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A phase I and pharmacokinetic study of NK105, a paclitaxel-incorporating micellar nanoparticle formulation

T Hamaguchi*[,1], K Kato[1], H Yasui[1], C Morizane[1], M Ikeda[1], H Ueno[1], K Muro[1], Y Yamada[1], T Okusaka[1], K Shirao[1], Y Shimada[1], H Nakahama[2] and Y Matsumura[3]

[1]Department of Medicine National Cancer Center Hospital, 5-1-1 Tsukiji, Chuo-ku, Tokyo 104-0045, Japan; [2]Clinical Trial Coordinating Division, National Cancer Center Hospital, 5-1-1 Tsukiji, Chuo-ku, Tokyo 104-0045, Japan; [3]Investigative Treatment Division, Research Center for Innovative Oncology, National Cancer Center Hospital East, 6-5-1 Kashiwanoha, Kashiwa, 277-8577, Japan

This phase I study was designed to examine the maximum tolerated dose (MTD), the dose-limiting toxicities (DLTs), the recommended dose (RD) for phase II, and the pharmacokinetics of NK105, a new polymeric micelle carrier system for paclitaxel (PTX). NK105 was administered as a 1-h intravenous infusion every 3 weeks, without antiallergic premedication. The starting dose was 10 mg m^{-2}, and the dose was escalated according to the accelerated titration method. Nineteen patients were recruited. The tumour types treated included pancreatic ($n=11$), bile duct ($n=5$), gastric ($n=2$), and colonic ($n=1$) cancers. Neutropenia was the most common haematological toxicity. A grade 3 fever developed in one patient given 180 mg m^{-2}. No other grades 3 or 4 nonhaematological toxicities, including neuropathy, was observed during the entire study period. DLTs occurred in two patients given 180 mg m^{-2} (grade 4 neutropenia lasting for more than 5 days). Thus, this dose was designated as the MTD. Grade 2 hypersensitivity reactions developed in only one patient given 180 mg m^{-2}. A partial response was observed in one patient with pancreatic cancer. The maximum concentration (C_{max}) and area under the concentration (AUC) of NK105 were dose dependent. The plasma AUC of NK105 at 150 mg m^{-2} was approximately 15-fold higher than that of the conventional PTX formulation. NK105 was well tolerated, and the RD for the phase II study was determined to be 150 mg m^{-2} every 3 weeks. The results of this phase I study warrant further clinical evaluation.

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Paclitaxel (PTX), an antimicrotubule agent, has a wide spectrum of antitumour activity including ovarian, breast, stomach, lung, and head and neck cancers (Rowinsky *et al*, 1990; Carney, 1996; Crown and O'Leary, 2000). The clinically used PTX preparation is a mixture of Cremophor EL and ethanol because of PTX's poor water solubility. However, the use of Cremophor EL is known to be associated with acute hypersensitivity reactions (Weiss *et al*, 1990; Rowinsky and Donehower, 1995; Kloover *et al*, 2004). Other PTX preparations that have been categorised as drug delivery systems (DDS) have also been developed. These preparations include Xyotax (polyglutamate-conjugated PTX; Singer *et al*, 2003; Boddy *et al*, 2005), Abraxane (PTX coated with albumin; Ibrahim *et al*, 2002; Deisai *et al*, 2003; Nyman *et al*, 2005), and Genexol-PM (a PTX micelle in which PTX has been simply solubilised; Kim *et al*, 2004). The common advantage shared by these formulations is that they are injectable intravenously without the mixture of Cremophor EL and ethanol. Among them, Abraxane has been approved for metastatic breast cancer by the Food and Drug Administration in the USA based on the results of a randomised phase 3 trial. In this trial, Abraxane demonstrated significantly higher response rates, compared with standard PTX, and a significantly longer time to progression (Gradishar *et al*, 2005). In addition, the incidence of grade 4 neutropenia was significantly lower for Abraxane than for PTX. However, peripheral sensory neuropathy was more common in the arm (Gradishar *et al*, 2005).

NK105 is a PTX-incorporating 'core-shell-type' polymeric micellar nanoparticle formulation (Hamaguchi *et al*, 2005). This particle can be injected intravenously without the use of Cremophor EL or ethanol as a vehicle. Therefore, NK105 is expected to possess a clinical advantage similar to that of the above-mentioned PTX formulations. The difference between NK105 and the other PTX dosage forms is that NK105 is expected to yield a markedly higher plasma and tumour area under the concentration (AUC), compared with those for the other PTX formulations. Moreover, regarding the toxic profiles, the repeated administration of NK105 to rats at 7-day intervals produced significantly fewer toxic effects on peripheral nerves than free PTX. Macromolecular drugs, including NK105, have been developed based on the characteristic macroscopic features of solid tumours, such as hypervasculature, the presence of vascular permeability factors stimulating extravasation within cancer, and the suppressed lymphatic clearance of macromolecules. These characteristics, which are unique to solid tumours, constitute the basis of the enhanced permeability and retention (EPR) effect (Matsumura and Maeda, 1986; Maeda *et al*, 2000; Duncan, 2003). The *in vivo*

*Correspondence: Dr T Hamaguchi; E-mail: thamaguc@ncc.go.jp
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antitumour activity of NK105 was significantly more potent than that of free PTX, probably because of enhanced tumour exposure through the EPR effect (Hamaguchi *et al*, 2005).

We conducted a phase I clinical trial using NK105 in patients with advanced solid tumours. The objectives of this trial were to determine the maximum tolerated dose (MTD), the phase II recommended dose (RD), and the pharmacokinetics of NK105.

PATIENTS AND METHODS

The protocol and all materials were approved by the Institutional Review Board of the National Cancer Center, Tokyo. This study was conducted in compliance with the Good Clinical Practice Guidelines of the International Conference on Harmonization and the Declaration of Helsinki Principles. Written informed consent was obtained from all the patients.

Therapeutic agent

NK105 was supplied by Nippon Kayaku Co. Ltd. (Tokyo, Japan) in 20-ml glass vials containing a dose equivalent to 30 mg of PTX. When reconstituted in 10 ml of 5% glucose solution and diluted with a total volume of 250 ml of 5% glucose, the reconstituted solution was stable for 24 h at room temperature. In our preclinical study, DLS and HPLC analysis showed that less than 2% of PTX incorporated in the micelles was released for 24 h at room temperature (data not shown).

Figure 1 shows the schematic structure of NK105, a PTX-entrapped polymeric micelle formulation. The NK105 polymers were constructed using polyethylene glycol (PEG) as the hydrophilic component and modified polyaspartate as the hydrophobic component. PEG is believed to form the outer shell of the micelle, producing a 'stealth' effect that enables NK105 to avoid being captured by the reticuloendothelial system.

The modified polyaspartate chain is hydrophobic and is believed to form the hydrophobic inner core of the micelles in aqueous media. The hydrophobic inner core enables NK105 to entrap a sufficient amount of PTX. NK105 has a diameter of about 90 nm (Hamaguchi *et al*, 2005).

Patients

Patients with solid tumours refractory to conventional chemotherapy and for whom no effective therapy was available were eligible for enrolment in this study, provided that the following criteria were met: a histologically confirmed malignant tumour; a performance status of $\leqslant 2$; an age of $\geqslant 20$ and <75 years; a normal haematological profile (neutrophil count $\geqslant 2000\,mm^{-3}$, platelet count $\geqslant 100\,000\,mm^{-3}$, hemoglobin $\geqslant 9\,g\,dl^{-1}$); normal hepatic function (total bilirubin level $\leqslant 1.5\,mg\,dl^{-1}$, AST and ALT $\leqslant 2.5$ times the upper normal limit); normal renal function (serum creatinine $\leqslant 1.5\,mg\,dl^{-1}$); normal cardiac function (New York Heart Association (NYHA) classification of $\leqslant 1$); normal pulmonary function ($PaO_2 \geqslant 60$ mm Hg); no chemotherapy within 4 weeks (6 weeks for nitrosourea or mitomycin C) of the administration of NK105; and a life expectancy of more than 2 months. Patients with serious infections (including hepatitis B, hepatitis C, or HIV) were ineligible for enrolment in the study. Patients who had been previously treated with a taxane were excluded because of assessing neuropathy. Patients were also excluded if they were pregnant or lactating. Additionally, any patient whom the investigators considered ineligible was excluded.

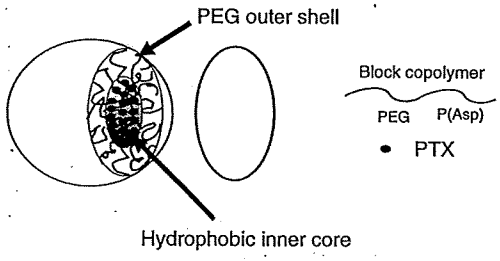

Figure 1 Schematic structure of NK105. A polymeric micelle carrier of NK105 consists of a block copolymer of PEG (molecular weight of about 12 000) and modified polyaspartate. PEG is believed to be the outer shell of the micelle. PEG is believed to form the outer shell of the micelle. NK105 has a highly hydrophobic inner core, and therefore can entrap a sufficient amount of PTX.

Drug administration

NK105 was dissolved in 5% glucose solution for injection at room temperature. NK105 was administered intravenously without in-line filtration and without premedication. NK105 solution was infused using an electric pump at a speed of $250\,ml\,h^{-1}$.

Dosage and dose escalation

The starting dosage of NK105 was $10\,mg\,m^{-2}$, which is one-third of the toxic dose low in dogs. NK105 was administered once every 3 weeks, and the treatment was continued unless a severe adverse event or disease progression was observed. Dose escalation was performed according to the previously described accelerated titration method (Simon *et al*, 1997; Matsumura *et al*, 2004).

Toxicity was graded from 1 to 4 using the National Cancer Institute Common Toxicity Criteria (version 2.0). Intrapatient dose escalation was not permitted. The MTD was defined as the level at which two out of six patients experienced dose-limiting toxicities (DLTs). The recommended dosage for a phase II trial was defined by the Efficacy and Safety Assessment Committee based on the safety, pharmacokinetics, and efficacy results of this trial. DLT was defined as grade 4 neutropenia lasting more than 5 days, a platelet count of less than $25\,000\,\mu l^{-1}$, or grade 3 or higher non-haematological toxicity, with the exception of nausea, vomiting, appetite loss, and hypersensitivity.

Pretreatment assessment and follow-up care

A complete medical history and physical examination, performance status evaluation, complete blood cell count (CBC), blood chemistry, urinalysis, electrocardiogram (ECG), and a computed tomography (CT) examination were performed in each patient. Other examinations were performed only in the presence of a specific clinical indication. Patients were physically examined every day until the second administration of NK105; CBC and blood chemistry tests were performed on day 3 and weekly thereafter. An ECG examination was repeated before each administration of NK105. Tumour marker levels were also measured before every administration. Tumour response was evaluated according to the Response Evaluation Criteria in Solid Tumors criteria (Therasse *et al*, 2000).

Liquid chromatography/tandem mass spectrometry determination of PTX concentrations

The PTX concentrations determined in the present phase I study represented the total drug concentrations (both micelle-entrapped and released). It was difficult to measure released PTX and micelle-entrapped PTX separately, because the equilibrium between both forms could not keep constant during the separating procedure. PTX was extracted from human plasma (0.2 ml) or urine (0.5 ml) by deproteinisation with acetonitrile. The quantifications of PTX in plasma and urine were performed using liquid chromatography/tandem mass spectrometry. Reversed-phase column-switching

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chromatography was conducted using an ODS column and detection was enabled by electrospray ionisation of positive mode.

Pharmacokinetic analysis

The following pharmacokinetic parameters were calculated for each patient using a non-compartmental model using the WinNonlin Professional version 4.1 program (Pharsight Corporation, Mountain View, CA, USA). The maximum concentration (C_{max}) was the maximum observed plasma concentration of PTX, and the time-to-the-maximum concentration (T_{max}) was the time corresponding to C_{max}. The area under the concentration (AUC)–time curve from time zero up to the last quantifiable time point (AUC_{0-t}) was calculated using the linear trapezoidal rule, and the area under the concentration–time curve from zero until infinity ($AUC_{0-inf.}$) was calculated as the sum of AUC_{0-t} and the extrapolated area under the zero moment curve from the last quantifiable time point to infinity calculated by dividing the plasma concentration of the last quantifiable time point (observed value) by the elimination rate constant. The half-life of the terminal phase ($t_{1/2Z}$) was calculated as $\log_e 2/\lambda z$, where λz is the elimination rate constant calculated from the terminal linear portion of the log of the concentration in plasma. Total clearance (CL_{tot}), the volume of distribution at steady state (V_{ss}), and renal clearance (CL_r) were calculated using the following equations, where D is the dose and $AUMC_{inf.}$ the area under the first moment curve from time zero until infinity:

$$CL_{tot} = D/AUC_{inf.}$$

$$V_{ss} = AUMC_{inf.}/AUC_{inf.} \times CL_{tot}$$

$$CL_r = \text{cumulative urinary excretion}/AUC_{inf.} / \text{body surface area}$$

RESULTS

Patient characteristics

Nineteen eligible patients were recruited for the study (Table 1). All the patients had received chemotherapy before enrolment. Prior therapies ranged from 1 to 3 regimens of chemotherapy. None of the patients had received taxane chemotherapy. All the patients were included in the safety and response analyses.

Dosing

Dosage escalation started at 10 mg m^{-2} and was increased up to 180 mg m^{-2}. In total, 73 administrations were performed in 19 patients. Eighteen patients received more than two administrations. The maximum number of treatments was 14 courses at 150 mg m^{-2}; the average number of administrations at all levels was 3.8 courses. Up until 80 mg m^{-2}, grade 2 toxicity was not observed during the first course.

According to the original protocol, the dosage of NK105 should have been doubled for each escalation until grade 2 toxicity. However, the safety committee recommended that the dosage should be raised by 40% instead of 100% at 110 mg m^{-2} and that a modified Fibonacci escalation method should be implemented. Therefore, we recruited three patients at dosage level 5 (110 mg m^{-2}) and re-started the dose identification study using a modified Fibonacci method.

Table 1 Patient characteristics

Number of patients	19
Male/female	13/6
Age (years)	
Median	57
Range	43–72
ECOG PS	
Median	0
0	10
1	9
Prior treatment	
Chemotherapy regimens	
Median	1
Range	1–3

Haematological toxicity

Significant myelosuppression was not observed up to level 4 (80 mg m^{-2}). At level 7 (180 mg m^{-2}), two out of five patients appeared to have acquired DLTs, namely grade 4 neutropenia lasting for more than 5 days. On the basis of these results, 180 mg m^{-2} was considered to be the MTD, with neutropenia as the DLT. Since a dosage of 150 mg m^{-2} was considered to be the recommended dosage for phase II studies, an additional four patients were enrolled at a dosage of 150 mg m^{-2}; one patient developed DLT, namely grade 4 neutropenia lasting for more than 5 days (Table 2). During the entire period of this study, G-CSF was never used to rescue patients.

Nonhaematological toxicity

The NK105 injection was generally uneventful and well tolerated in terms of nonhaematological toxicities (Table 2). Most of the toxicities were grade 1; none of the patients manifested grade 4 toxicity. A few patients developed a grade 1 elevation in AST or ALT, but these changes were transient. Pain or local toxicity in the area of the injection was not observed in any of the patients treated with NK105. No infusion-related reactions were observed; such reactions sometimes occur during liposomal drug administration. Patients were not premedicated with steroids or antihistamines. Only one patient at 180 mg m^{-2} developed grade 2 hypersensitivity. After the first course, the patient received premedication of hydrocortisone and did not develop such hypersensitivity after that. The other 18 patients did not experience any hypersensitivity during the study. Neuropathy occurred in a typical stocking/glove distribution and was manifested by numbness. Three patients at level 6 (150 mg m^{-2}) and three patients at level 7 (180 mg m^{-2}) experienced grade 1 neurotoxicity during 1 cycle. Of the four patients who received multicycle treatment more than five times, only three patients developed grade 2 neuropathy and the other patient developed grade 1 neuropathy. Even one patient who received 14 cycles of treatment experienced only grade 2 neuropathy.

Pharmacokinetics

The plasma concentrations of PTX after the intravenous infusion of NK105 were determined in each of the patients enrolled at a dose of 150 mg m^{-2} (Figure 2A). The C_{max} (Figure 2B) and AUC (Figure 2C) increased as the doses were escalated from 10 to 180 mg m^{-2}. The pharmacokinetic parameters are summarised in Table 3. The $t_{1/2Z}$ ranged from 7.0 to 13.2 h, and a slight tendency towards a dose-dependent extension of this parameter was observed. The CL_{tot} ranged from 280.9 to 880.4 ml h^{-1} m^{-2}, and the V_{ss} ranged from 3668.9 to 10 400.3 ml m^{-2}. Although these parameters were slightly reduced depending on the dose, linear pharmacokinetics was assumed to have been observed in the dose range from 10 to 180 mg m^{-2}. The AUC of NK105 at 150 mg m^{-2} (recommended phase II dose) was about 15-fold larger than that of conventional PTX at dose of 210 mg m^{-2} (conventional dose for a

Table 2 Haematological and nonhaematological toxicities (cycle 1 and all cycles)

	10–110 mg m^{-2} (n=7) grade				150 mg m^{-2} (n=7) grade				180 mg m^{-2} (n=7) grade			
	1	2	3	4	1	2	3	4	1	2	3	4
Cycle 1												
Leukopenia	2	0	2	0	1	5	1	0	1	1	3	0
Neutropenia	1	0	1	1	0	2	1	3[a]	0	0	3	2[b]
Thrombocytopenia	1	0	0	0	2	0	0	0	4	0	0	0
Hemoglobin	1	0	0	0	2	2	0	0	1	0	0	0
Neuropathy	0	0	0	0	3	0	0	0	3	0	0	0
Myalgia	1	0	0	0	3	0	0	0	2	1	0	0
Arthralgia	1	0	0	0	4	0	0	0	3	0	0	0
Hypersensitivity	0	0	0	0	0	0	0	0	0	1	0	0
Rash	1	0	0	0	1	3	0	0	4	0	0	0
Fatigue	1	0	0	0	5	0	0	0	4	0	0	0
Fever	2	0	0	0	2	0	0	0	1	0	1	0
Anorexia	0	0	0	0	3	0	0	0	1	0	0	0
Nausea	1	0	0	0	1	0	0	0	1	0	0	0
Stomatitis	0	0	0	0	1	0	0	0	1	0	0	0
Alopecia	3	0	—	—	5	0	—	—	5	0	—	—
All cycles												
Leukopenia	3	0	2	0	1	4	2	0	1	1	3	0
Neutropenia	1	0	1	1	1	1	1	4	0	0	3	2
Thrombocytopenia	1	0	0	0	3	0	0	0	4	0	0	0
Hemoglobin	1	0	0	0	1	5	0	0	1	0	0	0
Neuropathy	2	0	0	0	1	3	0	0	4	0	0	0
Myalgia	1	1	0	0	3	0	0	0	2	1	0	0
Arthralgia	2	0	0	0	4	0	0	0	3	0	0	0
Hypersensitivity	0	0	0	0	0	0	0	0	0	1	0	0
Rash	1	0	0	0	3	3	0	0	4	0	0	0
Fatigue	3	0	0	0	5	1	0	0	4	0	0	0
Fever	3	0	0	0	3	1	0	0	1	0	1	0
Anorexia	2	1	0	0	2	1	0	0	2	0	0	0
Nausea	1	0	0	0	1	0	0	0	2	0	0	0
Stomatitis	1	0	0	0	2	0	0	0	1	0	0	0
Alopecia	2	2	—	—	4	3	—	—	4	1	—	—

[a]One of three patients developed DLT, namely grade 4 neutropenia lasting for more than 5 days. [b]These two patients developed DLT, namely grade 4 neutropenia lasting for more than 5 days.

3-week regimen in Japanese patients) (Tamura *et al*, 1995). The V_{ss} and CL_{tot} of NK105 were significantly lower than those of conventional PTX.

The cumulative urinary excretion rates of PTX (0–73 h) after the administration of NK105 were 2.8–9.2%. These values were low, similar to those reported after the administration of conventional PTX (Tamura *et al*, 1995). The CL_r ranged from 11.7 to 66.4 ml h^{-1} m^{-3}, and was slightly decreased with the dose. Since the ratio of CL_r to CL_{tot} was 3–9%, CL_r hardly contributed to CL_{tot}.

Therapeutic response

Six patients (two gastric, two bile duct, one colon, and one pancreatic) were evaluated as having had a stable disease for longer than 4 weeks at the time of the study's completion. A partial response was seen in a patient with metastatic pancreatic cancer who had been treated at 150 mg m^{-2}, and in whom the size of the liver metastasis had decreased by more than 90%, compared to the baseline scan (Figure 3A). This patient had previously undergone treatment with gemcitabine. The antitumour response was maintained for nearly 1 year. In a patient with stomach cancer who was treated at 150 mg m^{-2}, about 40% reduction was observed in a peritoneal metastasis, but a liver metastasis remained stable (Figure 3B).

DISCUSSION

The observed toxicities of NK105 were similar to those expected for conventional PTX. The DLT was neutropenia. The recommended phase II dose using a 3-week schedule was determined to be 150 mg m^{-2}. This recommended dose of NK105 is less than that of conventional PTX (210 mg m^{-2}). Since the plasma AUC of the recommended dose of NK105 was 15- to 20-fold higher than that of the recommended dose of conventional PTX (210 mg m^{-2}), whether the so-called therapeutic window of NK105 is wider than that of conventional PTX should be determined in a future phases II or III trial, although the therapeutic window of NK105 appears to be wider than that of free PTX in mice experiments (Hamaguchi *et al*, 2005).

In general, haematological toxicity was mild and well managed in this trial. PTX is known to cause cumulative peripheral neuropathy resulting in the discontinuation of treatment with PTX. At a dose of 150 mg m^{-2}, three out of seven patients experienced only grade 1 neuropathy during the first cycle. Since the patients enrolled in this trial had almost intractable cancer, such as pancreatic or stomach, a relatively small number of patients received multiple cycles of treatment. Therefore, NK105-related neurotoxicity could not be evaluated in this study. However, three out of four patients who received more than five cycles of treatment experienced transient grade 2 peripheral neuropathy, and other patient developed transient grade 1 peripheral neuropathy. Future phase II trials may clarify whether NK105 is less toxic in terms of peripheral neuropathy when compared with conventional PTX, Abraxane, and other PTX compounds. Another characteristic adverse effect of PTX is hypersensitivity, which may be mainly caused by Cremophor EL. Since NK105 is not formulated in a Cremophor EL-containing solvent, we presumed that hypersensitivity would be diminished.

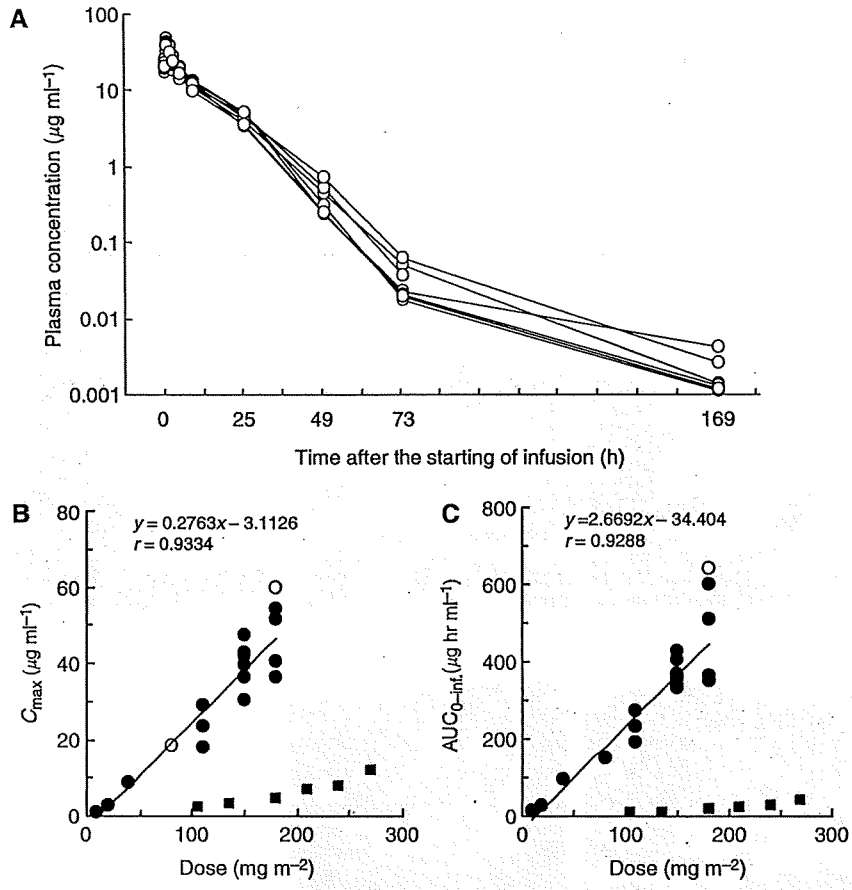

Figure 2 (**A**) Individual plasma concentrations of PTX in seven patients following 1-h intravenous infusion of NK105 at a dose of 150 mg m^{-2}. (**B**) Relationships between dose and C_{max}, and (**C**) between dose and $AUC_{0-inf.}$ of PTX in patients following 1-h intravenous infusion of NK105. Regression analysis for dose *vs* C_{max} was applied using all points except one patient at 80 mg m^{-2} whose medication time became 11 min longer and one patient at 180 mg m^{-2} who had medication discontinuation and steroid medication. (Plots were shown as open circle). Regression analysis for dose *vs* $AUC_{0-inf.}$ was applied using all points except one patient who had medication discontinuation and steroid medication. (Plot was shown as open circle.) Relationships between dose and C_{max}, and $AUC_{0-inf.}$ in patients following conventional PTX administration were plotted (closed square, see Tamura *et al*, 1995).

Table 3 Pharmacokinetic parameters

	Dose (mg m^{-2})	*n*	C_{max} (μg ml^{-1})	$AUC_{0-inf.}$ (μg h ml^{-1})	$t_{1/2}$ (h)	CL_{tot} (ml h^{-1} m^{-2})	V_{ss} (ml m^{-2})	UE[a] (%)	CL_r (ml h m^{-2})
NK105	10	1	0.9797	11.4	9	880.4	10400.3	7.5	66.4
	20	1	2.8971	29.1	8.5	687.9	8027	8.6	59.4
	40	1	8.8334	93.9	13.2	426.1	5389.8	5.2	22
	80	1	18.4533	149.3	7	535.8	5875.8	4.7	25.3
	110	3	23.3924	232	9.7	483.3	5881.2	7.6	35.6
			±5.6325	±39.1	±1.6	±82.7	±1512.0	±1.7	±6.9
	150	7	40.1699	369.8	10.6	408.6	4527.1	5.3	21.6
			±5.5334	±35.2	±1.3	±37.3	±639.5	±1.5	±6.5
	180	4[b]	45.6278	454.5	11.3	416.5	4983.4	5.9	23.7
			±8.6430	±119.1	±0.6	±104.7	±887.5	±1.4	±4.2

[a]UE, urinary excretion. [b]One patient at 180 mg m^{-2} level was omitted from the calculation of summary pharmacokinetic parameters, as there was administrating interruption for developing allergic reactions.

Indeed, the results of this clinical trial show that NK105 can be administered safely as a short infusion (1 h) without the administration of antiallergic agents like dexamethasone and antihistamine, although one patient at 180 mg m^{-2} developed transient grade 2 hypersensitivity at the first course. Therefore, NK105 may offer advantages in terms of safety and patient convenience and comfort.

The pharmacokinetic analysis of NK105 suggests that the distribution of PTX-incorporating micelles is mostly restricted to the plasma and, in part, to extracellular fluids in the body. This is consistent with data obtained in a preclinical study (Hamaguchi *et al*, 2005) showing that the distribution of NK105 in tissues is characterised by an EPR effect, similar to that of tumour and inflammatory lesions, or by the presence of a reticuloendothelial

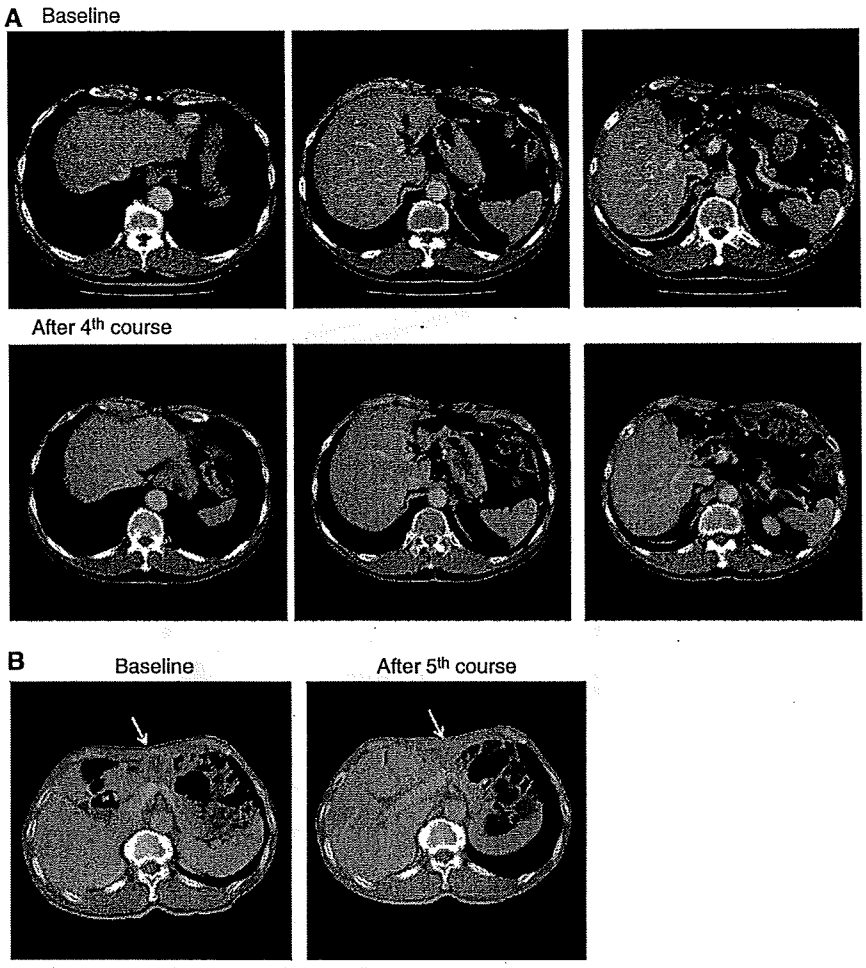

Figure 3 Serial CT scans. (**A**) A 60-year-old male with pancreatic cancer who was treated with NK105 at a dose level of 150 mg m^{-2}. Baseline scan (upper panels) showing multiple metastasis in the liver. Partial response, characterized by a more than 90% decrease in the size of the liver metastasis (lower panels) compared with the baseline scan. The antitumour response was maintained for nearly 1 year. (**B**) A 64-year-old male with stomach cancer who was treated with NK105 at a dose level of 150 mg m^{-2}. Baseline scan (left panel) showing a peritoneal metastasis and liver metastasis. About 40% reduction (right panel) was observed in peritoneal metastasis, but not in the liver metastasis after fifth course.

Table 4 Pharmacokinetic parameters

	Dose (mg m^{-2})	*n*	C_{max} (μg ml^{-1})	$AUC_{0-inf.}$ (μg h^{-1} ml^{-1})	$t_{1/2}$ (h)	CL_{tot} (ml h^{-1} m^{-2})	V_{ss} (ml m^{-2})	UE (%)	CL_r (ml h m^{-2})
NK105	150	7	40.1699 ±5.5334	369.8 ±35.2	10.6 ±1.3	408.6 ±37.3	4527.1 ±639.5	5.3 ±1.5	21.6 ±6.5
PTX	210	5	6.744 ±2.733	23.18 ±10.66	13.3 ±1.5	10740 ±4860	58900 ±24700	9.45 ±3.76	1020 ±648
XYOTAX[a]	233	4	NA	1583 ±572	120 ±28	276 ±63	6200 ±2100	NA	NA
Abraxane	300	5	13.52 ±0.95	17.61 ±3.70	14.6 ±2.04	17700 ±3894	370000 ±85100	NA	NA
Genoxol-PM	300	3	3.107 ±1.476	11.58 ±4.28	11.4 ±2.4	29300 ±13800	NA	NA	NA

[a]Conjugated taxanes.

system. When compared with conventional PTX at a dose of 210 mg m^{-2} (conventional dose for a 3-week regimen in Japanese patients), NK105 at a dose of 150 mg m^{-2} (recommended phase II dose) exhibited more than 15-fold larger plasma AUC and a 26-fold lower CL_{tot}. The larger plasma AUC is consistent with the stability of the micelle formulation in plasma. The V_{ss} of NK105 was 13-fold lower than that of conventional PTX. This suggests that PTX may have a relatively lower distribution in normal tissue, including normal neural tissue, following NK105 administration. Regarding the drug distribution in tumours, nanoparticle drug carriers have been known to preferentially accumulate in tumour tissues utilising the EPR effect (Matsumura and Maeda, 1986;

Maeda *et al*, 2000; Duncan, 2003). We speculate that NK105 accumulates more in tumour tissues than free PTX, since NK105 is very stable in the circulation and exhibits a markedly higher plasma AUC than free PTX. Moreover, a polymeric micelle carrier system for a drug has the potential to enable the sustained release of the drug inside a tumour following the accumulation of micelles in the tumour tissue (Hamaguchi *et al*, 2005; Uchino *et al*, 2005; Koizumi *et al*, 2006). Regarding NK105 in particular, this sustained release may begin at a PTX-equivalent dose of $<1\,\mu g\,ml^{-1}$ (data not shown). Consequently, the released PTX is distributed throughout the tumour tissue where it kills the cancer cells directly.

In the present study, NK105 appeared to exhibit characteristic pharmacokinetics different from those of other PTX formulations including conventional PTX, Abraxane, Genexol-PM, and Xyotax. For example, previous clinical PK data at each phase II recommended dose shown that plasma AUC and C_{max} were 11.58 and 3.1 in Genexol-PM (Table 4). The antitumour activities seen in two patients with intractable cancers are encouraging. In addition, we recently demonstrated in preclinical study that combined NK105 chemotherapy with radiation exerts a significantly more potent antitumour activity, compared with combined PTX therapy and radiation (Negishi *et al*, 2006). This data on NK105 justifies its continued clinical evaluation.

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Preclinical and clinical studies of anticancer drug-incorporated polymeric micelles

YASUHIRO MATSUMURA

Investigative Treatment Division, Research Center for Innovative Oncology, National Cancer Center Hospital East, Kashiwa, Chiba, Japan

Abstract
Tumour-targeted delivery of therapeutic agents is a longstanding pharmacological goal to improve selectivity and Therapeutic Index. Most scientists have sought to use 'active' receptor-mediated tumour-targeting systems, however the 'passive' targeting afforded by the Enhanced Permeability and Retention (EPR) effects provides a versatile and non-saturable opportunity for tumour-selective delivery. Polymeric micelles are ideally suited to exploit the EPR effect, and they have been used for the delivery of a range of anticancer drugs in preclinical and clinical studies. Here I overview some of the more important approaches, assessing usefulness and seeking to identify the most promising ways to apply the phenomenon of passive targeting for improved clinical outcome.

Keywords: *Micelles, anticancer agent, EPR effect, clinical trial*

Preface

Several problems of anticancer agents are recognized, such as their low therapeutic indices and limited efficacy due to the nonselective nature of their therapeutic targets and their inability to accumulate selectively in cancer tissues. Therefore, it would be desirable to develop modalities by which cytotoxic drugs can be selectively targeted to tumour tissues and allowed to act effectively on only the cancer cells in the tumor. The role of drug delivery systems (DDS) has drawn attention in this context. DDS could be used for active or passive targeting of tumor tissues. The former refers to the development of monoclonal antibodies directed against tumour-related molecules that allow targeting of the tumour, because of specific binding between the antibody and its antigen. However, the application of DDS using monoclonal antibodies is restricted to tumours expressing high levels of related antigens.

About a quarter of a century ago, after training as a surgeon, I started my career in the field of DDS under the supervision of Prof. Maeda. We made intensive efforts to ascertain the mechanism of accumulation of macromolecules in solid tumours. Finally, we succeeded in publishing the first paper, in 1986, on the enhanced permeability and retention (EPR) effect (Matsumura and Maeda 1986). Passive targeting is based on this EPR effect. The EPR effect is based on the pathophysiological characteristics of solid tumour tissues: hypervascularity, incomplete vascular architecture, secretion of vascular permeability factors stimulating extravasation within cancer tissue, and absence of effective lymphatic drainage from tumours that impedes the efficient clearance of macromolecules accumulated in solid tumour tissues.

Several techniques to maximally use the EPR effect have been developed, e.g. modification of drug structures and development of drug carriers. Polymeric micelle-based anticancer drugs were originally developed by Prof. Kataoka et al. in late the 1980's or early 1990's (Yokoyama et al. 1990; 1991a, b, c; Kataoka et al. 1993). Polymeric micelles were expected to increase the accumulation of drugs in tumour tissues utilizing the EPR effect and to incorporate various kinds of drugs into the inner core by chemical conjugation or physical entrapment with relatively high stability. The size of the micelles

Correspondence: Y. Matsumura, Investigative Treatment Division, Research Center for Innovative Oncology, National Cancer Center Hospital East, Kashiwa, Chiba, Japan.

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can be controlled within the diameter range of 20–100 nm, to ensure that the micelles do not pass through normal vessel walls; therefore, a reduced incidence of the side effects of the drugs may be expected due to the decreased volume of distribution.

In this chapter, polymeric micelle systems for which clinical trials are now underway are reviewed.

NK105, paclitaxel-incorporating micellar nanoparticle

Paclitaxel (PTX) is one of the most useful anticancer agents known for various cancers, including ovarian, breast and lung cancers (Carney 1996; Khayat et al. 2000). However, PTX has serious adverse effects, e.g. neutropenia and peripheral sensory neuropathy. In addition, anaphylaxis and other severe hypersensitive reactions have been reported to develop in 2–4% of patients receiving the drug even after premedication with antiallergic agents; these adverse reactions have been attributed to the mixture of Cremophor EL and ethanol which was used to solubilize PTX (Weiss et al. 1990; Rowinsky and Donehower 2003). Of the adverse reactions, neutropenia can be prevented or managed effectively by administering a granulocyte colony-stimulating factor. On the other hand, there are no effective therapies to prevent or reduce nerve damage which is associated with peripheral neuropathy caused by PTX; therefore, neurotoxicity constitutes a significant dose-limiting toxicity (DLT) of the drug (Rowinsky et al. 1993; Wasserheit et al. 1996).

Preparation and characterization of NK105

To construct NK105 micellar nanoparticles (Figure 1), block copolymers consisting of polyethylene glycol (PEG) and polyaspartate, so-called PEG-polyaspartate described previously (Yokoyama et al. 1990; 1991a, b, c; Kataoka et al. 1993), were used. PTX was incorporated into polymeric micelles formed by physical entrapment utilizing hydrophobic interactions between PTX and the block copolymer polyaspartate chain. After screening of many candidate substances, 4-phenyl-1-butanol was employed for the chemical modification of the polyaspartate block to increase its hydrophobicity. Treating with a condensing agent, 1,3-diisopropylcarbodiimide, the half of carboxyl groups on the polyaspartate were esterified with 4-phenyl-1-butanol. Molecular weight of the polymers was determined to be approximately 20,000, (PEG block: 12,000; modified polyaspartate block: 8000). NK105 was prepared by facilitating the self-association of NK105 polymers and PTX. NK105 was obtained as a freeze-dried formulation and contained *ca.* 23% (w/w) of PTX, as determined by reversed-phase liquid-chromatography using an ODS column with mobile phase consisting of acetonitrile and water (9:11, v/v) and detection of ultraviolet absorbance at 227 nm. Finally, NK105, a PTX-incorporating polymeric micellar nanoparticle formulation with a single and narrow size distribution, was obtained. The weight-average diameter of the nanoparticles was approximately 85 nm ranging from 20 to 430 nm.

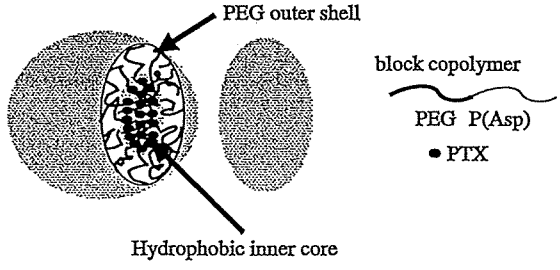

Figure 1. Preparation and characterization of NK105. The micellar structure of NK105 PTX was incorporated into the inner core of the micelle.

Pharmacokinetics and pharmacodynamics of NK105

Colon 26-bearing CDF1 mice were given a single iv injection of PTX 50 or 100 mg/kg, or of NK105 at an equivalent dose of PTX. Subsequently, the time-course changes in the plasma and tumour levels of PTX were determined in the PTX and NK105 administration groups; furthermore, the pharmacokinetic parameters of each group were also determined. NK105 exhibited slower clearance from the plasma than PTX, while NK105 was present in the plasma for up to 72 h after injection; PTX was not detected after 24 h or later of injection. The plasma concentration at 5 min ($C_{5\,min}$) and the AUC of NK105 were 11- to 20-fold and 50- to 86-fold higher for NK105 than for PTX, respectively. Furthermore, the half-life at the terminal phase ($t_{1/2}z$) was 4–6 times longer for NK105 than for PTX. The maximum concentration (C_{max}) and AUC of NK105 in Colon 26 tumours were approximately 3 times and 25 times higher for NK105 than for PTX, respectively. NK105 continued to accumulate in the tumours until 72 h after injection. The tumour PTX concentration was higher than 10 μg/g even at 72 h after the intravenous injection of NK105 50 and 100 mg/kg. By contraries, the tumour PTX concentrations at 72 h after the intravenous administration of free PTX 50 and 100 mg/kg were below detection limits and less than 0.1 μg/g, respectively.

In vivo *antitumour activity*

BALB/c mice bearing s.c. HT-29 colon cancer tumours showed decreased tumour growth rates after the administration of PTX and NK105. However, NK105 exhibited superior antitumour activity as compared with PTX ($P < 0.001$). The

antitumour activity of NK105 administered at a PTX-equivalent dose of 25 mg/kg was comparable to that obtained after the administration of free PTX 100 mg/kg. Tumour suppression by NK105 increased in a dose-dependent manner. Tumours disappeared after the first dosing to mice treated with NK105 at a PTX-equivalent dose of 100 mg/kg, and all mice remained tumour-free thereafter. In addition, less weight loss was induced in mice which were given NK105 100 mg/kg than in those which were given the same dose of free PTX.

Neurotoxicity of PTX and NK105

Treatment with PTX has resulted in cumulative sensory-dominant peripheral neurotoxicity in humans, characterized clinically by numbness and/or paraesthesia of the extremities. Pathologically, axonal swelling, vesicular degeneration, and demyelination were observed. We, therefore, examined the effects of free PTX and NK105 using both electrophysiological and morphological methods.

Prior to drug administration, there were no significant differences in the amplitude of caudal sensory nerve action potential (caudal SNAP) between two drug administration groups. On day 6 after the last dosing (at week 6), the amplitude of the caudal SNAP in the control group increased in association with rat maturation. The amplitude was significantly smaller in the PTX group than in the control group ($P < 0.01$), while the amplitude was significantly larger in the NK105 group than in the PTX group ($P < 0.05$) and was comparable between the NK105 group and the control group (Figure 2). Histopathological examination of longitudinal paraffin-embedded sections of the sciatic nerve 5 days after the sixth weekly injection revealed degenerative changes. The NK105 administration group showed only a few degenerative myelinated fibers in contrast to the PTX administration group which indicated markedly more numerous degenerative myelinated fibers.

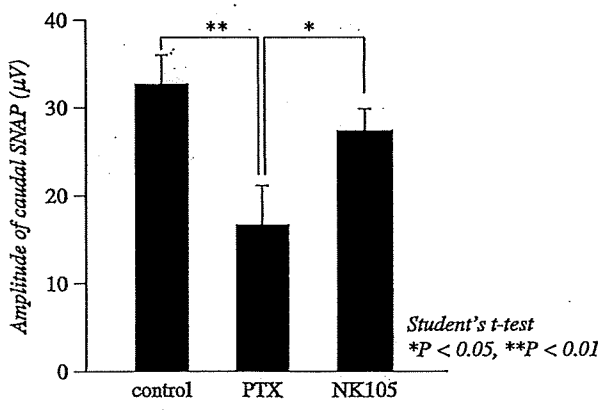

Figure 2. Effects of PTX or NK105 on the amplitude of rat caudal sensory nerve action potentials as examined 5 days after weekly injections for 6 weeks. Rats ($n = 14$) were injected with NK105 or PTX at a PTX-equivalent dose of 7.5 mg/kg. About 5% glucose was also injected in the same manner to animals in the control group.

Clinical study

A phase I study was designed to determine maximum tolerated dose (MTD), DLTs, the recommended dose (RD) for phase II and the pharmacokinetics of NK105 (Kato et al.).

NK105 was administered by 1-hour intravenous infusion every 3 weeks without anti-allergic premedication. The starting dose was 10 mg PTX equivalent/m^2, and dose escalated according to the accelerated titration method. To date, 17 patients (pts) have been treated at the following doses: 10 mg/m^2 ($n = 1$); 20 mg/m^2 ($n = 1$); 40 mg/m^2 ($n = 1$); 80 mg/m^2 ($n = 1$); 110 mg/m^2 ($n = 3$); 150 mg/m^2 ($n = 5$); 180 mg/m^2 ($n = 5$). Tumor types treated have included: pancreatic ($n = 9$), bile duct ($n = 5$), gastric ($n = 2$), and colon ($n = 1$). Neutropenia has been the predominant hematological toxicity and grade 3 or 4 neutropenia was observed in pts treated at 110, 150 and 180 mg/m^2. One patient at 180 mg/m^2 developed grade 3 fever. No other grade 3 or 4 non-hematological toxicity including neuropathies was observed. DLTs were observed in pts with at the 180 mg/m^2 (grade 4 neutropenia lasting for more than 5 days), which was determined as MTD. Allergic reactions were not observed in any of the patients except one patient at the 180 mg/m^2. A partial response was observed in one pancreatic cancer pt who received more than 12 courses of NK105 (Figure 3). Despite of the long time usage, only grade 1 or 2 neuropathy was observed by modifying the dose or period of drug administration. Colon and gastric cancer pts experienced stable disease lasting 10 and 7 courses, respectively. The C_{max} and AUC of NK105 showed dose-dependent characteristics. The plasma AUC of NK105 at 180 mg/m^2 was approximately 30-fold higher than that of commonly-used paclitaxel formulation.

Accrual is ongoing at the 150 mg/m^2 dose level to determine RD. DLT was grade 4 neutropenia. NK105 generates prolonged systemic exposure to PTX in plasma. Tri-weekly 1-hour infusion of NK105 was feasible and well tolerated, with antitumor activity in pancreatic cancer pt. NK105 is planning to be evaluated in Phase II studies of patients with pancreatic, gastric, or ovarian cancer.

NC-6004, cisplatin-incorporating micellar nanoparticle

Cisplatin [*cis*-dichlorodiammineplatinum (II): CDDP] is a key drug in the chemotherapy for cancers, including lung, gastrointestinal, and genitourinary cancer (Roth 1996; Horwich et al. 1997). However, we often find that it is necessary to

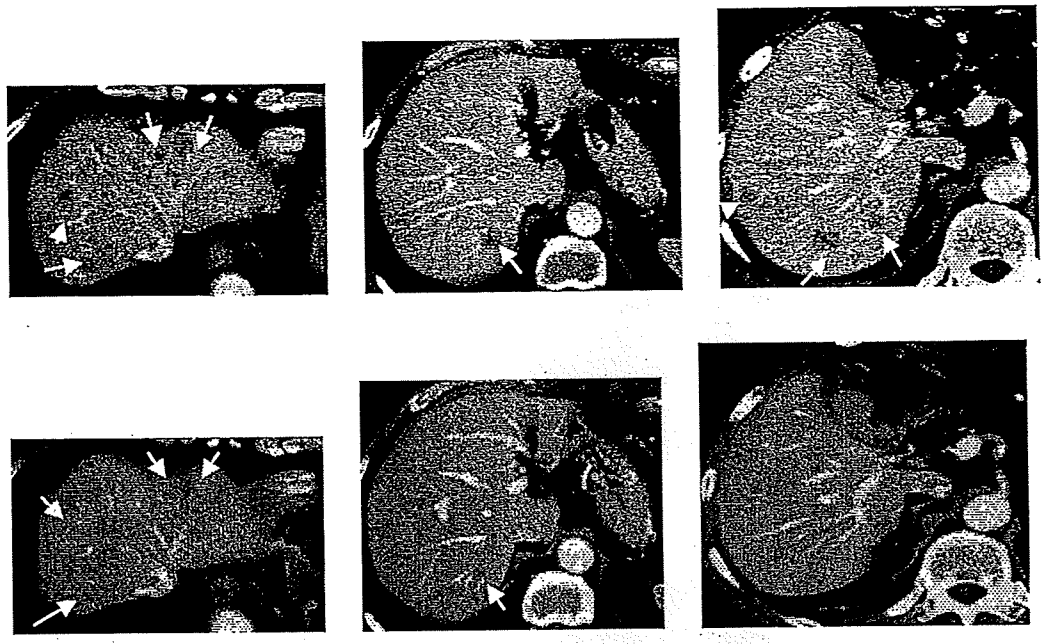

Figure 3. Serial CT scans. (A) A 60-year-old male with pancreatic cancer who was treated with NK105 at a dose level of 150 mg/m^2. Baseline scan (upper panels) showing multiple metastasis in the liver. Partial response, characterized by a more than 90% decrease in the size of the liver metastasis (lower panels) compared with the baseline scan. The antitumor response was maintained for nearly 1 year.

discontinue treatment with CDDP due to its adverse reactions, e.g. nephrotoxicity and neurotoxicity, despite its persisting effects (Pinzani et al. 1994). Platinum analogues, e.g. carboplatin and oxaliplatin (Cleare et al. 1978), have been developed to date to overcome these CDDP-related disadvantages. Consequently, these analogues are becoming the standard drugs for ovarian cancer (du Bois et al. 2003) and colon cancer (Cassidy et al. 2004). However, those regimens including CDDP are considered to constitute the standard treatment for lung cancer, stomach cancer, testicular cancer (Horwich et al. 1997), and urothelial cancer (Bellmunt et al. 1997). Therefore, the development of a DDS technology is anticipated, which would offer the better selective accumulation of CDDP into solid tumours while lessening its distribution into normal tissue.

Preparation and characterization of NC-6004

NC-6004 were prepared according to the slightly modified procedure reported by Nishiyama et al. (2003) (Figure 4). NC-6004 consists of PEG, a hydrophilic chain which constitutes the outer shell of the micelles, and the coordinate complex of poly(glutamic acid) (P(Glu)) and CDDP, a polymer-metal complex-forming chain which constitutes the inner core of the micelles. The molecular weight of PEG-P(Glu) as a sodium salt was approximately 18,000 (PEG: 12,000; P(Glu): 6000). The CDDP-incorporated polymeric micelles were clearly discriminated from typical micelles from amphiphilic block copolymers. The driving force of the formation of the CDDP-incorporated micelles is the ligand substitution of platinum(II) atom from chloride to carboxylate in the side chain of P(Glu). The molar ratio of CDDP to the carboxyl groups in the copolymers was 0.71 (Nishiyama et al. 2003). A narrowly distributed size of polymeric micelles (30 nm) was confirmed by the dynamic light scattering (DLS) measurement. Also, the static light scattering (SLS) measurement revealed that the CDDP-loaded micelles showed no dissociation upon dilution and the CMC was less than 5×10^{-7}, suggesting remarkable stability compared with typical micelles from amphiphilic block copolymers (Nishiyama et al. 2003). It is assumed that the interpolymer cross-linking by Pt(II) atom might contribute to stabilization of the micellar structure.

The release rates of CDDP from NC-6004 were 19.6 and 47.8% at 24 and 96 h, respectively. In distilled water, furthermore, NC-6004 was stable without releasing cisplatin.

Pharmacokinetics and pharmacodynamics

FAAS could measure serum concentrations of platinum up to 48 h after i.v. injection of NC-6004 but could measure them only up to 4 h after i.v. injection of CDDP. NC-6004 showed a very long blood retention profile as compared with CDDP. The AUC_{0-t} and C_{max} values were significantly higher in animals given NC-6004 than in animals given CDDP, namely, 65-fold and 8-fold; respectively, ($P < 0.001$ and 0.001, respectively). Furthermore, the CL_{tot} and Vss values were significantly lower in animals given NC-6004 than in animals given

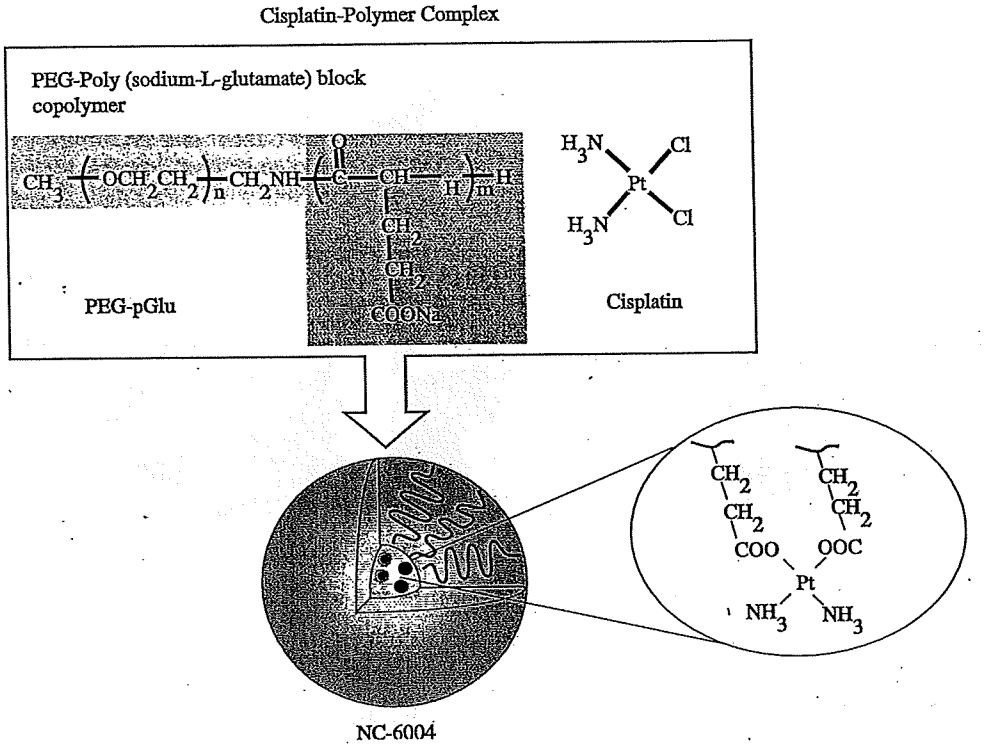

Figure 4. Preparation and characterization of cisplatin-incorporating polymeric micelles (NC-6004). Chemical structures of cisplatin (CDDP) and polyethylene glycol poly(glutamic acid) block copolymers [PEG-P(Glu) block copolymers], and the micellar structures of CDDP-incorporating polymeric micelles (NC-6004).

CDDP, i.e. one-nineteenth and one-seventy fifth, respectively, ($P < 0.01$ and 0.01, respectively).

Regarding the concentration–time profile of platinum in various tissues after i.v. injection of CDDP or NC-6004, all organs measured exhibited the highest concentrations of platinum within 1 h after administration in all animals given CDDP. Furthermore, animals given NC-6004 exhibited the highest tissue concentrations of platinum in the liver and spleen at late time points (24 and 48 h after administration, respectively). However, the concentrations decreased on day 7 after administration. In addition, and in a similar manner to other drugs, which are incorporated in polymeric carriers, NC-6004 demonstrated accumulation in organs of the reticuloendothelial system, e.g. liver and spleen. At 48 h after administration, tissue concentrations of platinum in the liver and spleen were 4.6- and 24.4-fold higher for NC-6004 than for CDDP. On the other hand, a marked increase in tissue platinum concentration was observed immediately after administration in the kidneys of animals given CDDP. Renal platinum concentration at 10 min and 1 h after administration were 11.6- and 3.1-fold lower, respectively, in animals given NC-6004 than in animals given CDDP. Furthermore, the maximum concentration (C_{max}) in the kidney was 3.8-fold lower at the time of NC-6004 administration than at the time of CDDP administration.

Regarding the tumour accumulation of platinum, tumour concentrations of platinum peaked at 10 min after administration of CDDP. On the other hand, tumour concentrations of platinum peaked at 48 h after administration of NC-6004. The maximum concentration (C_{max}) in tumour was 2.5-fold higher for NC-6004 than for CDDP ($P < 0.001$). Furthermore, the tumour AUC was 3.6-fold higher for NC-6004 than for CDDP (81.2 and 22.6 μg/ml h in animals given NC-6004 and CDDP, respectively).

In vivo *antitumour activity*

BALB/c nude mice implanted with a human gastric cancer cell line MKN-45 showed decreased tumour growth rates after i.v. injection of CDDP and NC-6004. In the administration of CDDP, the CDDP 5 mg/kg administration group showed a significant decrease ($P < 0.01$) in tumour growth rate as compared with the control group. However, the NC-6004 administration groups at the same dose levels as CDDP showed no significant difference in tumour growth rate. Regarding time-course changes in body weight change rate, the CDDP 5 mg/kg administration group showed a significant decrease ($P < 0.001$) in body weight as compared with the control group. On the other hand, NC-6004 administration group did not show a decrease in body weight as compared with the control group.

Nephrotoxicity of CDDP and NC-6004

In the CDDP 10 mg/kg administration group, 4 of 12 rats died from toxicity within 7 days after drug administration. No deaths occurred in the NC-6004 10 mg/kg administration group. Regarding renal function, the BUN concentrations on day 7 after the administration of 5% glucose, CDDP 10 mg/kg, and NC-6004 10 mg/kg were 20.8 ± 3.0, 65.3 ± 44.4 and 20 ± 4.5 mg/dl, respectively. The plasma concentrations of creatinine on day 7 after the administration of 5% glucose, CDDP 10 mg/kg, and NC-6004 10 mg/kg were 0.27 ± 0.03, 0.68 ± 0.23 and 0.28 ± 0.04 mg/dl, respectively. The CDDP 10 mg/kg administration group showed significantly higher plasma concentrations of BUN and creatinine as compared with the control group ($P < 0.05$ and 0.001, respectively), with the NC-6004 10 mg/kg administration group ($P < 0.05$ and 0.001, respectively) (Figure 5). Light microscopy indicated tubular dilation with flattening of the lining cells of the tubular epithelium in the kidney from all animals in the CDDP 10 mg/kg administration group. On the other hand, no histopathological change was observed in the kidneys from all animals in the NC-6004 10 mg/kg administration group.

Neurotoxicity of CDDP and NC-6004

Neurophysiological examination revealed that motor nerve conduction velocities (MNCVs) in animals given 5% glucose, CDDP, and NC-6004 were 44.2 ± 3.5, 40.94 ± 5.08 and 40.62 ± 0.63 m/s, respectively. No significant difference was found among the groups with respect to MNCV. Furthermore, sensory nerve conduction velocities (SNCVs) in animals given 5% glucose, CDDP, and NC-6004 were 42.86 ± 8.07, 35.48 ± 4.91 and 43.74 ± 5.3 m/s, respectively. Animals given NC-6004 showed no delay in SNCV as compared with animals given 5% glucose. On the other hand, animals given CDDP showed a significant delay ($P < 0.05$) in SNCV as compared with animals given NC-6004 (Figure 6). The analysis by ICP-MS on sciatic nerve concentrations of platinum could not detect platinum in the sciatic nerve from animals given 5% glucose (data not shown). Sciatic nerve concentrations of platinum

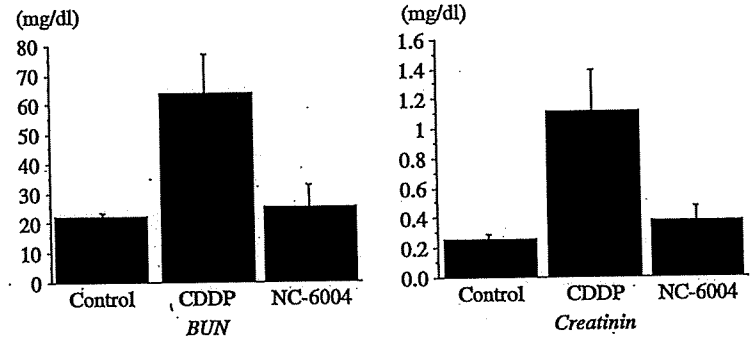

Figure 5. Nephrotoxicity of CDDP and NC-6004. Plasma concentrations of blood urea nitrogen (BUN) and creatinine were measured after a single i.v. injection of 5% glucose ($n = 8$), CDDP at a dose of 10 mg/kg ($n = 12$), NC-6004 at a dose of 10 mg/kg ($n = 13$) on a CDDP basis.

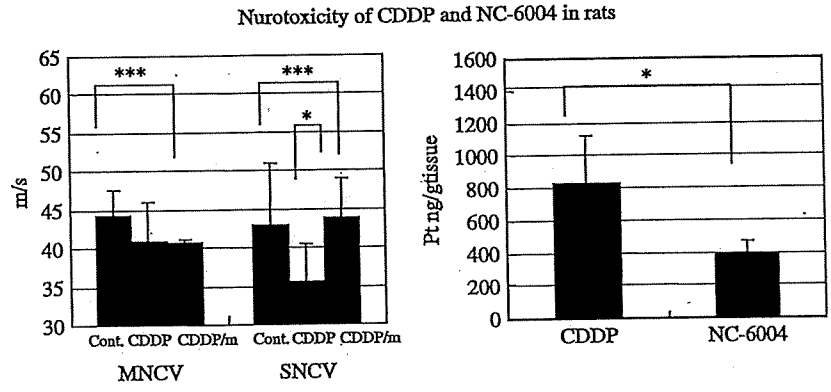

Figure 6. Neurotoxicity of CDDP and NC-6004 in rats. Rats ($n = 5$) were given CDDP (2 mg/kg), NC-6004 (an equivalent dose of 2 mg/kg CDDP), or 5% glucose, all intravenously twice a week, 11 administrations in total. Sensory nerve conduction velocity (SNCV) and motor nerve conduction velocity (MNCV) of the sciatic nerve at week 6 after the initial administration. The platinum concentration in the sciatic nerve. Rats were given CDDP (5 mg/kg, $n = 5$), NC-6004 (an equivalent dose of 5 mg/kg CDDP, $n = 5$), or 5% glucose ($n = 2$), all intravenously twice a week, four administrations in total. On day 3 after the final administration, a segment of the sciatic nerve was removed and the platinum concentration in the sciatic nerve was measured by ICP-MS. The data are expressed as the mean ± SD $*P < 0.05$.

in animals given CDDP and NC-6004 were 827.2 ± 291.3 and 395.5 ± 73.1 ng/g tissue. Therefore, the concentrations were significantly ($P < 0.05$) lower in animals given NC-6004. This finding is believed to be a factor which reduced neurotoxicity following NC-6004 administration as compared with the CDDP administration.

Present situation of a clinical study of NC-6004

A phase 1 clinical trial of NC-6004 is now under way in United Kingdom. Starting dose of NC-6004 was 10 mg/m^2. NC-6004 was administered once every 3 weeks with only 1000 ml water loading. In Japan, a phase 1 trial will be stared soon in the National Cancer Center Hospital.

NK012, SN-38-incorporating micellar nanoparticle

The antitumor plant alkaloid camptothecin (CPT) is a broad-spectrum anticancer agent which targets the DNA topoisomerase I. Although CPT has showed promising antitumor activity *in vitro* and *in vivo* (Gallo et al. 1971; Li et al. 1972), it has not been used clinically because of its low therapeutic efficacy and severe toxicity (Gottlieb et al. 1970; Muggia et al. 1972). Among CPT analogs, irinotecan hydrochloride (CPT-11) has recently been demonstrated to be active against colorectal, lung, and ovarian cancer (Cunningham et al. 1998; Saltz et al. 2000; Noda et al. 2002, Negoro et al. 2003; Bodurka et al. 2003). CPT-11 itself is a prodrug and is converted to 7-ethyl-10-hydroxy-CPT (SN-38), a biologically active metabolite of CPT-11, by carboxylesterases (CEs). SN-38 exhibits up to 1000-fold more potent cytotoxic activity against various cancer cells *in vitro* than CPT-11 (Takimoto and Arbuck 2001). Although CPT-11 is converted to SN-38 in the liver and tumor, the metabolic conversion rate is less than 10% of the original volume of CPT-11 (Rothenberg et al. 1993; Slatter et al. 2000). In addition, the conversion of CPT-11 to SN-38 depends on the genetic interindividual variability of CE activity (Guichard et al. 1999). Thus, direct use of SN-38 might be of great advantage and attractive for cancer treatment. For the clinical use of SN-38, however, it is essential to develop a soluble form of water-insoluble SN-38. The progress of the manufacturing technology of "micellar nanoparticles" may make it possible to use SN-38 for *in vivo* experiments and further clinical use.

Preparation and characterization of NK012

NK012 is an SN-38-loaded polymeric micelle constructed in an aqueous milieu by the self-assembly of an amphiphilic block copolymers, PEG-PGlu(SN-38). The molecular weight of PEG-PGlu(SN-38) was determined to be approximately 19,000 (PEG segment: 12,000; SN-38-conjugated PGlu segment: 7000). NK012 was obtained as a freeze-dried formulation and contained *ca.* 20% (w/w) of SN-38 (Figure 7). The mean particle size of NK012 is 20 nm in diameter with a relatively narrow range. The releasing rates of SN-38 from NK012 in phosphate buffered saline at 37°C were 57 and 74% at 24 and 48 h, respectively, and that in 5% glucose solution at 37°C were 1 and 3% at 24 and 48 h, respectively. These results indicate that NK012 can release SN-38 under neutral condition even without the presence of a hydrolytic enzyme, and is stable in 5% glucose solution. It is suggested that NK012 is stable before administration and starts to release SN-38, the active component, under physiological conditions after administration.

Cellular sensitivity of NSCLC and colon cancer cells to SN-38, NK012, and CPT-11

The IC_{50} values of NK012 for the cell lines ranged from 0.009 μM (Lovo cells) to 0.16 μM (WiDR cells). The growth-inhibitory effects of NK012 are 43–340 fold more potent than those of CPT-11, whereas the IC_{50} values of NK012 were 2.3–5.8 fold higher than those of SN-38.NK012 exhibited a higher cytotoxic effect against each cell line as compared with CPT-11 (× 43–340 fold sensitivity). On the other hand, the IC_{50} values of NK012 were a little higher than those of SN-38, similar to the cytotoxic feature also reported in a previous study about micellar drugs (Uchino et al. 2005).

Pharmacokinetic analysis of NK012 and CPT-11 using HT-29-bearing nude mice

After injection of CPT-11, the concentrations of CPT-11 and SN-38 for plasma declined rapidly with time in a log-linear fashion. On the other hand, NK012 (polymer-bound SN-38) exhibited slower clearance. The clearance of NK012 in the HT-29 tumor was significantly slower and the concentration of free SN-38 was maintained at more than 30 ng/g even at 168 h after injection.

Anti-tumor activity and the distribution of NK012 and CPT-11 in SBC-3/Neo or SBC-3/VEGF tumors

In order to determine whether the potent antitumor effect of NK012 is enhanced in the tumors with high vascularity, we used vascular endothelial growth factor-secreting cells SBC-3/VEGF. There was no significant difference in the *in vitro* cytotoxic activity of each drug between SBC-3/Neo and SBC-3/VEGF. Gross findings of SBC-3/VEGF tumors are reddish as compared with SBC-3/Neo tumors. Deviating from the ordinary experimental tumor model, tumors were allowed to

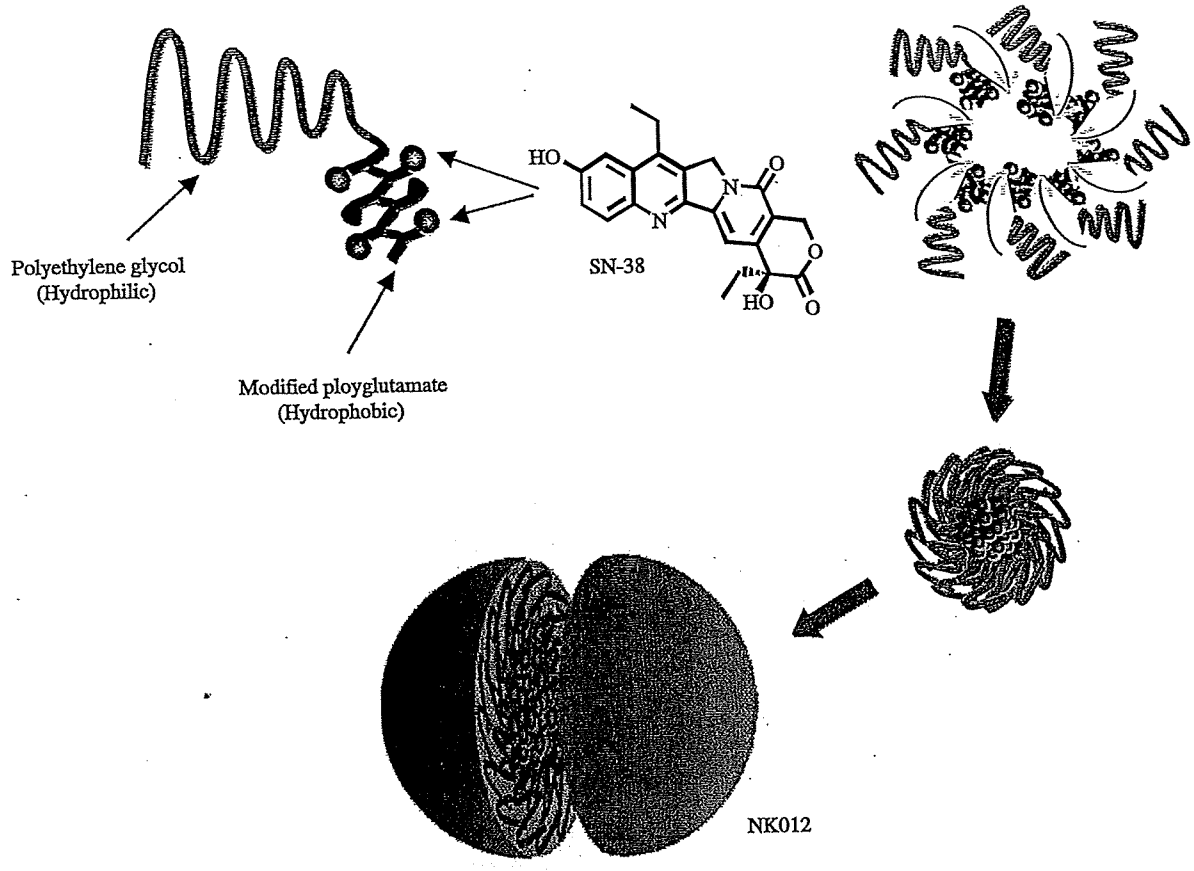

Figure 7. Schematic structure of NK012. A polymeric micelle carrier of NK012 consists of a block copolymer of PEG (molecular weight of about 5000) and partially modified polyglutamate (about 20 unit). Polyethylene glycol (hydrophilic) is believed to be the outer shell and SN-38 was incorporated into the inner core of the micelle.

grow until they became massive in size, around 1.5 cm (Figure 8), and then the treatment was initiated. NK012 at doses of 15 and 30 mg/kg showed potent anti-tumor activity against bulky SBC-3/Neo tumors (1533.1 ± 1204.7 mm^3) as compared with CPT-11 (Figure 8). Striking antitumor activity was observed in mice treated with NK012 (Figure 8) when we compared the antitumor activity of NK012 with CPT-11 using SBC-3/VEGF cells. SBC-3/VEGF bulky masses (1620.7 ± 834.0 mm^3) disappeared in all mice, although relapse 3 months after treatment was noted in one mouse treated with NK012 20 mg/kg (Figure 8). On the other hand,

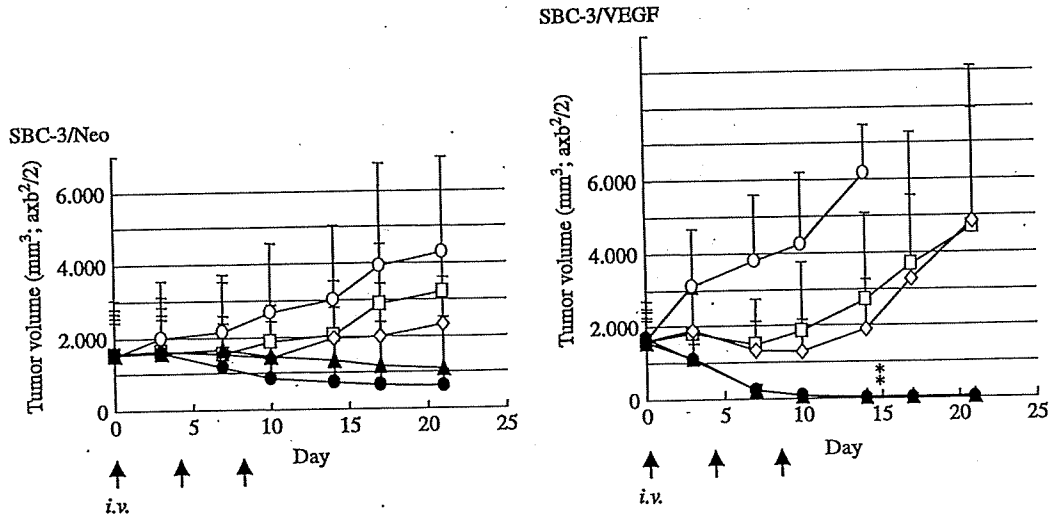

Figure 8. Intravenous administration of NK012 or CPT-11 was started when the mean tumor volumes of groups reached a massive 1500 mm^3. The mice were divided into test group (□: control; □: CPT-11 20 mg/kg/day; □: CPT-11 40 mg/kg/day; ▲: NK012 15 mg/kg/day; and □: NK012 30 mg/kg/day). NK012 or CPT-11 was administered i.v. on days 0, 4 and 8. Each group consisted of 4 mice. *$P < 0.05$.

SBC-3/VEGF were not eradicated and rapidly regrew after a partial response in mice treated with CPT-11. Approximate 10% body weight loss was observed in mice treated with NK012 20 mg/kg, but no significant difference was observed in comparison with mice treated with CPT-11 30 mg/kg.

We then examined the distribution of free SN-38 in the SBC-3/Neo and SBC-3/VEGF masses after administration of NK012 and CPT-11. In the case of CPT-11 administration, the concentrations at 1 and 6 h after the administration were less than 100 ng/g both in the SBC-3/Neo and SBC-3/VEGF tumors, and were almost negligible at 24 h in both tumors. There was no significant difference in the concentration between the SBC-3/Neo and SBC-3/VEGF tumors. On the other hand, in the case of NK012 administration, free SN-38 was detectable in the tumors even at 72 h after the administration. The concentrations of free SN-38 were higher in the SBC-3/VEGF tumors than those in the SBC-3/Neo tumors at any time point during the period of observation (significant at 1, 6, 24 h. $*P < 0.05$).

Tissue distribution of SN-38 after administration of NK012 and CPT-11

We examined the concentration–time profile of free SN-38 in various tissues after i.v. administration of NK012 and CPT-11. All organs measured exhibited the highest concentration of SN-38 at 1 h after administration in mice given CPT-11. On the other hand, mice given NK012 exhibited prolonged distribution in the liver and spleen. In a similar manner to other micellar drugs (Yokoyama et al. 1991a, b, c; Uchino et al. 2005), NK012 demonstrated relatively higher accumulation in organs of the reticuloendothelial system. In the lung, kidney and small intestine, the highest concentration of free SN-38 was achieved at 1 h after injection of NK012 and the concentration was almost negligible at 24 h. Although the concentrations of free SN-38 in the small intestine were relatively high at 1 h after administration of NK012 and CPT-11, those rapidly decreased. Interestingly, there was no significant difference in the kinetic character of free SN-38 in the small intestine between mice treated with NK012 and CPT-11.

Synergistic antitumour activity of the NK012 combined with 5-fluorouracil

In two phase III trials, the addition of CPT-11 to bolus or infusional 5FU/LV regimens clearly yielded greater efficacy than treatment with 5FU/LV alone, with a doubling of the tumor response rate and prolongation of the median survival time by 2–3 months (Douillard et al. 2000; Saltz et al. 2001).

We demonstrated that the novel SN-38-incorporating polymeric micelles, NK012, exerted superior antitumor activity and less toxicity as compared to CPT-11 (Koizumi et al. 2006). Therefore, we speculated that the use of NK012 in place of CPT-11 in combination with 5FU may also yield superior results.

Comparison of the antitumor effect of combined NK012/5FU and CPT-11/5FU. The therapeutic effect of CPT-11/5FU was apparently inferior to that of NK012/5FU or even NK012 alone at the MTD. A more potent antitumor effect, namely 100% CR rate, was obtained in the NK012 alone and NK012/5FU groups, as compared with the 0% CR rate in the CPT-11/5FU (Nakajima and Matsumura 2007).

Specificity of cell cycle perturbation. We studied the difference in the effects between NK012 and CPT-11 on the cell cycle. The data indicate that both NK012 and CPT-11 had a tendency to accumulate the cells in the S phase, although the effect of NK012 was stronger and maintained for a more prolonged period than that of CPT-11. The histograms show aneuploidy of the tumor and that administration of NK012 or CPT-11 caused apoptosis of a proportion of the tumor cells (Nakajima and Matsumura 2007).

Present situation of a clinical study of NK012

A phase 1 study of NK012 is now under way in the National Cancer Center, Tokyo and Kashiwa in patients with advanced solid tumours. NK012 is infused intravenously over 60 min every 21 days until disease progression or unacceptable toxicity occurs.

Conclusion

A quarter of a century has passed since the EPR effect was discovered (Matsumura and Maeda 1986). Now the phrase EPR has become a fundamental principle in the field of DDS. Until recently, the EPR had not been recognized in the field of oncology. However, many oncologists have now become acquainted with it, since some drugs such as doxil, abraxane, and several PEGylated proteinacious agents formulated based on the EPR have been approved in the field of oncology. Micelle carrier systems described in this chapter are obviously categorized as DDS based on the EPR. I believe that some anticancer agents incorporating micelle nanoparticles may be approved for clinical use soon.

Our next task is to develop DDS utilizing the EPR effect, which can accumulate selectively in solid tumours but also allow distribution of the delivered

bullets (anticancer agents) through the entire mass of the solid tumor tissue.

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