reach a final concentration of 50 μg/mL and stirred at 25 °C for 2 h. Tris was then added to a final concentration of 132 mg/mL, and stirred overnight at 4 °C for repeated hydrophilization of the liposome surface. To remove any residual SLX and Tris, the solution was ultrafiltrated with 20 mM HEPES (pH 7.2) through an Amicon XM300 membrane. The preparation of liposomes without SLX was similar to the CDDP-SLX-Lip case except for the process for binding SLX. In the studies using animals, CDDP-Lip and CDDP-SLX-Lip were further concentrated 20-fold by ultrafiltration with 20 mM HEPES buffer (pH 7.2) using an Amicon XM300 membrane.

2.5. Physiochemical characterization of CDDP-SLX-Lip

Average particle size and zeta-potential of liposomes that were prepared in water were determined by dynamic light scattering spectrophotometry (Zetasizer Nano-S90, Malvern, Worcestershire, UK) at 25 °C. The instrument was calibrated with standard latex nanoparticles (Malvern, Worcestershire, UK). Experimental values were the average of three different formulations.

2.6. Analysis of lipid concentration

Lipid concentrations of CDDP-Lip and CDDP-SLX-Lip were measured as total cholesterol in the presence of 0.5% TritonX-100 using a Determiner TC555 kit. The lipid concentration was calculated from the molar ratio of each lipid (4.5) by the following formula (Eq. (1)):

$$\text{lipid concentration (mg/mL)} = \text{cholesterol concentration (mg/mL)} \times 4.5 \quad (1)$$

2.7. Measurement of CDDP, calculation of CDDP concentration and definition of encapsulation efficiency and loading efficiency

CDDP-SLX-Lip were diluted to 10,000-fold with distilled water and the concentration of platinum was measured using automatic a flameless atomic absorption spectrophotometer (FAAS) (Model AA-6700, Shimadzu, Kyoto, Japan). Potassium dichloroplatinate was used as a standard. A calibration curve with platinum concentrations in the range of 50–250 ng/mL was run before analysis of each sample type. The amounts of CDDP were calculated by the following formula (Eq. (2)):

$$\text{CDDP concentration} = A \times \frac{300}{195} \quad (2)$$

where A is the concentration of platinum, 300 is the molecular weight of CDDP, and 195 is the molecular weight of platinum. "Encapsulation efficiency" and "loading efficiency" were defined by the following formula Eqs. (3) and (4), respectively.

$$\text{encapsulation efficiency (\%)} = \frac{\text{amount of CDDP in liposomes}}{\text{initial amount of CDDP}} \times 100 \quad (3)$$

$$\text{loading efficiency} = \frac{\text{CDDP concentration (mg/mL)}}{\text{lipid concentration (mg/mL)}} \quad (4)$$

Namely, "CDDP to lipid weight ratio" was defined as "CDDP loading efficiency".

2.8. ^{195}Pt NMR analysis

CDDP-SLX-Lip were concentrated by ultrafiltration using an Amicon XM300 membrane, and suspended in D_2O to a final platinum concentration of 137 mM. CDDP and CDDP3 were dissolved in D_2O to final concentrations of 6.6 and 137 mM, respectively. Sodium hexachloroplatinate was dissolved in D_2O to a final concentration of 50 mM as the external standard liquid. Each sample was put into 5-mm-width NMR sample tubes (GL Sciences, Tokyo, Japan) and ^{195}Pt NMR spectra were measured at 25 °C using NMR system (Model INOVA-600, Varian, Palo Alto, CA, USA).

2.9. Evaluation of CDDP leakage from CDDP-SLX-Lip

CDDP-SLX-Lip were stored in 20 mM HEPES buffer (pH 7.2) at 4 °C for 3 months. To remove any CDDP leakage from CDDP-SLX-Lip, the liposomes solution was ultrafiltrated using an Amicon XM300 membrane. The concentration of platinum incorporated into the liposomes was measured by FAAS and the amount of CDDP was calculated as described above. The CDDP concentration in CDDP-SLX-Lip after storage for 3 months was compared with that of CDDP in the liposomes immediately after preparation.

2.10. Acute toxicity evaluation

CDDP (18 and 25 mg CDDP/kg body weight), CDDP-SLX-Lip (18, 25 and 50 mg CDDP/kg body weight), saline solution and empty liposomes with SLX (lipid: 700 mg/kg body weight) were administered into the tail veins ($n = 4$) of female BALB/c mice (8 weeks) and the survival rate was examined for 14 days after administration. The lipid dose of empty liposomes with SLX was adjusted to the lipid dose in the case of CDDP-SLX-Lip at 50 mg CDDP/kg body weight. The body weight was measured simultaneously as an indicator of systemic toxicity. Body weight was measured for 5 days after administration with electric balance (Model EK-600i, A &D, Tokyo, Japan). Body weight (%) was calculated by the following formula Eq. (5).

$$\text{body weight (\%)} = \frac{\text{body weight at measurement day after injection}}{\text{body weight before injection}} \times 100 \quad (5)$$

The statistical analysis of the body weight change data were carried out by Mann–Whitney U-test.

For histological and histochemical analysis, CDDP or CDDP-SLX-Lip were injected into the tail vein of normal mice with a dose of either 25 mg CDDP/kg body weight. The kidney, spleen and liver were excised at 3 days after administration and fixed in 10% neutral formalin solution. Paraffin-embedded 2 μm-thick sections were stained with hematoxylin and eosin (HE). TUNEL staining was carried out to detect apoptosis with an in situ apoptosis detection kit followed by HE staining.

All the animal experiments throughout this study were conducted in full compliance with local and national ethical and regulatory principles for animal care.

2.11. Cell cultures

EAT cells and A549 cells were cultured in DMEM supplemented with 10% heat-inactivated FBS, 100 U/mL penicillin and 100 μg/mL streptomycin at 37 °C under atmosphere of 5% CO_2/95% air. HUVEC was cultured in medium for HUVEC (KJB-110, DS Pharma, Japan) supplemented with 10% FBS, 100 U/mL penicillin and 100 μg/mL streptomycin at 37 °C under atmosphere of 5% CO_2/95% air.

2.12. Detection of E-selectin on HUVEC

Anti-E-selectin monoclonal antibody was prepared from the ascites fluid of female Balb/c mice (8 weeks), which received CCL-3 hybridoma. Glass slides in 12-well plates were seeded with 1×10^5 HUVEC per well and cells were incubated in 500 μL of medium at 37 °C for 24 h. EAT cells were cultured until 100% confluent. Five hundred microliter of the supernatant culture medium of EAT or the complete medium of EAT was added to 500 μL of the culture medium of HUVEC. TNF-α was added at 10 ng/mL and HUVEC were cultured for 4 h at 37 °C under atmosphere of 5% CO_2/95% air. After 4 h, HUVEC were then fixed with 3.7% formaldehyde in PBS and at room temperature for 15 min and washed twice with PBS and 0.1% TritoX-100 in PBS. 0.1% of BSA in PBS was added to the each well and incubated at room temperature for 20 min. Anti-E-selectin monoclonal antibody was added at 10 μg/mL and incubated at room temperature for 1 h. HUVEC were then washed twice with PBS, stained with 5 μg/mL FITC labeled anti-mouse polyclonal antibody at room temperature for 1 h and washed twice with PBS. For staining cytoskeleton, rhodamine phalloidin was added at 5 U/mL to HUVEC cultures and incubated at room temperature for 20 min and washed twice with PBS and water. The fluorescence of FITC and rhodamine was observed with fluorescent microscope (Model CKX41, Olympus, Tokyo, Japan).

2.13. Detection of E-selectin in vascular vessels of EAT tumor section

EAT cells (5×10^6 cells/mouse) were transplanted subcutaneously in the back of female BALB/C nude mice. After 10 days, tumors were excised and fixed in 10% neutral formalin solution (Wako) for 24 h. After fixation, the tissues were dehydrated, cleared, infiltrated and embedded with paraffin. Then 4 μm-thick sections were cut out for hematoxylin and eosin (HE) staining and for double immunohistochemistry. For immunological staining, sections were deparaffinized and blocked with 10% goat serum containing 3% TritonX-100 for 1 h at room temperature, sections were incubated with anti-E-selectin antibody (10 μg/mL) for 1 h at 37 °C and rinsed three times in PBS for 5 min each. Then sections were further incubated with FITC labeled goat anti-mouse IgG antibody (Santa Cruz) and *lycopersicon esculentum* lectin (LEL) conjugated with Texas red (Vector Labs) for 1 h at room temperature followed by three times of wash with PBS for 5 min. The sections were mounted with glycerol–PBS (9:1) and observed under an Olympus IX81 microscope equipped with a light fluorescence device (Olympus).

2.14. Targeting tumor of CDDP-SLX-Lip

To prepare EAT tumor-bearing mice, 5×10^6 cells were subcutaneously injected into the right femoral region of 6-week-old female BALB/c mice. Ten days after injection, CDDP-SLX-Lip, CDDP-Lip or CDDP were injected into the tail veins at a dose of 2 mg CDDP/kg body weight. At 48 h after administration, the tumors were excised and soaked in 1 mL of 70% HNO_3 per 0.1 g of each tumor tissue followed by incubation in a water-bath at 60 °C for 1 h. After being cooled to room temperature, supernatant was diluted 4-fold with distilled water. To determine the recovery of platinum, blank tumor tissues samples were spiked with 125 ng CDDP for 1 h, followed by digestion with nitric acid and dilution with distilled water. The amount of platinum in the tumor tissues was measured by FAAS and the amounts of CDDP were calculated as described above. The recovery of platinum after incubation of tumor tissues with CDDP was 82–95%. The statistical analysis was carried out by the standard Student's *t*-test.

2.15. In vivo antitumor activity

To prepare A549 tumor-bearing mice, 1×10^7 cells were subcutaneously injected into the right femoral region of 6-week-old female BALB/c mice at 5, 12 and 19 days after injection, CDDP-SLX-Lip, CDDP-Lip or CDDP were injected into the tail veins at a dose of 25 mg CDDP/kg body weight ($n = 4$). Saline solution was injected into control group ($n = 4$). At 5, 12, 19 and 26 days after injection, the length and width of the tumors were measured using digital calipers (Model CD-20C, Mitsutoyo, Japan), and tumor volume was calculated by the following formula (Eq. (6)).

$$\text{volume } (\text{mm}^3) = \text{length} \times \text{width}^2 \times 0.5 \quad (6)$$

The statistical analysis was carried out by the standard Student's *t*-test.

3. Results

3.1. Conversion of CDDP3 to CDDP

CDDP has a structure coordinating chloride ions at the *cis* location (Fig. 1A) while CDDP3 has nitrate ions in place of chloride (Fig. 1B) with solubility in water about 10 times higher than that of

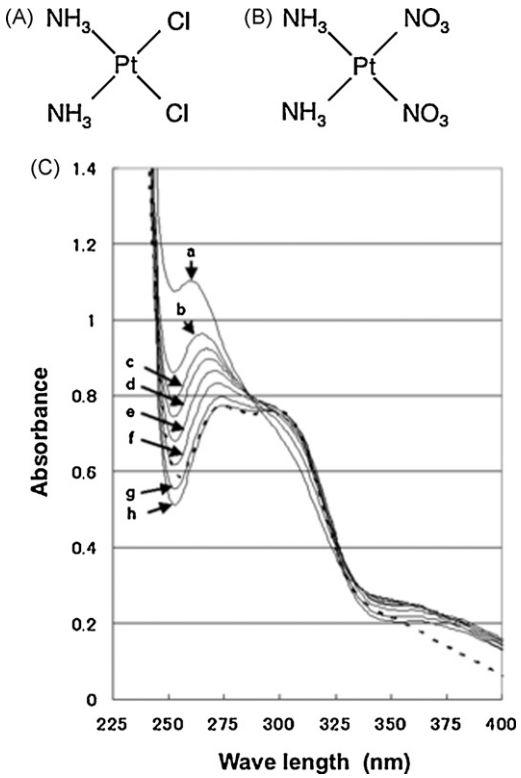

Fig. 1. Conversion from *cis*-diamminedinitratoplatinum (II) (CDDP3) to CDDP. Chemical structures of CDDP (A) and CDDP3 (B). (C) Time-dependent shifts in absorption spectrum of 13.7 mM CDDP3 placed in 150 mM NaCl solution for a, 0; b, 5; c, 10; d, 15; e, 30; f, 60; g, 120; h, 180 min. The dotted line shows the absorption spectrum of 6.6 mM CDDP solution at 24 h after dissolving in 150 mM NaCl solution.

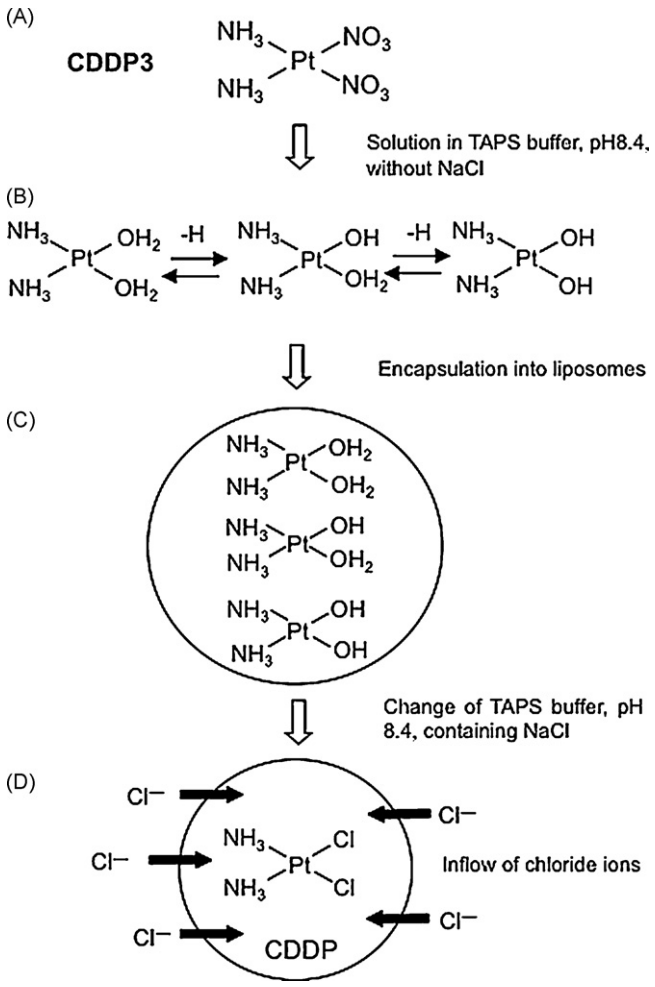

Fig. 2. Scheme of CDDP encapsulation into liposomes using CDDP3. (A) CDDP3 in TAPS, pH 8.4, without NaCl. (B) CDDP3 is in a reversible equilibrium state where H_2O molecules are coordinated due to high solubility of CDDP3 in water. (C) CDDP3 are incorporated in liposomes at this stage, they will show various molecular forms in the liposomes. (D) Change of buffer TAPS, pH 8.4, containing 150 mM NaCl, makes flow of chloride ions into the liposomes and then CDDP is produced by forming coordinate bonds preferentially with chloride ions.

CDDP. The absorption spectra showed that CDDP3 gradually converted to CDDP during incubation in 150 mM NaCl for 24 h (Fig. 1C). Since CDDP3 is soluble in water and stable under chloride ion free conditions, encapsulation of CDDP3 into liposomes at high concentrations as depicted in Fig. 2 should be feasible since the low solubility of CDDP in water impairs encapsulation into liposomes. CDDP3 was encapsulated into liposomes with SLX and the conversion to CDDP in the presence of chloride ions was monitored as the chemical shift (δ) by ^{195}Pt NMR. The chemical shifts of ^{195}Pt were referenced to sodium hexachloroplatinate ($\delta = 0$ ppm). After incubation of CDDP3-encapsulated liposomes with chloride ion for 96 h, the chemical shift (δ) indicated only −2160 ppm, which is identical to the chemical shift (δ) of CDDP (Fig. 3). No chemical shift of CDDP3 ($\delta = -1620$ ppm) was detected indicating that CDDP3 in SLX liposomes efficiently converted to CDDP in the presence of chloride ions. The chemical shifts of −1620 ppm and −2160 ppm are consistent with those of CDDP3 and CDDP, respectively, as described by Rosenberg (1978).

3.2. Characterization of CDDP liposomes prepared from CDDP3

Encapsulation of CDDP in liposomes under various conditions was summarized in Table 1. When encapsulation was started with

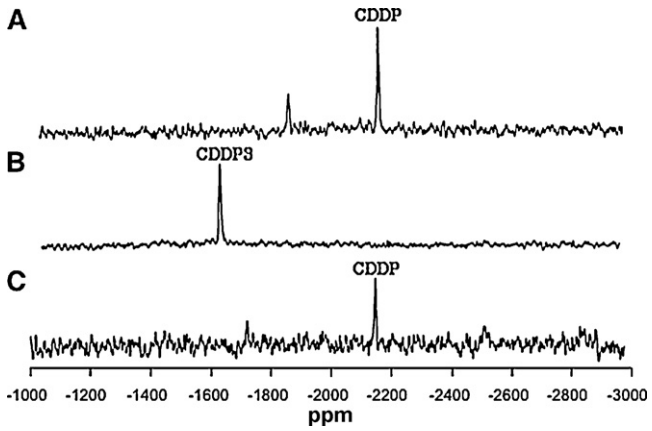

Fig. 3. Conversion of CDDP3 in the liposomes with SLX to CDDP detected by ^{195}Pt NMR. (A) 6.6 mM of CDDP in deuterium oxide; (B) 137 mM of CDDP3 in deuterium oxide; (C) CDDP3 encapsulated liposomes with SLX were treated with 150 mM NaCl for 96 h.

10 mg of CDDP3 and 4.5 mg of lipid, the resultant quantity of CDDP incorporated into SLX-Lip was 211 μg CDDP/3.5 mg lipid/mL and the loading efficiency was 6×10^{-2}. It is important to note that the quantity of CDDP in SLX-Lip increased from 211 μg to 821 μg depending on the amount of lipid. However, it was difficult to make the encapsulation efficiency higher than 10%. Since we found the loading efficiency was almost constant during the course of experiment, we took the loading efficiency as a parameter specific to the encapsulation method. On the other hand, the quantity of CDDP in SLX-Lip was 0.7 μg CDDP/3.5 mg lipid/mL and the loading efficiency was 2×10^{-3} when CDDP was directly encapsulated into liposomes. Actually 1.4 mg was the maximum amount of CDDP for encapsulation while 10 mg was available for CDDP3 in a similar condition. Thus, CDDP3 dramatically improved CDDP encapsulation by almost 300 times in quantity and 42 times in encapsulation efficiency when compared with direct encapsulation of CDDP into liposomes at the initial lipid amount of 4.5 mg. The CDDP loading efficiency appeared to be improved 30 times. The CDDP loading efficiency was improved by almost 4 times when compared with that of 1.4×10^{-2} for SPI-077 (Harrington et al., 2001; Kim et al., 2001). We successfully concentrated CDDP-SLX-Lip and CDDP-Lip up to 4.2 mg CDDP/70 mg lipid/mL, which was 20 times more than the concentration of CDDP in SPI-077. Dynamic laser scattering of the CDDP-SLX-Lip prepared from CDDP3 showed a mean diameter of about 160 nm (Table 1). The ζ potential of the liposomes was negative irrespective of the material of encapsulation (Table 1). Even after 6 months of storage at 4 °C, the leakage of CDDP from liposomes was only about 6% of the total amount of CDDP incorporated into liposomes just after preparation.

3.3. In vivo acute toxicity

The acute toxicity of CDDP-SLX-Lip was evaluated in normal mice by injection via tail veins. The mice were observed for 14 days after injection. The survival rate was 75% when mice received CDDP-SLX-Lip at doses of 18 or 25 mg CDDP/kg body weight. In contrast, the survival rates were 25% and 0% when mice received CDDP at doses of 18 and 25 mg CDDP/kg body weight, respectively (Fig. 4A). The mice did not die when they received empty liposomes with SLX. From these results encapsulation of CDDP in liposomes was found remarkably effective to protect mice from toxicity. This effect of encapsulation was not only recognized in the survival rate but also in the loss of body weight. When CDDP was administered at doses of 18 mg CDDP/kg body weight and 25 mg CDDP/kg body weight, the loss of body weight was 20% during 5 days and 25% during 4 days, respectively. The mice, which received CDDP-SLX-Lip at

Table 1
Physicochemical characteristics of CDDP liposomes prepared with CDDP or CDDP3 ($n = 3$).

	Method of encapsulation			
	I[a]	II[b]		
CDDP (mg)[c]	1.4	0	0	0
CDDP3 (mg)[c]	0	10	10	10
Lipid (mg)[c]	4.5	4.5	9	18
Lipid concentration (mg/mL)[d]	3.5 ± 0.4	3.5 ± 0.3	7.8 ± 0.5	16.5 ± 0.8
Particle size (nm)[e]	158 ± 6.5	150 ± 5.7	152 ± 5.5	160 ± 6.2
ζ potential (mV)	−57 ± 5.3	−55 ± 2.8	−50 ± 3.8	−54 ± 5.2
CDDP concentration (μg/mL)[f]	0.7 ±0.2	211 ± 8	402 ± 0.5	821 ± 0.3
CDDP encapsulation efficiency (%)[g]	0.05	2.11	4.02	8.21
CDDP loading efficiency[h]	2×10^{-3}	6×10^{-2}	5×10^{-2}	5×10^{-2}

[a] Direct encapsulation of CDDP into liposomes.
[b] Encapsulation of CDDP3 into liposomes followed by conversion into CDDP in TAPS buffer containing NaCl.
[c] Initial amount used to prepare 1 mL of CDDP liposome.
[d] Total cholesterol in CDDP liposome solution was measured using a Determiner TC555 Kit.
[e] Measured by photon correlation spectroscopy with a Nano-S90 (Malvern). Polydispersity index was between 0.1 and 0.5 in each case.
[f] The amount of platinum was measured and the amount of CDDP was calculated as defined by Eq. (2) in Section 2.7.
[g] Encapsulation efficiency was calculated as defined by Eq. (3) in Section 2.7.
[h] Loading efficiency was calculated as defined by Eq. (4) in Section 2.7.

the dose of 18, 25 and 50 mg CDDP/kg body weight, showed the loss of body weight by about 15% during 3 days and recovered the loss by less than 10% during 5 days (Fig. 4B). Liposomes without CDDP had no significant effect on the body weight. These results support the possibility that CDDP-SLX-Lip can significantly reduce the toxicity of CDDP *in vivo*.

3.4. Effect of CDDP-SLX-Lip on normal tissues

The effect of CDDP-SLX-Lip and CDDP on normal tissues of mice was histologically evaluated (Fig. 5). Kidney, spleen and liver were excised from mice, which received a dose of 25 mg CDDP/kg body weight. Since mice died at day 4 from the injection of CDDP, tissues were prepared at day 4 after injection. Tissues were stained with HE and by TUNEL method to assess for apoptosis. Abnormal changes were not found in the kidney in mice which received both CDDP-SLX-Lip and CDDP (Fig. 5a,c) but TUNEL positive tubular epithelial cells were sporadically detected after CDDP treatment (Fig. 5d). CDDP-SLX-Lip treatment also did not produce any abnormal changes in the spleen (Fig. 5e,f). However, CDDP treatment of mice induced atrophy of the follicles with necrosis and a decrease in cell number in the white pulp (Fig. 5g). In follicles, phagocytosed dead lymphocytes were observed. TUNEL positive cells were also found in the white pulp (Fig. 5h). In liver, abnormal cells and TUNEL positive cells were not found after the administration of either CDDP-SLX-Lip (Fig. 5i,j) or CDDP (Fig. 5k,l).

3.5. Induction of E-selectin on HUVEC by EAT cells

Since SLX can bind to E-selectin, it is important to ascertain whether E-selectin expression occurs or can be induced on vascular endothelial cells in the tumor to validate tumor targeting. As shown in Fig. 6, E-selectin expression was induced on HUVEC, when stimulated by TNF-α. Although not all tumors may produce TNF-α, it is possible that tumors should express multiple cytokines, which can through a paracrine mechanism induce E-selectin expression on surrounding endothelial cells. The conditioned medium of EAT cells was in fact able to induce E-selectin expression on HUVEC in vitro while control medium did not (Fig. 6).

3.6. Expression of E-selectin on vascular endothelial walls in tumor

The thin section prepared from the solid EAT tissue was subjected to the assessment for the expression of E-selectin on vascular endothelial walls in the tumor. As shown in Fig. 7, E-selectin and blood vessels in the section were stained with anti-E-selectin antibody and LEL, which has specific affinity to fucose on the vascular endothelial cells. Since the sites of E-selectin expression agreed well with vascular walls, the vascular endothelial cells were judged to express E-selectin in the tumor tissue. These results as well as those in HUVEC suggest that the angiogenic vascular endothelial cells in EAT can be stimulated by cytokines or factors that are secreted from EAT cells to induce E-selectin expression.

3.7. Accumulation of CDDP in tumors

We previously reported that the accumulation of liposomes with SLX in the tumor was highest at 48 h after injection when evaluated by *in vivo* imaging using Cy5.5-encapsulated liposomes with SLX (Hirai et al., 2007a). On the basis of these data, the accumulation of CDDP-SLX-Lip in tumors was evaluated at 48 h after injection. CDDP-SLX-Lip or CDDP-Lip were independently administrated into the tail veins of mice bearing EAT tumors. The accumulation of CDDP in the tumors was evaluated by the amount of platinum derived from CDDP at 48 h after injection. The accumulation of CDDP from CDDP-SLX-Lip in the tumors was 6 times higher than that by CDDP-Lip indicating the potential targeting ability of CDDP-SLX-Lip *in vivo* (Fig. 8).

3.8. Antitumor effect of CDDP-SLX-Lip in vivo

The antitumor effect of CDDP-Lip and CDDP-SLX-Lip was evaluated in a mouse xenograft model of A549 lung carcinoma cells because CDDP is widely used for the treatment of lung carcinoma. When CDDP was administrated at 25 mg/kg body weight, all mice died at day 4 after injection. The volume of the tumors that were exposed to either CDDP-Lip or CDDP-SLX-Lip was significantly smaller than that of the non-treated tumors. A difference in tumor volumes between the two different CDDP containing liposomes could not be detected until 12 days after injection. CDDP-SLX-Lip suppressed the growth of tumors much more effectively than CDDP-Lip 19–26 days after injection. Suppression of tumor growth by CDDP-Lip (arrow a in Fig. 9) could be attributed to an enhanced permeability and retention effect (EPR). Further suppression induced by CDDP-SLX-Lip (arrow b in Fig. 9) might be accounted for by the effect of active targeting through the binding of SLX to the tumor vascular endothelial cells.

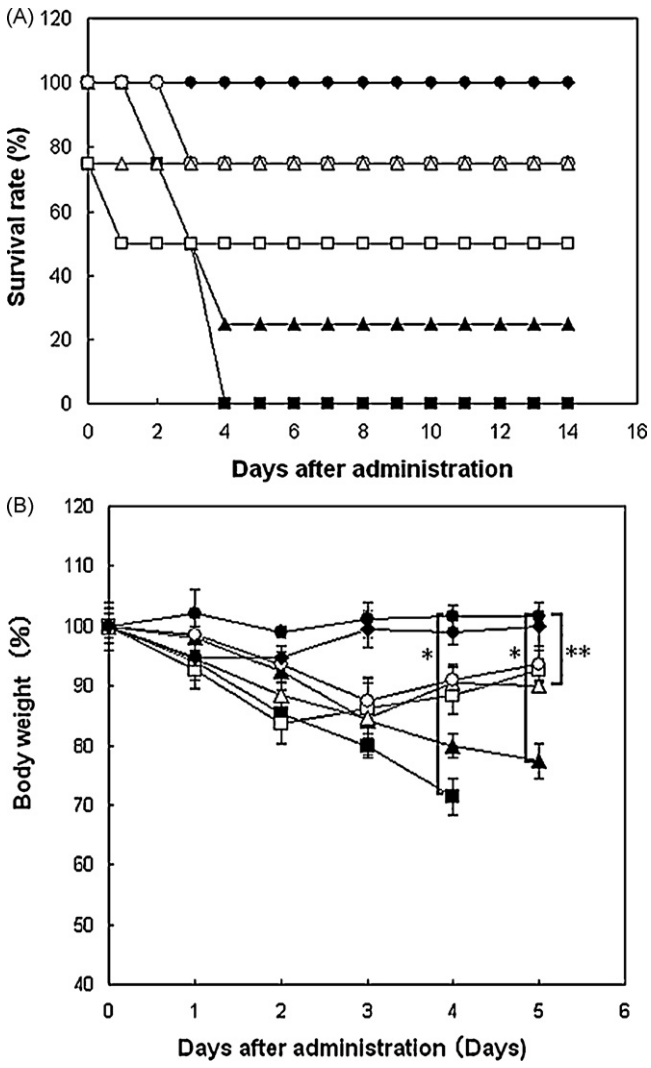

Fig. 4. Survival rate and body weight change of normal mice that received CDDP-SLX-Lip. (A) Survival rate (%); (B) body weight (%). Keys: ▲, CDDP solution (18 mg CDDP/kg body weight); ■, CDDP solution (25 mg CDDP/kg body weight); ○, CDDP-SLX-Lip (18 mg CDDP/kg body weight); △,CDDP-SLX-Lip (25 mg CDDP/kg body weight); □, CDDP-SLX-Lip (50 mg CDDP/kg body weight); ♦, empty liposomes; ●, saline solution. Each sample was injected into normal mice (female, 8 weeks) via tail veins. Results are expressed as the mean ($n = 4$); bars, ±SE. $^{*}P < 0.005$; **not significant ($P > 0.05$).

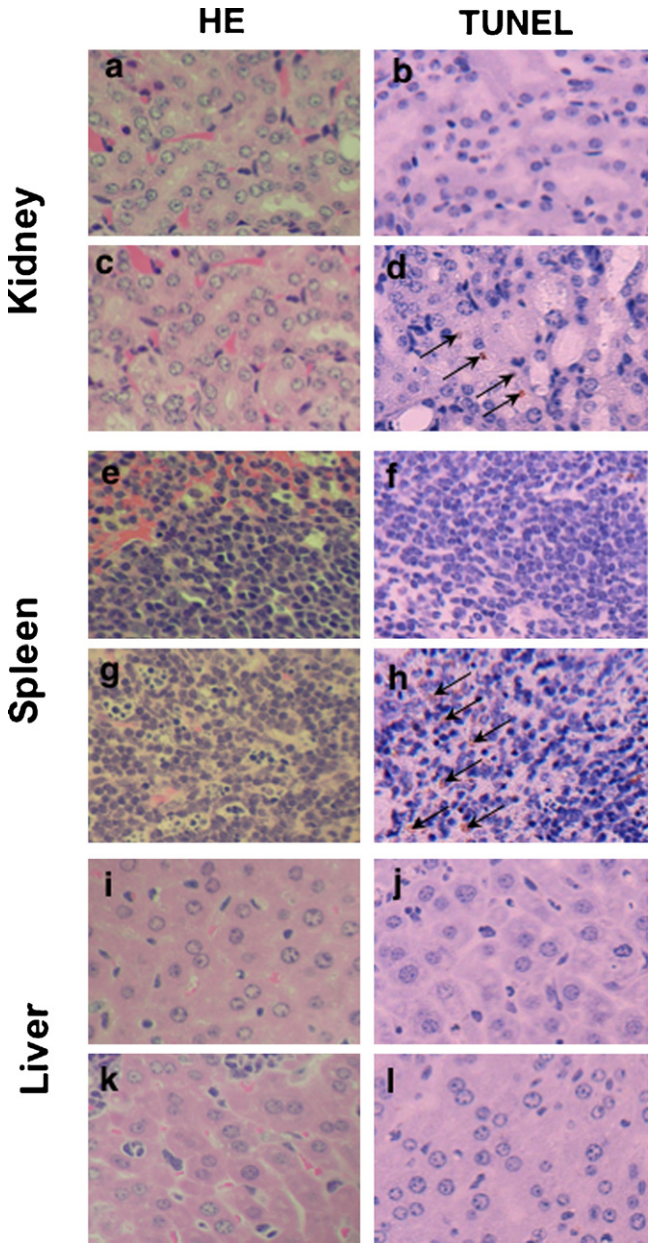

Fig. 5. Histochemical analysis of organs, which received CDDP and CDDP-SLX-Lip. CDDP-SLX-Lip (a, b, e, f, i, j) or CDDP (c, d, g, h, k, l) was injected into each normal mouse (Balb/c, female, 8-week-old) via tail veins at the dose of 25 mg CDDP/kg body weight. At 3 days after administration, kidney (a, b, c, d), spleen (e, f, g, h) and liver (i, j, k, l) were excised and fixed. HE staining (a, c, e, g, i and k) and TUNEL immunohistochemical staining (b, d, f, h, j and l) of the slices were observed. Black arrows indicate TUNEL positive cells. Objective lens was 60×.

4. Discussion

Here we have established a simple and novel method to encapsulate CDDP into liposomes at significantly high concentrations. We then applied this methodology to generate liposomes containing SLX to selectively target tumors and to substantially eliminate or reduce the deleterious and toxic side effects of high dose of CDDP. To achieve high concentrations of CDDP that could be encapsulated into liposomes, we chose to use CDDP3. Since CDDP3 is a hydrophilic derivative of CDDP and readily converts to CDDP in the presence of chloride ions (Fig. 1C), the entire encapsulation procedure could be executed in an aqueous phase. As shown in Fig. 2, CDDP3 was first dissolved at a saturated concentration in a buffer without chloride ions and encapsulated into liposomes. CDDP3 in the liposomes was then converted into CDDP by replacing buffer with buffer containing 150 mM NaCl. As the result, the CDDP encapsulation efficiency and the CDDP loading efficiency were drastically improved when compared with the conventional method of directly encapsulating CDDP. The CDDP loading efficiency in CDDP-SLX-Lip was improved by almost 4 times even when compared with the antecedent CDDP liposome, SPI-077 (Harrington et al., 2001; Kim et al., 2001). The amount of CDDP encapsulated in this study was considerably higher than could be accounted for by the enhanced solubility of CDDP3 in water as compared to CDDP. The negatively charged surface of the liposomes was designed to avoid being bound by blood proteins, such as opsonin, as well as to enhance the retention in blood. CDDP3 in aqueous solution is positively charged, so that it is conceivable that CDDP3 can be electrostatically bound to negatively charged lipids when encapsulated into liposomes.

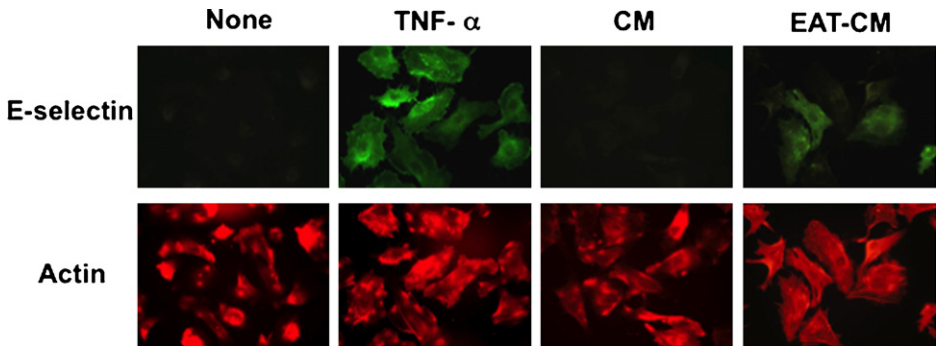

Fig. 6. Evaluation of E-selectin expressed on HUVEC. Cells were cultured in medium for HUVEC supplemented 10% FBS (None), or with 10 ng/mL of TNF-α (TNF-α), in DMEM supplemented 10% FBS (CM), or with EAT cultured DMEM supplemented 10% FBS (EAT-CM) for 4 h. To detect E-selectin, anti-E-selectin antibody was used followed by FITC labeled anti-mouse IgG polyclonal antibody (E-selectin). Actin filaments were stained with rhodamine labeled phalloidin (Actin). The magnification was 40×.

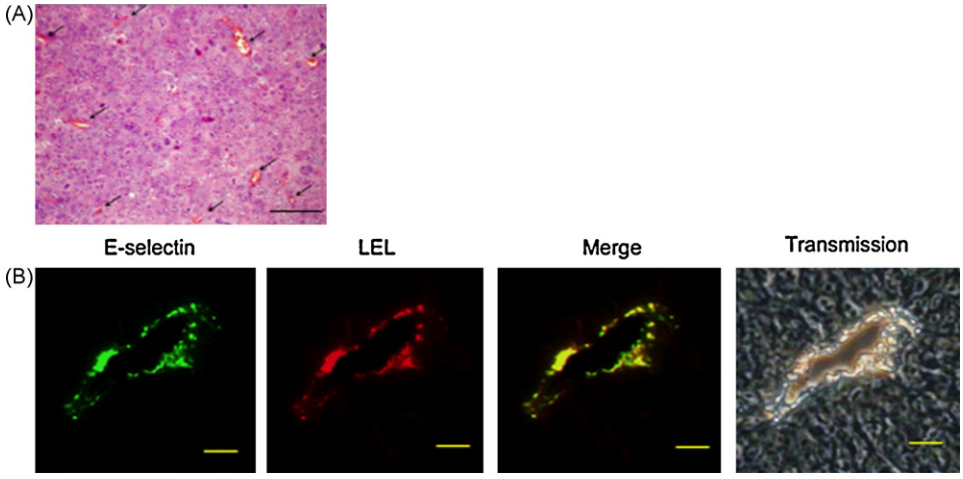

Fig. 7. The expression of E-selectin in vascular vessels of solid EAT. (A) HE staining of the section. Arrows indicated locations of vascular vessels. Scale bar: 100 μm. (B) Vascular vessel stained for E-selectin and for LEL. After deparaffinized, the section was incubated with anti-E-selectin antibody (10 μg/mL) for 1 h at 37 °C, then incubated with FITC labeled goat anti-mouse IgG and LEL conjugated with Texas red for 1 h at room temperature. Merge, colocalization of E-selectin and vascular endothelial cells was shown in yellow. Scale bar showed 20 μm.

The mean diameter of CDDP-SLX-Lip particle in the present study was about 160 nm (Table 1). Due to the SLX moiety, CDDP-SLX-Lip more than likely bind to the E-selectin on tumor vascular endothelial cells where they may enter the gaps between endothelial cells of the capillary bed, which are in the range of 100–300 nm and thereby penetrate into the tumor (Drummond et al., 1999; Gabizon, 1992; Huang et al., 1992, 1993; Wu et al., 1993).

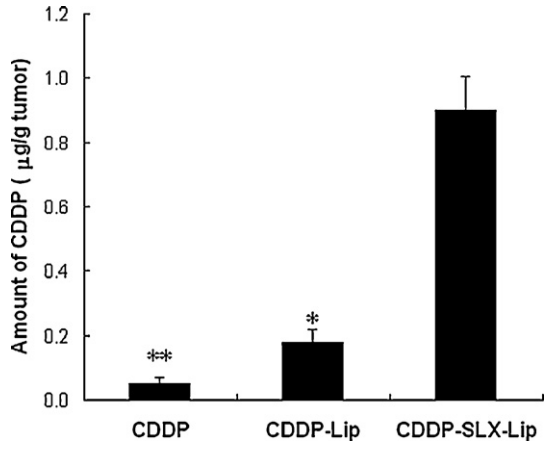

Fig. 8. Accumulation of CDDP in the tumor in vivo. At day 10 after transplantation of EAT cells, CDDP-SLX-Lip, CDDP-Lip or CDDP (2 mg/kg body weight as CDDP) were administered from tail veins of mice. At 48 h after injection the tumor tissues were excised and the amount of platinum were measured by FAAS. Results are expressed as the mean ± SD ($n = 3$). *$P < 0.01$ compared with CDDP-Lip. **$P < 0.005$ compared with CDDP.

CDDP-SLX-Lip were evaluated *in vivo* for acute toxicity and antitumor activity with target potential. The acute toxicity of CDDP was apparently and remarkably reduced by the encapsulation of CDDP in SLX liposomes. When CDDP was injected at 25 mg CDDP/kg body weight, significant toxicity in the kidney was not obvious by HE staining (Fig. 5c) and the TUNEL assay showed only a small number of positive cells in kidney (Fig. 5d). In this part of the study, the period between administration of CDDP and removal of tissues was 3 days, which was probably too short for CDDP to exhibit any significant nephrotoxicity. To observe more dramatic nephrotoxic effects of CDDP, it would probably require longer periods of administration at lower doses of CDDP. As for the acute toxicity, we can conclude that CDDP-SLX-Lip are relatively safe as drug when compared to CDDP with an excellent survival rate as shown in Fig. 4. It is noteworthy that CDDP-SLX-Lip loading of 25 mg CDDP/kg body weight showed significant antitumor activity in vivo (Fig. 9). While an EPR effect should allow the accumulation of CDDP-Lip in tumors (Matsumura and Maeda, 1986) active targeting by CDDP-SLX-Lip exhibited an additive effect. In this context, CDDP-SLX-Lip were more effective than CDDP-Lip at 19 and 26 days after administration (Fig. 9). The accentuated antitumor activity appearing in the late stages may be related to leakage of CDDP from CDDP-SLX-Lip into the tumor. Furthermore, the expression of E-selectin on tumor vascular endothelial cells may be upregulated by tumor-

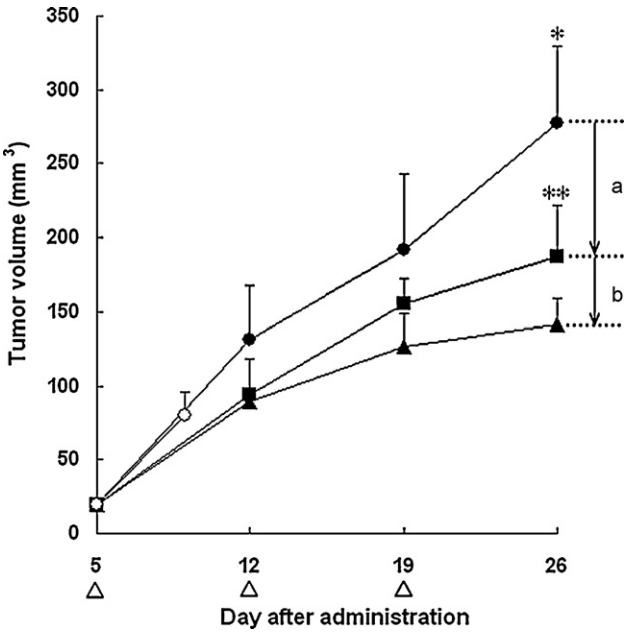

Fig. 9. Comparison of tumor growth suppression with CDDP-SLX-Lip, CDDP-Lip and CDDP in A549-bearing mice. Keys: ▲, CDDP-SLX-Lip (25 mg CDDP/kg body weight); ■,CDDP-Lip (25 mg CDDP/kg body weight); ○, CDDP solution (25 mg CDDP/kg body weight); ●, saline. Each sample was injected via tail veins of A549-bearing mice on days 5, 12 and 19 after tumor cell transplantation. At each day of 5, 12, 19 and 26 after transplantation, each tumor volume (mm^3) was measured. Each open triangle at the horizontal axis shows the time of administration. Results are expressed as the mean ± SD ($n = 4$). $^*P < 0.01$ compared with saline. $^{**}P < 0.05$ compared with CDDP-Lip. Vertical arrows indicate the effects of EPR (a) and active targeting (b).

derived vascular endothelial cell growth factor (VEGF) (Aoki et al., 2001), which could account for the enhanced antitumor activity of CDDP-SLX-Lip versus CDDP-Lip. CDDP-SLX-Lip might therefore be more effective than unconjugated CDDP on a wide range of tumors because a number of tumors are sensitive to VEGF-induced angiogenesis (Szekanecz et al., 1999).

Recently, the number of E-selectin-positive vessels was found to be higher in invasive micropapillary breast carcinoma than in invasive ductal carcinoma which was correlated with histological grade (Wei et al., 2008). Furthermore, TNF-α expression, which is known to induce E-selectin in vascular endothelial cells (Murakami et al., 2000), showed a significant positive correlation with the rate of proliferation, histological grade, lymph node metastasis and microvessel density (Cui et al., 2008). Targeting E-selectin should be a feasible and practical therapeutic strategy for breast carcinoma with poor prognosis. Further detailed studies such as distribution, clearance, toxicity, application for various tumor cells and doses with CDDP-SLX-Lip are underway.

5. Conclusion

We successfully established a novel efficient technology to encapsulate CDDP in liposomes at high concentrations. Targeting E-selectin on the vascular endothelial cells in tumor tissues by using CDDP-SLX-Lip should be effective in providing for selective tumor uptake.

The increased loading efficiency of CDDP together with the ability of targeting E-selectin are expected to enhance the pharmaceutical availability of CDDP and to improve the therapeutic index.

CDDP-SLX-Lip should provide a way of developing novel antitumor therapy with CDDP, decreasing the side effects without sparing the antitumor activity.

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