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In vitro and *in vivo* anti-tumor effects of novel Span 80 vesicles containing immobilized *Eucheuma serra* agglutinin

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ABSTRACT

The lectin *Eucheuma serra* agglutinin (ESA) is known from previous studies to specifically bind to high-mannose type *N*-glycans and to induce apoptotic cancer cell death *in vitro*. In this study, Span 80 vesicles, with an average diameter between about 200 and 400 nm, containing immobilized ESA were prepared from the nonionic surfactant Span 80, also known as sorbitan monooleate. The vesicles were investigated *in vitro* and *in vivo* to evaluate the vesicles's potential applicability as novel drug delivery system. The results obtained are promising since the following was observed: (i) vesicular ESA had the same hemagglutinating activity as free ESA, demonstrating its biological activity when bound to the vesicles; (ii) vesicles containing immobilized ESA decreased the viability of Colo201 cancer cells *in vitro* while the growth of normal cells was not affected; (iii) the vesicles showed binding to Colo201 cells *in vitro* and caused inhibition of cancer cell growth in nude mice to which the vesicle-treated cells were added; (iv) the vesicles diminished tumor growth after intravenous administration to nude mice which contained an implanted Colo201 tumor; (v) the vesicles showed a tendency to accumulate at the site of the tumor 6 h after *i.v.* administration to nude mice. Thus, all measurements carried out indicate that this type of Span 80 vesicle can be considered as promising alternatives to conventional phospholipid-based vesicles.

1. Introduction

In recent years there have been numerous investigations of novel drug delivery systems (DDS) for elucidating their applicability as drug carriers for the treatment of various diseases (Allen and Cullis, 2004; Ferrari, 2005; Lian and Ho, 2001; Peer et al., 2007; Couvreur and Vauthier, 2006). Phospholipid vesicles (liposomes), i.e. vesicles composed of natural phospholipids, are often used as DDS (Lian and Ho, 2001; Sharma and Sharma, 1997; Barenholz, 2001; Torchilin, 2005), e.g. for active targeting of specific colon cancer cells (Sato et al., 1988; Koning et al., 2002; Hatziantoniou et al., 2006; Garg et al., 2009). On the other hand, it has been demonstrated that nonionic vesicles prepared from Span 80 have promising physico–chemical properties (high membrane fluidity with temperature dependent fusiogenicity) which make this type of vesicle an attractive possible alternative to the commonly used liposomes (Kato et al., 1993; Kato and Hirata, 1996; Kato and Hirashita, 1997; Ohama et al., 2005; Sugahara et al., 2005). In the food and cosmetic industries, Span 80 is generally known as sorbitan monooleate, although commercial Span 80 is a heterogeneous mixture of sorbitan mono-, di- tri, and tetraesters (Kato et al., 2006).

Span 80 vesicles can be prepared by a recently developed two-step emulsification method which yields vesicles with a membrane composition which is significantly different from commercial Span 80 (Kato et al., 2006). The bilayer membrane of Span 80 vesicles forms under thermodynamic control during the vesicle preparation, with partial elimination of those components present in commercial Span 80 which hinder formation of stable bilayers. Span 80 vesicles have rather fluid membranes; addition of soybean

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lecithin and cholesterol (at 9 and 4.5 wt%, respectively) lead to a stabilization of the membrane with a lowering of the membrane permeability (Kato et al., 2008). Furthermore, the two-step emulsification allows the preparation of vesicles with relatively high encapsulation yields for water soluble molecules by entrapping the molecules as inner phase solution, just before the first emulsification is carried out (Figure S1 in Supplementary Material, and Kato et al., 2006; Kato et al., 2008).

Tumor-specific "active targeting" is often achieved by immobilizing tumor-specific ligands such as antibodies, peptides or saccharides onto liposomal drug carrier systems (Peer et al., 2007; Torchilin, 2005; Forssen and Willis, 1998). While most tumor-specific ligands have no intrinsic anti-tumor activity, several lectins are known to possess anti-tumor activity against human cancer cells (Karasaki et al., 2001; Timoshenko et al., 2001; Wang et al., 2000). In this case targeting and anti-tumor activity are combined in one and the same molecule. One particular lectin with such "dual activity" is the lectin *Eucheuma serra* agglutinin (ESA) (Kawakubo et al., 1997). It can be extracted in the two isoforms ESA-1 and ESA-2 from marine red algae (Kawakubo et al., 1997). ESA-1 and ESA-2 have the same molar mass (27,950 g/mol) but differ in isoelectric points (pI = 4.75 for ESA-1 and pI = 4.95 for ESA-2) (Kawakubo et al., 1997). ESA-2 is specific for high-mannose type *N*-glycans (Hori et al., 2007). We have previously shown that ESA has a specific affinity to various cancer cells (specifically to the human colon cancer cell line Colo201), inducing apoptotic cell death *in vitro* (Sugahara et al., 2001) and *in vivo* (Fukuda et al., 2006).

In the work presented we have prepared Span 80 vesicles containing immobilized ESA and measured the activity of these vesicles against tumor cells *in vitro* and *in vivo*. Since ESA has a high affinity to Colo201 cells (see above), these cells were mainly chosen to investigate the tumor targeting properties of the vesicles. Different types of vesicles were prepared as reference systems and the anti-tumor activity of the different types of vesicles was compared by using a number of independent methods.

Contemporary liposomal DDS often contain poly(ethyleneglycol), PEG, immobilized onto the liposome surface. These "PEGylated liposomes", also called "stealth liposomes", generally show a decreased uptake by the reticuloendothelial system (RES), i.e. a prolonged blood circulation time, as compared to conventional liposomes (Couvreur and Vauthier, 2006; Zeisig et al., 1996). For this reason, we also prepared and used for *in vivo* studies PEGylated Span 80 vesicles. The different Span 80 vesicles prepared were as follows (Fig. 1): **CV**, "control vesicles", i.e. Span 80 vesicles without PEGylated lipids or ESA; **PV**, Span 80 vesicles containing PEGylated lipids (DSPE-PEG_{2000}); **EV**, Span 80 vesicles containing immobilized ESA; **EPV**, Span 80 vesicles containing PEGylated lipids and immobilized ESA; **EEPV**, Span 80 vesicles containing PEGylated lipids, immobilized ESA and entrapped ESA.

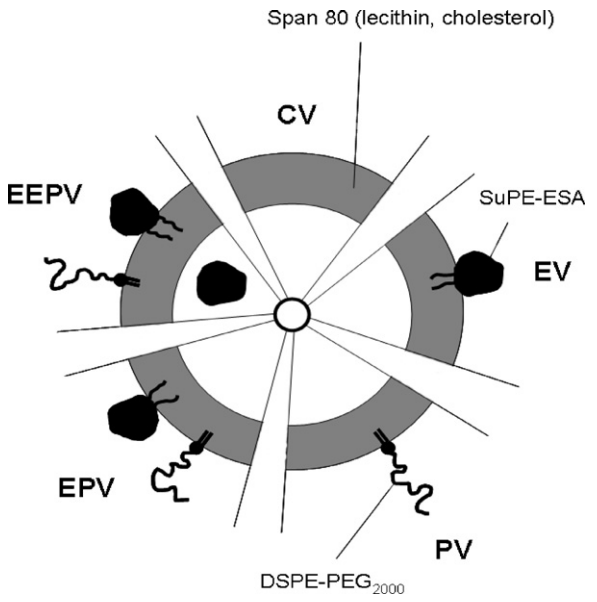

Fig. 1. Schematic representation of the different types Span 80 vesicles used. A cross section through one unilamellar Span 80 vesicle is shown in the center. The composition of the membrane of the different types of vesicles is illustrated. The highly schematic drawing is for an easier distinction of the different types of vesicles, only. The molecular details of the arrangement of the different components are not known. **CV**, Span 80 vesicles without PEGylated lipids or ESA ("control vesicles"); **PV**, Span 80 vesicles containing DSPE-PEG_{2000}; **EV**, Span 80 vesicles containing immobilized ESA; **EPV**, Span 80 vesicles containing DSPE-PEG_{2000} and immobilized ESA; **EEPV**, Span 80 vesicles containing DSPE-PEG_{2000}, immobilized ESA and entrapped ESA.

2. Materials and methods

2.1. Chemicals

Sorbitan monooleate (Span 80) and polyoxyethylene sorbitan monooleate (Tween 80) were purchased from Sigma–Aldrich (St. Louis, MO, USA). Lecithin from soybean was obtained from Wako Pure Chemical Industries (Osaka, Japan) and purified by acetone-precipitation (Inoue, 1974). 1,2-Distearoyl-*sn*-glycero-3-phosphoethanolamine-*N*-[methoxy (polyethyleneglycol)-2000] (DSPE-PEG_{2000}), which is a phospholipid to which a poly(ethyleneglycol) chain with a molar mass of 2000 g/mol is bound, was obtained from NOF Corporation (Tokyo, Japan). Cholesterol was from Wako Pure Chemical Industries.

Isothiocyanic acid octadecylester (IAOE) was synthesized from *N*,*N*-dichlorohexylcarbodiimide (DCCD) and 1-aminooctadecane as follows: In a first vessel, 3.4 g DCCD were first dissolved in 200 mL diethylether, cooled at −10 °C. 8 mL carbon disulphide was then added to this cooled solution. In a second vessel, 4.3 g 1-aminooctadecane were dissolved in 250 mL diethylether, and this solution was added to the cooled DCCD solution. The mixture was left standing at room temperature for 5 h. Afterwards, the solution was filtered using filter paper 5C (Advantec) to remove the byproduct thiourea. The filtrate was evaporated with a rotary evaporator and the obtained oily IAOE product was purified by recrystallization from diethylether.

The lectin ESA (*E. serra* agglutinin, mainly the isoform ESA-2 (Kawakubo et al., 1997) was extracted from the red alga *E. serra* and purified as described previously (Kawakubo et al., 1997). The phospholipid 1,2-dioleoyl-*sn*-glycero-3-phosphatidylethanolamine-*N*-succinyl (SuPE) was obtained from Avanti Polar Lipids (Alabaster, AL, USA). The radioisotope ^{125}I was obtained from MP Biomedicals Inc. (Irvine, CA, USA); ^{125}I was used to isotopically label bovine serum albumin (BSA) with 1,3,4,6-tetrachloro-3α-6α-diphenylglycouril (iodogen), obtained from Pierce Chemical Co. (Rockford, IL, USA). ^{125}I-labeled BSA was prepared as described previously (Hashizume et al., 1990). XRITC (amine-reactive X-rhodamine-5-(and-6)-isothiocyanate) was from Sigma Aldrich. All other reagents used were of guaranteed or biochemical grade.

2.2. Preparation of lipidic ESA-conjugates

The phospholipid-ESA conjugate was prepared as follows: 1 mg/mL of ESA was reacted with SuPE (1.25 mg/mL) in 0.15 M sodium carbonate buffer (pH 9.0) at room temperature. The reaction mixture was incubated for 2 h with vortexing for a few seconds every 30 min, followed by standing at 4 °C for 12 h. Residual SuPE in the buffer solution was removed by gel filtration with a PD-10 column packed with Sephadex G-25 (from Amersham Biosciences).

The IAOE-ESA conjugate was prepared as follows: 10 mg of IAOE was dissolved in 10 μL *N*,*N*-dimethyl sulfonamide (Wako Pure

Table 1
Preparation and characterization of the Span 80 vesicles used in the present study.

Vesicle type (see Fig. 1)	Inner phase: *A* in Figure S1 (Supplementary Material) (0.6 mL)	Content of Tween 80 solution: *B* in Figure S1 (Supplementary Material) (6.0 mL)	Vesicle diameter of refined vesicles (nm)	Vesicles diameter of extruded vesicles (nm)	Phase transition temperature T_m (°C)
CV	PBS	–	187 ± 32	104 ± 7	−40.3
PV	PBS	5.67 mg/mL DSPE-PEG_{2000}	197 ± 12	106 ± 8	−39.6
EV	PBS	18 nmol/mL ESA-SuPE	240 ± 24	100 ± 2	−36.8
EPV	PBS	5.67 mg/mL DSPE-PEG_{2000} + 108 nmol ESA-SuPE	298 ± 30	103 ± 5	−34.7
EEPV	PBS containing ESA (1 mg/mL)	5.67 mg/mL DSPE-PEG_{2000} + 108 nmol ESA-SuPE	362 ± 48	106 ± 6	−38.7

Inner phase, *A*: aqueous solution added at the first emulsification (Figure S1, Supplementary Material).
Tween 80 solution, *B*: aqueous Tween 80 solution at the second emulsification (Figure S1, Supplementary Material).
PBS: phosphate buffered saline (see Section 2).
DSPE-PEG_{2000}: 1,2-distearoyl-*sn*-glycero-3-phosphoethanolamine-*N*-[methoxy (polyethyleneglycol)-2000].
ESA-SuPE: ESA bound to 1,2-dioleoyl-*sn*-glycero-3-phosphatidylethanolamine-*N*-succinyl.

Chemical Industries), following by adding into 1 mg/mL ESA in 0.15 M sodium carbonate buffer. The incubation and purification of the solution were performed with the same manner as that in SuPE conjugation as mentioned above.

2.3. Preparation of Span 80 vesicles

All Span 80 vesicles were prepared with the two-step emulsification method described previously (Kato et al., 2003, 2006, 2008), including slight modifications, as outlined in Figure S1 (Supplementary Material) and described in the following. The incorporation of the lipidic ESA-conjugates into the vesicle membrane was carried out during the second emulsification step (Sugahara et al., 2001).

Span 80 (264 mg), purified lecithin (24 mg) and cholesterol (12 mg) were first dissolved in 3 mL *n*-hexane. 0.6 mL PBS (phosphate buffered saline composed of 137 mM NaCl, 2.7 mM KCl, 10 mM Na_2HPO_4, 2 mM KH_2PO_4) was added as inner phase, followed by the first emulsification for 6 min at 17,500 rpm using a micro-homogenizer Physcotron NS-310E (Microtec Co. Ltd., Funabashi, Japan). In the case of Span 80 vesicles containing entrapped molecules, the 0.6 mL PBS solution contained either ^{125}I-labeled BSA (about 2000 kcpm), or 1 mg/mL ESA (Table 1). The solvent of the water-in-oil emulsion obtained was evaporated in a rotary evaporator at 28 °C under reduced pressure, yielding a water lipid emulsion to which 6 mL PBS containing 96 mg Tween 80 (1.6 wt%) was added, followed by a mixing with the homogenizer for 2 min at 3500 rpm to obtain the heterogeneous Span 80 vesicle suspension. Depending on the type of vesicles prepared (Table 1), this Tween 80 solution contained the phospholipid-ESA conjugate, the IAOE-ESA conjugate, or DSPE-PEG_{2000}. The heterogeneous vesicle suspension was stirred with a magnetic stirrer for 3 h at room temperature, followed by storage overnight at 4 °C. The vesicles were then purified by ultracentrifugation (50,000 rpm at 4 °C for 240 min) in a Himac centrifuge CR15B (Hitachi Koki Co. Ltd., Tokyo, Japan) and the lower phase was purified by gel filtration on a 7 cm (diameter) × 50 cm (length) column containing Biogel-A5m (Bio-Rad Laboratories, Richmond, CA, USA). In comparison to our earlier description (Kato et al., 2006), gel filtration was used instead of dialysis to obtain the refined vesicle suspension. As shown previously by a HPLC analysis (Kato et al., 2006; Kato et al., 2008), the content of Tween 80 in the final vesicle preparation was negligibly small.

Polycarbonate membrane extrusions of all vesicle suspensions were carried out as described previously (Kato et al., 2008).

2.4. Characterization of Span 80 vesicles

The size of the vesicles was analyzed by dynamic light scattering (DLS) using a DLS-6000EW instrument (Otsuka Electronics Co. Ltd., Osaka, Japan) equipped with a 10 mW He–Ne laser source (632.8 nm); the polydispersity index was between 0.17 and 0.20. For the DLS measurements the vesicle suspension was diluted with PBS.

The morphology of the vesicles was analyzed by transmission electron microscoy (TEM) and the phase transition temperature (T_m) were determined as described before (Kato et al., 2008).

The amount of ESA immobilized on the Span 80 vesicles was determined with the Lowry method (Lowry et al., 1951).

2.5. Hemagglutinating test

The activity of the immobilized ESA was analyzed by assaying its hemagglutinating activity against sheep erythrocytes because it is known that free ESA exhibits hemagglutinating activity against sheep and trypsinized rabbit red blood cells (Kawakubo et al., 1997). The hemagglutinating activity assay was performed in a 2% (v/v) erythrocyte suspensions, as described previously (Kawakubo et al., 1997). The hemagglutinating activities of the Span 80 control vesicles (**CV**), of free ESA, and of Span 80 vesicles containing immobilized ESA (**EV**) were compared by considering the lowest concentration exhibiting positive agglutination as the titer of the activity.

2.6. Cells

Human colon cancer cell line Colo201 (ATTC#CCL-224) and human breast cancer cell line MCF-7 (ATCC#HTB-22) were obtained from ATTC (American Type Cell Collection, Manassas, VA, USA). Murine colon cancer cell line Colon26 derived from BALB/c mouse, were provided by the Institute of Development, Aging and Cancer, Tohoku University (Sendai, Japan). Human non-cancerous mammary epithelial cell line MCF10-2A was purchased from ATCC (Rockville, MD, USA). The cancer cells were cultured in E-RDF medium® (Kyokuto Pharmaceutical Industrial Co., Ltd., Tokyo, Japan) containing 10% fetal bovine serum (FBS) under humid conditions with 5% CO_2 at 37 °C in a CO_2 incubator. MCF10-2A cells were cultured in 10% FBS-E-RDF medium supplemented with 500 ng/mL of hydrocortisone and 20 ng/mL of epidermal growth factor (EGF) under the same culture condition of Colo201.

2.7. In vitro cytotoxicity test

Colo201 cells (1×10^5 cells/mL) were cultured on 48-well plate filled with 0.5 mL of 10% FBS-contained E-RDF medium. The cells were washed with PBS, and incubated for 24 h with 0.5 mL of 10% FBS-E-RDF medium containing the following one of the reagents: phosphate buffered saline (PBS) as a non-vesicle control; Span 80 control vesicles (**CV**: $OD_{600\,nm}$ = 0.260); or Span 80 vesicles containing immobilized ESA (**EV**: $OD_{600\,nm}$ = 0.260). The ESA-concentration

in the vesicle suspension was 0.054 mg/mL). After incubation, the cells were harvested, and washed twice with PBS, then resuspended in 1 mL of PBS. The viability of the cells in the suspension was evaluated with the trypan blue dying method (Gortzi et al., 2003; Konopka et al., 1996). Similarly, the cytotoxicity of **CV** and **EV** against MCF10-2A cells was also analyzed. A phase contrast microscopy analysis of Colo201 cells treated with **EV** was also performed, as outlined in the following: Colo201 cells and MCF10-2A cells were incubated for 12 h in E-RDF medium containing 10 vol% FBS and 1 vol% **EV**. After incubation, these cells were observed with a phase contrast microscope.

2.8. In vitro apoptosis test

DNA was extracted from Colo201 cells which were incubated in the presence of **EV** for 8 h, then electrophoresed in a 2% agarose gel to detect DNA laddering associated with apoptosis (Kato et al., 2003; Martin et al., 1995; Ioannou and Chen, 1996; Shirai et al., 2009).

2.9. In vitro cell binding test

In order to visualize the affinity of ESA to cancerous cells, a specific binding test was performed. ESA was first labeled with XRITC, a red fluorescence reagent, followed by addition of the XRITC-labeled ESA to Span 80 vesicles. These vesicles were then incubated with Colo201, MCF7, and MCF10-2A cells for a few minutes. Afterwards, micrographs were captured with a fluorescent microscope IX-FLA (Olympus corp., Tokyo, Japan).

2.10. Animal studies

Female Balb/*c-nu/nu* mice and female Balb/cByjJcl mice (4 weeks old) were purchased from Clea Japan Inc. (Tokyo, Japan). Human colon cancer cell line Colo201 or murine colon cancer cell line Colon26 ($1.0–5.0 \times 10^6$ cells per mice) were subcutaneously transplanted into 6 weeks old female Balb/c-*nu/nu* and Balb/cByjJcl mice, respectively; Colo201 cells from human are difficult to transplant into a mouse with normal immunocompetence. All the animal experimental protocols were in accordance with the Guide for Animal Experimentation, Ehime University, and approved by the Committee for Animal Experimentation, Ehime University.

2.11. Biodistribution analysis

BSA (50 μL, 5 mg/mL) was first labeled with the radioisotope ^{125}I (50 μL, 2 mCi/mL) with the iodogen method as described previously (Hashizume et al., 1990). Although iodine is specifically uptaken by the thyroid gland for the formation of the thyroid hormone, the labeling method has been often used for preparing a radioactive tracer in previous studies (Kuan et al., 1999; Foulon et al., 2000; Korde et al., 2000; Larsson et al., 2001). In this experiment, ^{125}I-BSA was used as a model molecule to monitor the biodistribution of the aqueous content of the vesicles.

^{125}I-BSA was encapsulated into four types of Span 80 vesicles, **CV**, **PV**, **EV** and **EPV**. After the preparation, the concentration of these vesicles was regulated to about 2000 kcpm based on the radioactivity of ^{125}I per 200 μL. These vesicles were intravenously injected into BALB/cA-*nu/nu* mice with transplanted Colo201, of which the tumor volume was approximately 1000 mm^3. The concentration of the injected vesicle suspension was about 2000 kcpm of dose (approximately $(2–5) \times 10^{11}$ vesicle particles/mL suspension). At 1, 3, 6 and 24 h after injection, the amount of radioactivity in the tumors, and in various organs and in the blood was measured using a well-type gamma counter ARC-3000 (Aloka, Tokyo, Japan). The accumulation amount in each tissue is represented as a "percentage of dose" calculated by Eq. (1).

$$\text{percentage of dose (\%)} = \frac{\text{radiation dose in tissue (cpm)}}{\text{radiation dose injected vesicle sample (cpm)}} 100 \quad (1)$$

2.12. In vivo anti-tumor activity test

In order to prepare tumor-bearing mice, Colo201 cells ($1–5 \times 10^6$ cells) were subcutaneously transplanted into the back of nude mice. When the tumor volume reached to 100–300 mm^3 a few weeks after the transplantation, **EPV**s or **EEPV**s (0.01 mL/g body weight) were intraperitoneally or intravenously injected every 3 days up to 15 days. Throughout the experiments, the tumor size and body weight of the mice were measured. The longest tumor diameter (length d_1) and the diameters crossing the longest diameters at right angles (widths d_2) were measured with a slide caliper, then the tumor volumes (V) were calculated according to the following equation $V\,(\text{mm}^3) = d_1\,(\text{mm}) \times d_2\,(\text{mm}) \times d_2\,(\text{mm})/2$ (Rad et al., 2007). The values of body weight and tumor volume at any time were divided by the body weight and the volume at the start of injection (day 0), respectively, to obtain normalized values. These values are represented as relative body weight (W_{mr}) and relative tumor volume (V_{tr}). In order to determine the anti-tumor activity, the tumor growth inhibition was defined as the ratio of the median tumor volume for the treated *vs.* control group (T/C) with the following Eq. (2), according to Rad et al. (2007).

$$\text{T/C (\%)} = \frac{\text{median tumor volume of treated group at day } X\ (\text{mm}^3)}{\text{median tumor volume of control group at day } X (\text{mm}^3)} 100 \quad (2)$$

The T/C value was used to evaluate of the anti-tumor effect of the samples at the terminal point of the logarithmic growth phase of the murine tumor. These measurement methods were applied in all other mouse experiments.

2.13. In vivo apoptosis test

Three days after the *i.v.* injection of **EPV**, the tumors were excised from the Colo201 tumor-bearing BALB/cA-*nu/nu* mice, and formalin-fixed paraffin-embedded tissue sections were subsequently prepared for *in situ* apoptosis detection by terminal deoxynucleotidyl transferase-mediated dUTP nick end labeling (TUNEL) using the In Situ Apoptosis Detection Kit (Takara Biomedicals, Shiga, Japan) (Fukuda et al., 2006) and immunohistochemistry with anti-single-stranded DNA antibody (DAKO Japan, Kyoto Japan).

2.14. Internalization test

The delivery of water soluble molecules encapsulated inside **EPV** to the tumor in mice was analyzed. **EPV** containing encapsulated fluorescein isothiocyanate (FITC) were intravenously injected to mouse (BALB/cByJJCl, 6 week olds, female) with about 500 mm^3 volume of colon tumor from mouse colon cancer cell line Colon26. At 0, 3, 6 and 24 h after the injection, the murine tumor was resected from the mouse. The tumor was quickly frozen in dry ice/acetone bath (about −80 °C), and then sliced to 5 μm thin sections with a microtome (Cryostat HM520). The section was fixed in Morphosave (Ventana Medical Systems, Tucson, AZ) for 15 min, and observed with a fluorescence microscope IX-FLA.

Table 2
Immobilization of ESA onto Span 80 vesicles.

Lipid anchor	Added amount of lipid anchor (μmol)[a]	Added amount of ESA (μg)[b]	Amount of immobilized ESA (μg)	ESA immobilization efficacy (%)[c]
–	–	250	12	4.7
IAOE	32.1	250	56	22
SuPE	2.9	250	121	48

[a] The values given are the amounts of lipid anchor added per 50 nmol ESA.
[b] Amount of ESA added (250 μg) per 132 mg Span 80.
[c] Percentage of immobilized ESA with respect to the amount of ESA added.

2.15. Statistical analysis

The statistical analysis of significancy between the data from two groups was performed using Student's *t*-test. Multiple comparisons were performed using the analysis of variance (ANOVA) with Statcel® (OMS publishing Inc., Saitama, Japan). The significancy was designated at $P < 0.05$.

3. Results

3.1. Preparation and characterization of the Span 80 vesicles

All Span 80 vesicles used in the study were prepared by the two-step emulsification method, as outlined in Figure S1 in Supplementary Material. For the vesicles containing PEGylated lipids (**PV**, **EPV**, **EEPV**) and for the vesicles containing ESA (**EV**, **EPV**, **EEPV**) DSPE-PEG_{2000} and ESA-SuPE were added before the second emulsification (Table 1 and Figure S1 in Supplementary Material).

Immobilization of ESA on the Span 80 vesicles occurred most efficiently if ESA was bound to SuPE (Table 2), i.e. if the ESA-SuPE conjugate was used. Vesicle binding of ESA alone was low; the immobilization efficacy was only 4.7% (Table 2). In the case of IAOE as anchor lipid, the immobilization efficacy was 22%, as compared to 48% if SuPE was used as lipid anchor (Table 2). Based on these immobilization trials, for all further measurements, ESA was immobilized onto Span 80 vesicles as ESA-SuPE conjugate.

The immobilized amounts of ESA and PEGylated lipid per Span 80 (based on an average Span 80 molecular mass of 737 g/mol, see Kato et al., 2006; Kato et al., 2008), were $(5.0 \pm 0.4) \times 10^{-5}$ mol% and $(3.1 \pm 0.6) \times 10^{-2}$ mol%, respectively.

The average sizes of the refined vesicles prepared were determined by DLS (Table 1). The diameters varied between about 200 nm and 400 nm. The polydispersity of the vesicles was relatively high, as can be seen also from the transmission electron micrographs shown in Fig. 2. The average size and the polydispersity of the vesicles could be reduced by passing the vesicle suspension through polycarbonate membranes with 100 nm pore diameters. The resulting vesicles had diameters of about 100 nm (Table 1).

The phase transition temperature of the different vesicle preparations was in the range of −35 to −40 °C (Table 1), in agreement with what we determined previously (Kato et al., 2008). The membrane of the vesicles at room temperature was therefore rather fluid in all cases.

3.2. Hemagglutinating activity of *EV*

To investigate the bioactivity of the immobilized ESA, the hemagglutinating activity of the Span 80 vesicles containing immobilized ESA (**EV**) was measured against sheep red blood cells and compared with the hemagglutinating activity of free ESA. Both, free ESA and **EV** showed the same activity (2.86 ng/mL). Both PBS alone and Span 80 vesicles without ESA (**CV**) did not show hemagglutinating activity. These results indicate that ESA could be immobilized under retention of its biological activity.

3.3. In vitro cytotoxicity and apoptotic behavior of *EV*

To detect a possible anti-tumor activity of **EV**, the cytotoxicity of **EV** against Colo201 was evaluated and compared with the activity of **CV**. The time-course of the cell viability is shown in Fig. 3. **EV** clearly showed a stronger cytotoxicity than **CV**. The viability of the Colo201 cells decreased to 17.2 ± 6.3% after 24 h

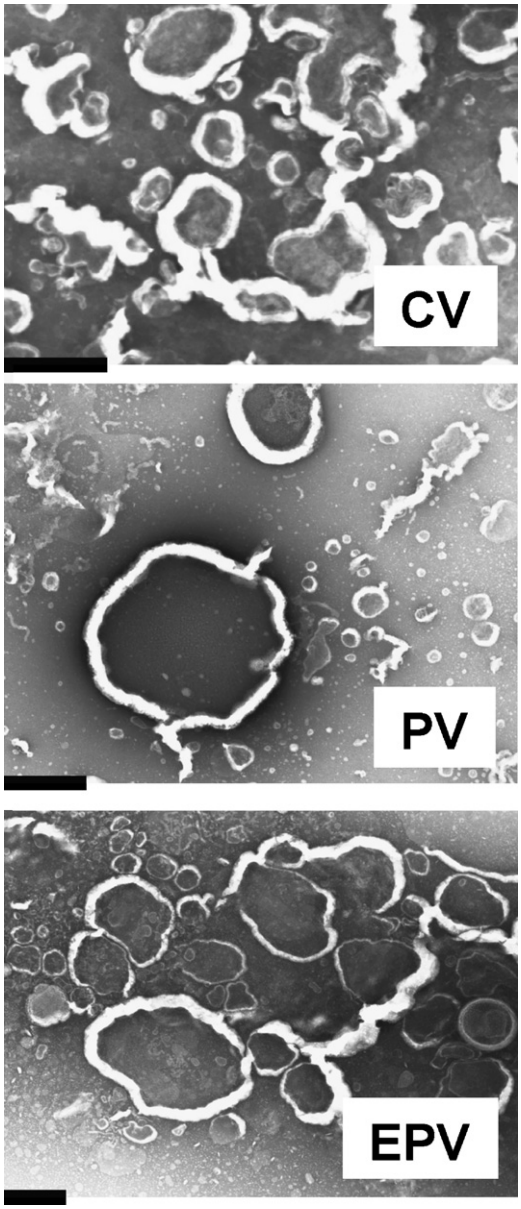

Fig. 2. Transmission electron micrographs (TEM) of Span 80 vesicles (**CV**), of Span 80 vesicles containing DSPE-PEG_{2000} (**PV**), and of Span 80 vesicles containing DSPE-PEG_{2000} and immobilized ESA (**EPV**). Negative staining method; length of the bar: 500 nm.

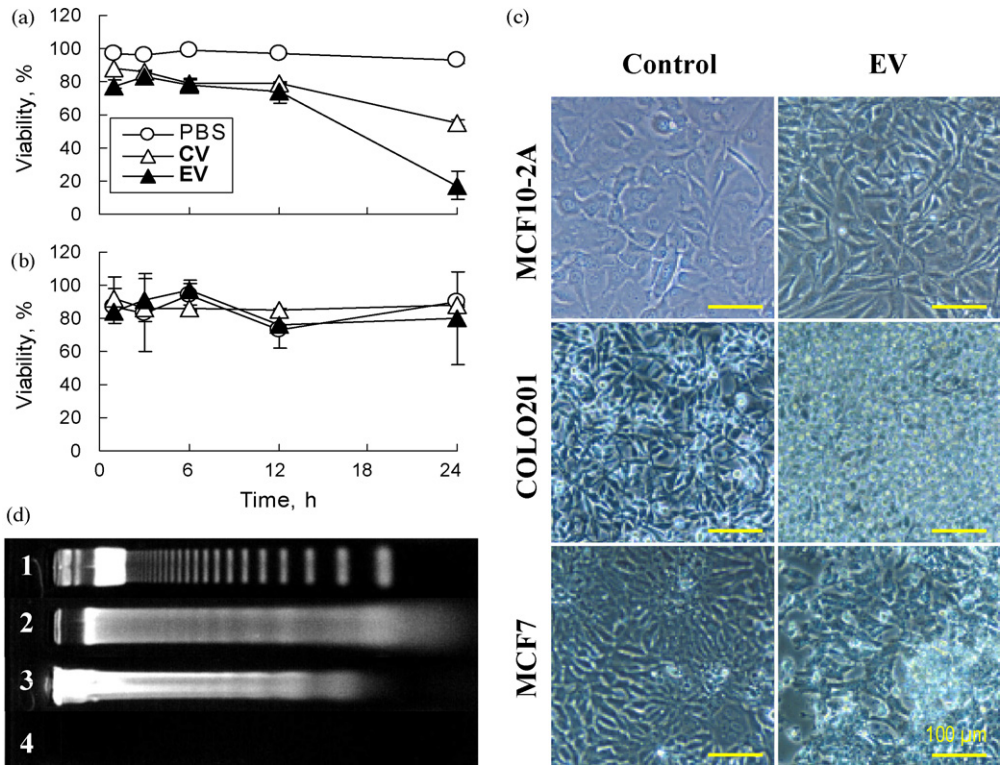

Fig. 3. (a) and (b) Time-course of the viability of Colo201 cells (a) and of MCF10-2A cells (b), number of independent measurements: $n = 2$ (c) Phase contrast micrographs of Colo201, MCF7 and MCF10-2A cells treated with **EV**. These cells were incubated for 12 h in E-RDF medium containing 10 vol% FBS and 1 vol% **EV** ($OD_{680} = 0.046$). Magnification: ×200. (d) Fragmentation of the DNA of Colo201 cells (lane 2), MCF7 cells (lane 3) and MCF10-2A cells (lane 4) treated with Span 80 vesicles containing immobilized ESA (**EV**) (lower lane). Lane 1: DNA ladder marker.

incubation while the cell viability in the presence of **CV** decreased to 55.1 ± 5.6% in the same period of time under the conditions used (Fig. 3a). On the other hand, these vesicles showed no effect on the viability of normal cells, MCF10-2A (Fig. 3b). The phase contrast microscopic observation of these cells after **EV**-treatment showed that morphological changes of the Colo201 and MCF7 cells (tumor cells) were induced, while there were no changes in the case of MCF10-2A cells (normal cells) (Fig. 3c). Our previous study indicated that ESA-treatment excites the Capase3 activity of Colo201 cells (Sugahara et al., 2001). Therefore, the morphological change of Colo201 cells treated with **EV** is considered to be associated with apoptosis. Moreover, we have already reported (Sugahara et al., 2001) that free ESA specifically combines with many tumor cells such as Colo201, HeLa and MCF7, inducing apoptotic death of the cancer cells, while free ESA did not combine with MCF10-2A significantly (from flow cytometric measurements) and did not injure the cell. These results suggest that ESA immobilized on **EV** also preferentially injures the cancer cells with high-mannose-type sugar chains (such as Colo201 and MCF7 cells).

The DNA fragmentation ("DNA laddering") in Colo201 cells treated with **EV** was determined by gel electrophoresis (Fig. 3d), as described previously (Sugahara et al., 2001). On the other hand, DNA fragmentation in human breast cancer cell line MCF7 was also detected, but not in the case of MFC10-2A (Fig. 3d). In our earlier study it was shown that ESA is toxic against human cancer cell lines (colon, uterine cervix, and breast) (Sugahara et al., 2001). The mechanism responsible for the ESA cytotoxicity involves the binding of ESA to the carbohydrates on the surface of the cells, which leads to an induction of apoptotic cell death as indicated by DNA laddering (Sugahara et al., 2001). The observed DNA laddering in the case of **EV** indicates that not only free ESA but also ESA which is immobilized onto Span 80 vesicles induces apoptotic cell death in colon cancer cell lines.

3.4. *In vitro* binding of ***EV*** to cancer cells

For investigating the affinity of **EV** to colon cancer cells, a fluorescent test for tumor cell binding was used by applying Span 80 vesicles containing immobilized XRITC-labeled ESA. ESA was first labeled with XRITC and then immobilized onto the vesicles to yield **XRITC-EV** (without preparation of a lipidic conjugate). Since XRITC is a hydrophobic red fluorescent dye, binding of XRITC-ESA is expected to be more efficient than ESA alone as shown in Table 2.

Colo201, MCF7, and MCF10-2A cells were incubated with **XRITC-EV** for a few minutes and then observed with the fluorescence microscope. The microphotographs are shown in Fig. 4a–f. Fluorescence was observed in Colo201 cells and MCF7 cells (Fig. 4d and e). There was no fluorescence in the MCF10-2A cells (Fig. 4f). These results indicate that Span 80 vesicles containing immobilized ESA binds to cancer cells Colo201 as well as to the cancer cells MCF7, but not to the normal cells MCF10-2A. As shown previously, ESA cell binding occurs *via* interactions between ESA and specific carbohydrates present on the surface of cancer cells (Sugahara et al., 2001). The cancer cell binding property of free ESA (Sugahara et al., 2001) remained if ESA was immobilized onto Span 80 vesicles (Fig. 4d and e).

3.5. *Biodistribution of the vesicles*

Prior to the *in vivo* anti-tumor activity tests in mice, we investigated whether *i.v.* administrated Span 80 vesicles containing immobilized ESA are preferentially taken up by the tumor, or whether there is no tumor specificity of the vesicles containing ESA. Furthermore, since liposomal DDS often contain PEGylated lipids to decrease uptake by the RES (Allen, 1994; Zeisig et al., 1996; Maruyama et al., 1997; Gabizon et al., 1997; Couvreur and Vauthier, 2006), Span 80 vesicles containing immobilized ESA *and* PEGylated

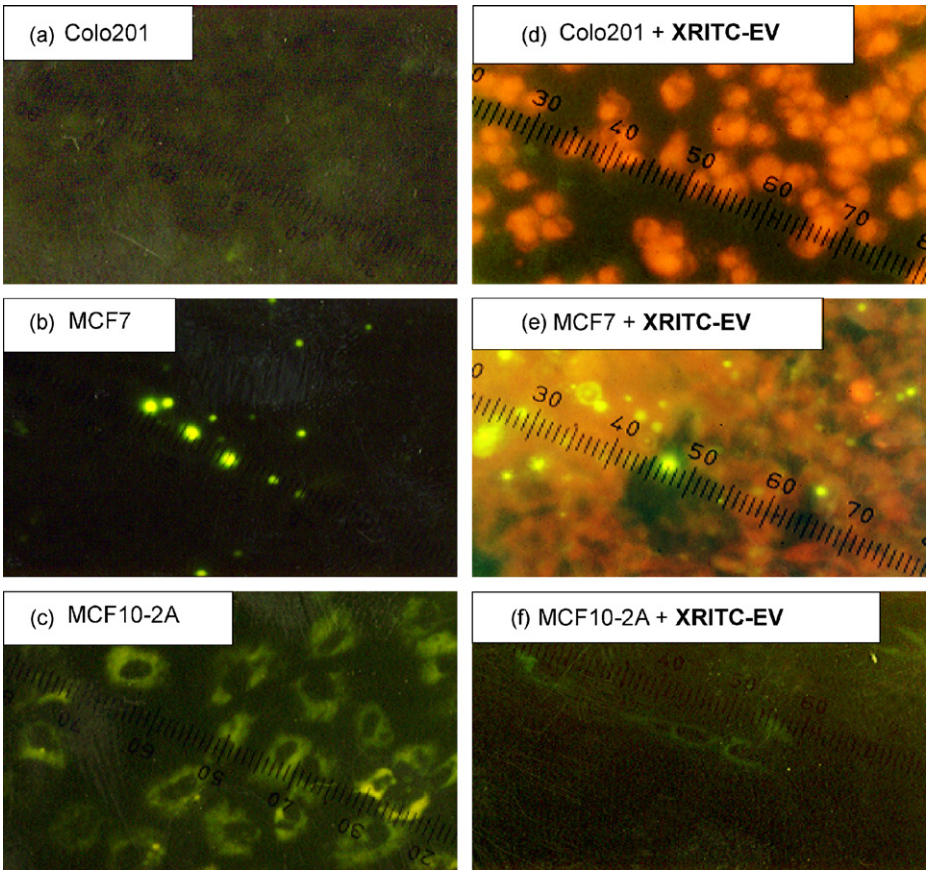

Fig. 4. Fluorescence micrographs of three types of cells before and after treatment with Span 80 vesicles containing immobilized XRITC-ESA (**XRITC-EV**). (a–c) Untreated cells; (d–f) cells after treatment with **XRITC-EV**. The cells used were Colo201 (a and d), MCF7 (b and e), and MCF-10-2A (c and f).

lipids (**EPV**) were prepared, and their *in vivo* behavior was directly compared with **EV** and **PV**. The vesicles were loaded with ^{125}I-BSA, and the delivery of ^{125}I-BSA encapsulated inside **EPV, EV** or **PV** was investigated by examining the biodistribution of ^{125}I-BSA in the nude mice bearing a Colo201 tumor. The accumulated amount of ^{125}I-BSA was evaluated based on the measured radioactivity and using Eq. (1). The results of this biodistribution experiment are shown in Figs. 5 and 6.

At 6 h after *i v*. injection, the tumor uptake of ^{125}I-BSA encapsulated in **EV** and **EPV** was by trend higher as compared to the uptake of ^{125}I-BSA encapsulated in **PV** and **CV** (Fig. 5). The uptake of ^{125}I-BSA in **EV** and **EPV** increased in the range of 1–6 h, while the uptake of ^{125}I-BSA in **CV** decreased (Fig. 5). On the other hand, immediately after *i.v*. injection, the uptake of ^{125}I-BSA in **PV**, **EV** and **EPV** by the liver, kidney and spleen was lower than the uptake of ^{125}I-BSA in **CV** (Fig. 6a–c). Fig. 6 shows that the lower uptake by the RES cannot be correlated with the presence of PEG in the vesicles. Therefore, there is no evidence (Fig. 6b) for the existence of a "stealth effect" caused by PEG in the case of Span 80 vesicles containing immobilized ESA. It seems that the presence of ESA in **EV**, without any PEGylated lipids, already lowers vesicle uptake by the RES.

In any case, the presence of PEGylated lipids in **EPV** did not significantly alter the biodistribution of the ESA-containing Span 80 vesicles. Furthermore, ESA was still biologically active in the presence of PEGylated lipids (Figs. 7 and 8). However, if specific antibodies against ESA are produced by the repeated injection of **EV** or **EPV** *in vivo*, the PEG on the **EPV** surface may inhibit the binding of the antibodies to ESA.

Although the number of mice used in the experiments reported in Fig. 5 was low (Table S1, Supplementary Material), there is a trend that ^{125}I-BSA encapsulated in **EV** or **EPV** is more efficiently taken

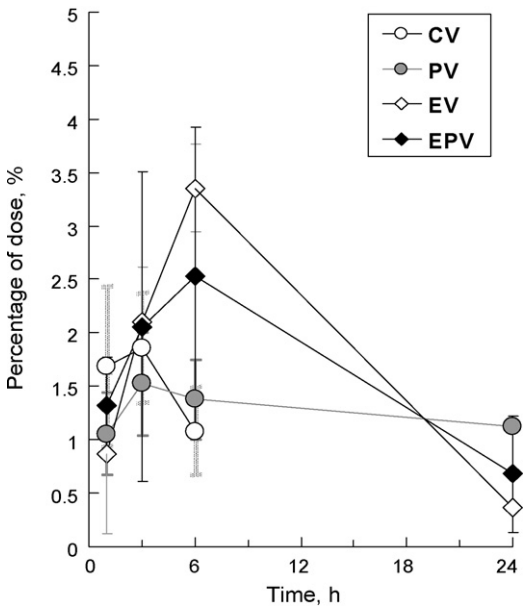

Fig. 5. Tumor accumulation in the BALB/cA-*nu/nu* mice bearing Colo201 tumors by using Span 80 vesicles containing entrapped ^{125}I-BSA (2000 kcpm). The Span 80 vesicles used were **CV** (opened circle), **EV** (opened rhombus), **PV** (closed circle) and **EPV** (closed rhombus). The vesicles were injected intravenously and the uptake of ^{125}I-BSA in the tumor tissue was measured at 1, 3, 6, and 24 h after injection. Mean values (±S.D.) are given for measurements carried out with 2–3 animals/experimental group. It was not possible to us to perform the experiments with a higher number of mice. Details about animal number used in these experiments are shown in Table S1 in Supplementary Material.

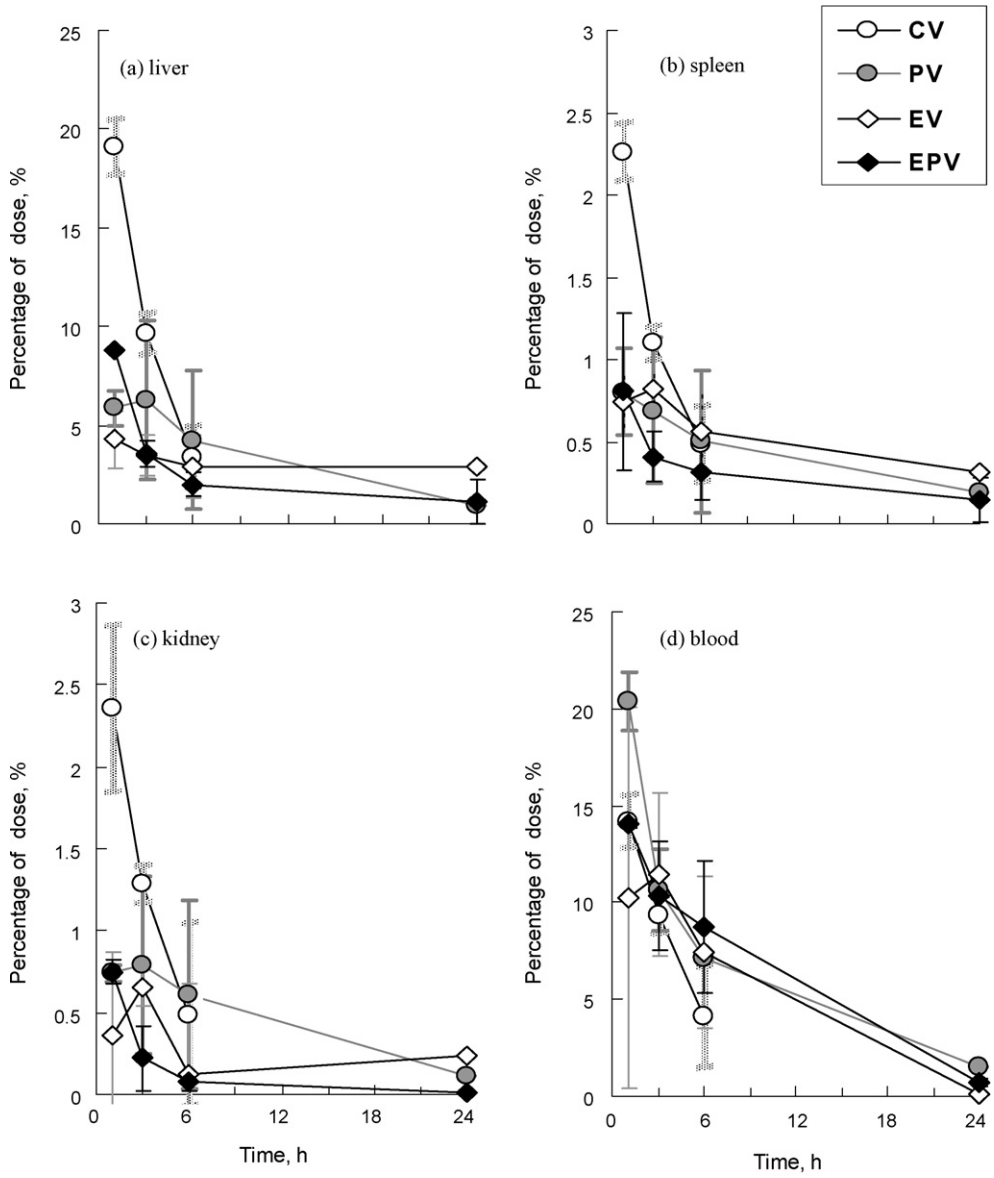

Fig. 6. Biodistribution of ^{125}I-BSA in Colo201 tumor-bearing BALB/cA-*nu*/*nu* mice after intravenous injection of Span 80 vesicles containing ^{125}I-BSA (2000 kcpm). The Span 80 vesicles used were **CV** (opened circle), **EV** (opened rhombus), **PV** (closed circle) and **EPV** (closed rhombus). The uptake of ^{125}I-BSA by liver (a), spleen (b), kidney (c) and in the whole blood (d) was measured at 1, 3, 6, and 24 h after injection. The time courses of the uptake of ^{125}I-BSA in the tumor are shown in Fig. 5. Mean values (±S.D.) are given for measurements carried out with 2–3 animals/experimental group. Details about animal number used in these experiments are shown in Table S1 in Supplementary Material.

up by the tumor than ^{125}I-BSA encapsulated in **PV** or **CV**. This is most likely due to specific interactions between ESA immobilized on **EV** or **EPV** and the carbohydrate chains on the surface of the tumor cells, as shown previously in an *in vitro* study using free ESA (Sugahara et al., 2001).

Recently, we found that **EPV** injected into Colon26 tumor burden mouse (Balb/cByjJcl) showed higher anti-tumor activity as compared to **EV** (data not shown). The results of this study will be presented in a forthcoming paper (in preparation). The difference in the anti-tumor activity between **EV** and **EPV** may be caused by a hindrance of the ESA-anti-ESA antibody binding by the PEG chains; anti-ESA antibodies are expected to be produced in the mouse upon repeated administration of **EV** or **EPV**. This means that **EV** are more rapidly removed *via* binding to anti-ESA antibodies than **EPV**. Therefore, the modification of the Span 80 vesicle with ESA *and* PEG is at the end expected to enhance the anti-tumor effect of **EPV**. For this reason, **EPV** was used instead of **EV** in the *in vivo* anti-tumor activity tests described in the following section.

3.6. Anti-tumor activity of *EPV* on Colo201 cancer xenografts in vivo

EPV was administered into Colo201 tumor-bearing mice, followed by a measurement of the weight of the mice and the volume of the tumor. The time-course of the relative body weight (W_{mr}) and of the relative tumor volume (V_{tr}) of the mice to which **EPV** was administrated *i.v.* (ESA-dose 2.0 μg/g-mouse-weight) is shown in Fig. 7, together with the corresponding values for **EEPV** (ESA-dose 2.5 μg/g-mouse-weight) and PBS as a control. In all three cases, W_{mr} increased similarly, suggesting that **EPV** and **EEPV** did not cause general toxicity in the mice.

The particle size of conventional PEGylated liposomes used *in vivo* is usually around 100 nm. From our previous studies (Kato et al., 2006; Kato et al., 2008), it was revealed that the membrane fluidity of Span 80 vesicles is considerably higher as compared to the fluidity of the membrane of conventional phospholipid vesicles. Therefore, Span 80 vesicles may more easily migrate through the

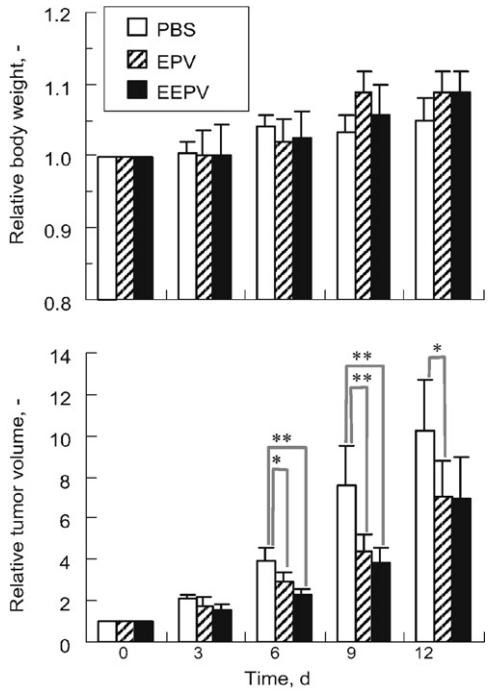

Fig. 7. Time courses of body weight of the mice (W_{mr}) and relative tumor volume (V_{tr}) of the nude mice bearing Colo201 tumors to which **EPV** or **EEPV** were injected. The amounts of ESA in **EPV** and in **EEPV** were 2.0 and 2.5 μg/mL, respectively. The day of vesicle injection is defined as day 0. Mean values (±S.D.) of W_{mr} and V_{tr} are shown with standard deviation (n = 5–10).

pore structure of the blood vessel wall near the tumor by fluctuating changes of the vesicle shape. Thus, it was revealed that administration of Span 80 vesicle with a particle size between 200 and 400 nm, easily prepared without extrusion, is effective enough for the treatment of the tumors. The fluidity of Span 80 vesicles can be seen as an advantage in this respect.

As shown in Fig. 7b, V_{tr} in the case of **EPV**- and **EEPV**-treated mice were lower than in the case of the control mice. In other *in vivo* experiments, the T/C values in the **EPV**- and **EEPV**-injected groups (on the 9th day) were 58.0 ± 4.3% and 51.1 ± 4.2%, respectively. The results suggested that the tumor growth inhibition effects of **EPV** and **EEPV** were basically due to the immobilized ESA and encapsulated-ESA. The findings are also supported by the result from a *semi in vivo* experiment as follows. Colo201 cells treated with **EV** could not be transplanted onto Balb/c-*nu*/*nu* mice at all, although Colo201 cells treated with **CV** or PBS could be transplanted (Figure S2, Supplementary Material). These results indicate that **EPV** and **EEPV** exhibited significant anti-tumor activity *in vivo* without addition of any of the known anti-cancer agents.

Furthermore, there was no indication of an allergic reaction possibly caused by the vesicle components. Please note that in the final Span 80 vesicle preparation the content of Tween 80, used during the second emulsification stage (Figure S1, Supplementary Material), was negligibly small (Kato et al., 2006).

3.7. ***EPV*** *administration induced apoptosis in transplanted Colo201 tumors*

To clarify whether the **EPV** administration induces apoptosis in tumor cells in the same manner as free ESA does, we analyzed the

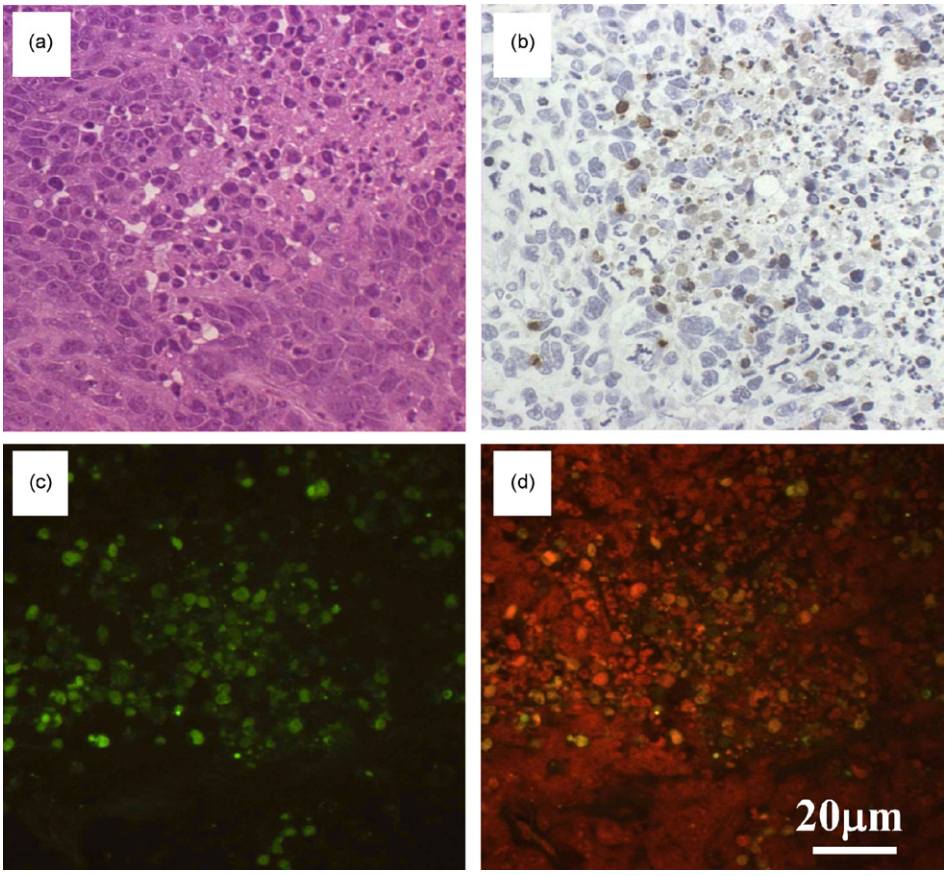

Fig. 8. Apoptosis of Colo201 tumor cells in mice at 72 h after intravenous administration of **EPV** in nude mice bearing Colo201 tumors: (a) hematoxylin–eosin staining; (b) immunohistochemistry for single-strand DNA; (c) TUNEL; (d) TUNEL (green) with propidium iodide (red); magnification: ×400.

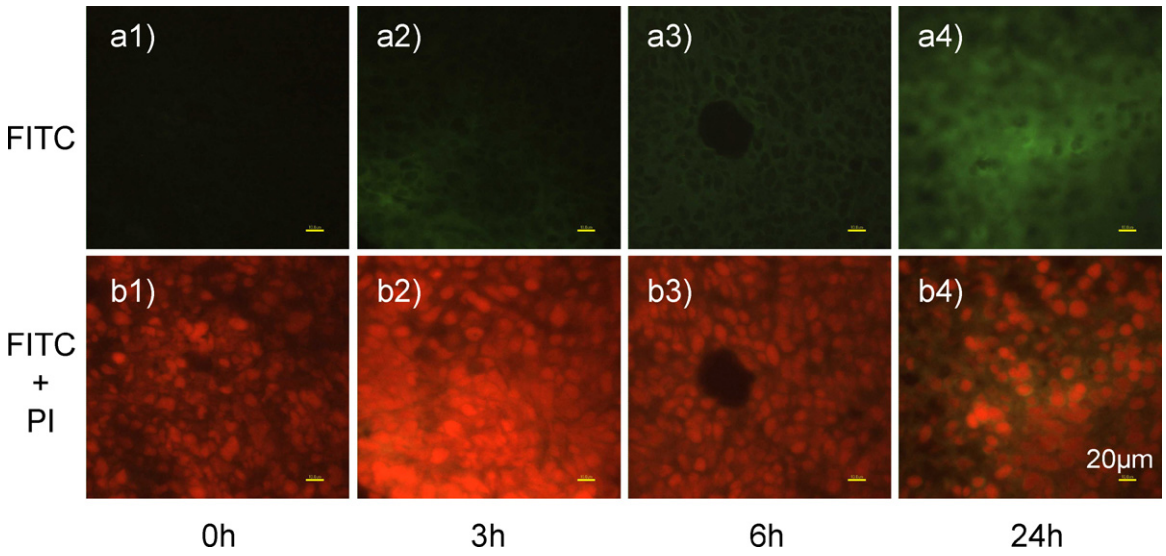

Fig. 9. Accumulation and internalization of **EPV** containing FITC (**FITC-EPV**) into Colon26 tumor cells in tumor-bearing mice. The fluorescence micrographs of the tumors at 0, 3, 6, 24 h after the injection of FITC-EPV with of FITC (green fluorescence) were shown in (a1–a4), respectively. The DNA-stained fluorescence micrographs of the above tumors, also labeled with propidium iodide (red fluorescence), were shown in (b1–b4): the micrographs of b1, b2, b3 and b4 correspond to those of a1, a2, a3, and a4, respectively. Scale bars: 20 μm.

apoptosis in Colo201 tumor grafts after **EPV** administration *in situ* (Fig. 8).

The TUNEL methods revealed numerous apoptotic signals in the tumor tissue, especially at the perivascular area as shown in Fig. 8c and d. Also, immunohistochemistry for ssDNA presented positive signals on the Colo201 tumor cells in mice which were treated with **EPV** (Fig. 8b). These signals were manifested mainly around the intratumoral blood vessels, suggesting that the cell death was induced *via* different mechanisms from that of central necrosis of the tumor which might be mainly induced by anoxia. Thus, these evidences might imply that **EPV** could induce apoptosis of tumor cells around the blood vessels with migration throughout the vessel walls. It seems that **EPV** caused the anti-tumor effect *in vivo* by inducing apoptosis in tumor cells. This is in agreement with the DNA laddering analysis of **EV**-treated cancer cells *in vitro* (Fig. 3d).

3.8. Drug internalization of *EPV* to tumor cells

For clarifying whether **EPV** could deliver the encapsulated-drug into a tumor *in vivo*, **EPV** containing encapsulated FITC (**FITC-EPV**) were injected intravenously into a Balb/cByjJcl mouse which contained a transplanted Colon26 tumor. The fluorescence micrographs of the mouse tumor were measured *in situ* (Fig. 9). In the tumor, the green fluorescence of **FITC-EPV** gradually increased with time at 6 h and 24 h after the injection, and the presence of FITC in the cytoplasm of tumor cells was confirmed, suggesting that FITC encapsulated in **EPV** was internalized into the cytoplasm of the tumor cells. This indicates that **EPV** could deliver the encapsulated-drug mimics (FITC) into tumor cells.

4. Concluding remarks

The novel lectin *E. serra* agglutinin (ESA) was immobilized onto Span 80 vesicles and the vesicles were investigated with respect to their potential as novel type of nonionic vesicular drug delivery system. The various measurements carried out indicate that the vesicles are rather promising systems for further exploring their usefulness for the delivery of encapsulated anti-tumor drugs. This optimistic conclusion is based on the following: (i) ESA on the surface of Span 80 vesicles showed hemagluttinating activity similar to free ESA, i.e. immobilization onto the vesicles did not lead to an inhibition of the biological activity; (ii) the vesicles showed apoptotic tumor cell cytotoxicity with little effects on the viability of the normal cells tested; (iii) the growth of implanted Colo201 tumors in nude mice could be reduced upon *i.v.* injection of the vesicles; (iv) the presence of fluorescent molecules originally trapped inside the vesicles was enriched in the tumor of tumor-bearing mice at 6 h after *i.v.* administration of the vesicles; (v) with respect to tumor accumulation after 6 h, **EV** and **EPV** are superior as compared to **PV** and **CV**. In the case of the uptake by the RES, **EV**, **PV** and **EPV** are superior as compared to **CV**.

From the study presented, there are two main results. First, the experiments carried out indicate that there is a considerable potential of using Span 80 vesicles as DDS for the treatment of tumor cells, as alternative system to conventional phospholipid-based vesicles. Second, ESA immobilized onto Span 80 vesicles shows anti-tumor activity, especially, if the vesicles contain PEGylated lipids. Span 80 vesicles containing immobilized ESA and PEGylated lipids (**EPV**) are lipidic microcapsules which show *in vivo* anti-tumor activity by themselves, without any entrapped anti-tumor agents. Experiments in which this type of Span 80 vesicles (**EPV**) containing encapsulated anti-tumor drugs is used, are in progress.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ijpharm.2010.01.033.

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