Spermidininium closo-dodecaborate-encapsulating liposomes as efficient boron delivery vehicles for neutron capture therapy†

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Boron neutron capture therapy (BNCT) has been attracting growing interest as one of the minimally invasive cancer therapies.1–3 Mercaptoundecahydrododecaborate (Na2[B12H11SH]; Na2BSH) and L-p-boronophenylalanine (L-BPA) have been used in BNCT for many years. L-BPA, in particular, has been widely used for the treatment of not only melanoma but also brain tumor4 and head and neck cancer5 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4 The accelerator-based BNCT is now undergoing phase I clinical study for the treatment of brain tumor and head and neck cancer3 because it can be taken up selectively by tumor cells through an amino acid transporter.4

In recent years, liposomal 10B carriers have attracted attention as some of the efficient boron delivery systems in BNCT.7–10 Several efficient in vivo BNCTs have been reported. Yanagi and coworkers demonstrated the first antitumor effect of Na2BSH-encapsulating liposomes conjugated with a monoclonal antibody specific for the carcinoembryonic antigen.9a-b Maruyama and coworkers developed transferrin-conjugating Na2BSH-encapsulating liposomes.9d,10 Although they succeeded in completely suppressing tumor growth in mice after neutron irradiation, the concentration of inner 10B of liposomes was limited in preparation due to osmotic reasons. For this reason, boron lipids embedded within the liposome bilayer have been studied.10–12 Hawthorne and coworkers developed liposomes incorporating Na2[1-(2-B10H9)-2-NH3B10H8] into the internal aqueous core and K[nido-7-CH3(CH2)15-7,8-C2B9H11] into the bilayer membrane to increase the boron content in liposomes.8,9,13

We previously developed Na2BSH-encapsulating 10% distearoyl boron lipid (DSBL)11b liposomes that have high boron content with excellent boron delivery efficacy to tumors.14 In this communication, we studied the effects of the counter cations of boron clusters on the preparation of high boron content liposomes for BNCT by overcoming osmotic pressure limitations.

We selected three closo-dodecaborates, Na2[B12H12], Na3[B12H4(OH)]15 and Na2[B12H11NH3]16 in addition to Na2BSH (Fig. 1). We first tested the cytotoxicity of the closo-dodecaborates toward colon 26 cells. The closo-dodecaborates are relatively nontoxic and the GI50 values of Na2[B12H12], Na2BSH, Na2[B12H11NH3], and Na2[B12H4(OH)] are 5.1, 2.1, 32.9, and 7.7 mM, respectively (Table S1 in the ESI†). Liposomes containing the closo-dodecaborates were prepared from DSPC, cholesterol, and DSPE-PEG2000 by the reverse phase evaporation method with sizes of approximately 100 nm in diameter. The results are summarized in Table 1. The final boron and phosphorus concentrations of liposome solution containing Na2[B12H12] were 3438 ± 2.0 and 2864 ± 18.3 ppm, respectively, and the B/P ratio was 1.2 (entry 1). The higher B/P ratio indicates the higher boron content in liposomes. The liposome yield was 58% based on the total phospholipid concentration in the preparation plus the total phospholipid used in the preparation. The B/P ratio of the liposome containing Na[B12H11NH3] was 2.2 (entry 2), which was slightly higher than those of liposomes containing Na2BSH, Na3[B12H4(OH)], and Na2[B12H12] (1.2–1.6, entries 1, 3, and 4). In the case of Na[B12H11NH3], an ammonium ion group served as one of the two counter cations of the closo-dodecaborate

Fig. 1 Structures of closo-dodecaborates used for encapsulation in liposomes.

† Electronic supplementary information (ESI) available: Experimental details and data. See DOI: 10.1039/c4cc04344h
read reached a maximum of 3.4 when the BSH:spd ratio was 1:1. Liposome yields showed a similar tendency to B/P ratios. The highest liposome yield was observed at the BSH to spd cation ratio of 1:1. Transmission electron microscopy (TEM) analysis of spd-BSH-encapsulating liposomes and Na2BSH-encapsulating liposomes was also carried out using Cryo-TEM (Fig. 3). It is notable that the liposomes interacted with each other in the case of Na2BSH-encapsulating liposomes, whereas the liposomes dispersed in solution without interacting with each other in the case of spd-BSH-encapsulating liposomes.

We next examined boron distribution of the spd-closo-dodecaborate-encapsulating liposomes in colon 26 tumor-bearing mice. The liposomes were injected at doses of 15, 30, and 100 mg [B] kg⁻¹ body weight via the tail veins. Na2BSH- and Na2[BSH₂H₂NH₃]⁻-encapsulating liposomes were also injected at a dose of 30 mg [B] kg⁻¹ as control experiments. The time courses of boron distribution in each organ are shown in Fig. 4. Blood boron concentrations of 460.7, 104.0, and 33.2 ppm were detected 24 h after injection of spd-BSH-encapsulating liposomes (100, 30, and 15 mg [B] kg⁻¹), respectively (Fig. 4a). Blood boron concentration in mice injected with 100 mg [B] kg⁻¹ of spd-BSH-encapsulating liposomes did not decrease notably during the 48 h period, whereas those in mice injected with 30 and 15 mg [B] kg⁻¹ of spd-BSH-encapsulating liposomes gradually decreased in a time-dependent manner. The time courses of boron concentrations in liver, kidneys, and spleen are shown in Fig. 4b-d, respectively. Boron concentrations of 528.5, 144.2, and 74.4 ppm in liver were observed 48 h after the injection of 100, 30, and 15 mg [B] kg⁻¹ of spd-BSH-encapsulating liposomes, respectively. In the meantime, maximum

**Table 1** Physical characteristics of liposomes containing closo-dodecaborates associated with sodium and various ammonium cations

<table>
<thead>
<tr>
<th>Entry</th>
<th>Boron cluster</th>
<th>B conc. a,b (ppm)</th>
<th>P conc. (ppm)</th>
<th>B/P c,d (%)</th>
<th>Yield e (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Na2BSH</td>
<td>3438 ± 2.0</td>
<td>2864 ± 18.3</td>
<td>1.2</td>
<td>58</td>
</tr>
<tr>
<td>2</td>
<td>Na2[BSH₂H₂NH₃]</td>
<td>4072 ± 22.8</td>
<td>1835 ± 38.5</td>
<td>2.2</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>Na2[BSH₂H₄OH]</td>
<td>2635 ± 18.4</td>
<td>1600 ± 99.0</td>
<td>1.5</td>
<td>39</td>
</tr>
<tr>
<td>4</td>
<td>Na2[BSH₂H₁₂]</td>
<td>3133 ± 10.3</td>
<td>1932 ± 13.3</td>
<td>1.6</td>
<td>47</td>
</tr>
<tr>
<td>5</td>
<td>(n-C₃H₉NH₂)BSH</td>
<td>2874 ± 47.7</td>
<td>2225 ± 15.8</td>
<td>1.3</td>
<td>54</td>
</tr>
<tr>
<td>6</td>
<td>(H₃NCH₂H₄NH₃)BSH</td>
<td>4711 ± 17.4</td>
<td>1833 ± 43.4</td>
<td>2.6</td>
<td>44</td>
</tr>
<tr>
<td>7</td>
<td>spd-BSH</td>
<td>13 867 ± 185.8</td>
<td>4046 ± 18.3</td>
<td>3.4</td>
<td>98</td>
</tr>
<tr>
<td>8</td>
<td>(Sperminium)BSH</td>
<td>9759 ± 139.6</td>
<td>3359 ± 44.5</td>
<td>2.7</td>
<td>87</td>
</tr>
<tr>
<td>9</td>
<td>spd-[BSH₂H₄NH₂]</td>
<td>13 970 ± 216.5</td>
<td>3943 ± 43.4</td>
<td>3.5</td>
<td>95</td>
</tr>
</tbody>
</table>

a In all cases, liposomes were prepared from DSPC, cholesterol, and DSPE-PEG2000 (1:1:0.11, molar ratio) by the REV method. b Data are expressed as means ± standard deviation (SD). c Boron and phosphorus concentrations of liposome solution were determined by ICP-AES. d Liposome yields were calculated from the phosphorus concentration of liposome solution based on the total phospholipids used in preparation. e Liposome yield was 95% (entry 9).
tumor boron concentrations of 202.7 and 82.4 ppm were achieved 36 h after injection at doses of 100 and 30 mg [B] kg⁻¹, respectively. Even at the low boron dose of 15 mg [B] kg⁻¹, the tumor boron concentration was 34.0 ppm at 36 h after injection (Fig. 4e). We also demonstrated the boron distribution of Na₂B₁₂H₁₁NH₃-encapsulating liposomes in tumor-bearing mice for comparison. Although blood and liver boron concentrations after injection of Na₂B₁₂H₁₁NH₃-encapsulating liposomes at a dose of 30 mg [B] kg⁻¹ were similar to those after injection of spd-B₁₂H₁₁NH₃-encapsulating liposomes at a dose of 30 mg [B] kg⁻¹, kidney and spleen boron concentrations after injection of Na₂B₁₂H₁₁NH₃-encapsulating liposomes were lower than those after injection of spd-B₁₂H₁₁NH₃-encapsulating liposomes up to 48 h. The tumor boron concentration at 36 h after injecting Na₂B₁₂H₁₁NH₃-encapsulating liposomes was 31.9 ppm, although the clearance of Na₂B₁₂H₁₁NH₃-encapsulating liposomes was slow (Fig. 4e).

A similar tendency was observed in spd-B₁₂H₁₁NH₃-encapsulating liposomes (Fig. S1, ESI†). Blood, kidney, and spleen boron concentrations gradually decreased after injection. Maximum tumor boron concentrations of 242.2, 88.7, and 35.4 ppm were achieved 6 h after injection at doses of 100, 30, and 15 mg [B] kg⁻¹, respectively. Interestingly, significant tumor boron accumulation was also observed in the case of Na₂B₁₂H₁₁NH₃-encapsulating liposomes.

Finally, we examined the antitumor effect of liposomes containing spd closo-dodecaborates in colon 26 tumor bearing mice exposed to thermal neutron irradiation. Thermal neutron irradiation of the tumor-transplanted left thighs of mice was carried out 36 h after injection. The tumor growth curves of mice are shown in Fig. 5 (and in Fig. S2, ESI†). “Hot control (−●−)” and “Cold control (−×−)” represent tumor volumes of mice injected with saline with and without thermal neutron irradiation, respectively. Tumor growth was significantly suppressed in mice treated with spd-[¹⁰B₂H₁₁NH₃] and spd-[¹⁰B₂H₁₁NH₃]-encapsulating liposomes at doses of 15, 30, and 100 mg [¹⁰B] kg⁻¹ and exposed to thermal neutron irradiation. The tumor completely disappeared within three weeks even when a dose of 15 mg [¹⁰B] kg⁻¹ was employed. Liposomes containing Na⁺[¹⁰B₂H₁₁NH₃] and Na⁺[¹⁰B₂H₁₁NH₃] also inhibited tumor growth at a dose of 30 mg [¹⁰B] kg⁻¹, and the tumor was completely controlled three weeks after thermal neutron irradiation. Tumor growth was suppressed in mice treated with Na⁺[¹⁰B₂H₁₁NH₃] solution (100 mg [¹⁰B] kg⁻¹) during the two weeks after thermal neutron irradiation. However, the tumor started to grow thereafter (Fig. 5). In contrast, tumor growth was not suppressed in mice treated with Na⁺[¹⁰B₂H₁₁NH₃] solution (100 mg [¹⁰B] kg⁻¹) even after thermal neutron irradiation (Fig. S2, ESI†).

Fig. 6 shows the survival curve of tumor-bearing mice after thermal neutron irradiation. All untreated mice without thermal neutron irradiation died within two weeks. Thermal neutron irradiation enhanced mouse survival and all mice exposed to thermal neutron irradiation died within 78 days. Prolonged survival was observed in mice injected with spd-[¹⁰B₂H₁₁NH₃]- and spd-[¹⁰B₂H₁₁NH₃]-encapsulating liposomes; 72% of the mice that received a dose of 15 mg [¹⁰B] kg⁻¹ survived up to 100 days after the thermal neutron irradiation. Furthermore, a remarkable antitumor effect...
was observed in the mice treated with spd-[10B]SH-encapsulating liposomes at a dose of 30 mg [10B] kg\(^{-1}\); 100% of the mice survived up to 100 days after the thermal neutron irradiation.

We succeeded in the preparation of high boron content liposomes. The use of spd as a counter cation of closo-dodecaborates was essential to obtain the liposomes with high yields and high B/P ratios. All of the mice injected with 30 mg [10B] kg\(^{-1}\) of spd-[10B]SH-encapsulating liposomes were completely cured while five of seven mice injected with 15 mg [10B] kg\(^{-1}\) of spd-[10B]SH- and spd-[10B\(_2\)H\(_{12}\)NH\(_3\)]-encapsulating liposomes were cured 100 days after thermal neutron irradiation. The results indicate that the total amount of phospholipids could be reduced to less than one-seventh of those used to prepare Na\(_2\)[10BSH]-encapsulating liposomes.

19 We believe that the spd-closo-dodecaborate-encapsulating liposomes are promising candidates for clinical use in BNCT.

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Notes and references
18 All protocols were approved by the Institutional Animal Care and Use Committee of Gakushuin University.
19 Conventionally, a preinjection of liposome at a high dose was given for an achievement of targeting through saturation of liver's scavenging capacity (see; Y. Y. Kao and R. L. Juliano, *Biochem. Biophys. Acta*, 1981, 677, 453). Such a high liposome dose may cause possible liver toxicity, since the liver's normal scavenging function is impaired. Indeed, an important character of an approved liposomal formulation (doxil) encapsulating an anticancer drug doxorubicin is the very high concentration of the encapsulated drug (also see; P. G. Tardi, N. L. Boman and P. R. Cullis, *J. Drug Targeting*, 1996, 4, 129).