Association of Paclitaxel Pharmacokinetics with the Development of Peripheral Neuropathy in Patients with Advanced Cancer

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Abstract

Purpose: The shortening of infusion time from 3 to 1 hour decreases the systemic exposure (area under the curve, AUC) of total and unbound paclitaxel but increases the AUC of its vehicle Cremophor EL, whereas the time above total paclitaxel concentrations of 0.05 μmol/L ($T_{>0.05}$) remains almost constant. As both Cremophor EL and paclitaxel are neurotoxic, we evaluated their pharmacodynamic effects on the development of peripheral neuropathy as the most important nonhematologic toxicity.

Experimental Design: Patients with advanced cancer of different origin were randomized to receive a maximum of 12 weekly-given 1- or 3-hour infusions of 100 mg/m^2 paclitaxel (Taxol). Twenty-four patients were assessable for both pharmacokinetics and peripheral neuropathy development evaluated by a clinical scoring system including sensory symptoms, strength, tendon reflexes, and vibratory sense.

Results: Patients with peripheral neuropathy development (n = 14) received more weeks of therapy (P = 0.056) and showed significantly higher $T_{>0.05}$ (P = 0.022) and overall systemic drug exposures (weeks of therapy × AUC) for total paclitaxel (P = 0.002) and unbound paclitaxel (P = 0.003) than those without peripheral neuropathy. In Kaplan-Meier analyses, $T_{>0.05} \geq$ 10.6 hours (P = 0.023), AUC of total paclitaxel $\geq$ 4.7 μg/mL × hour (P = 0.047), and AUC of unbound paclitaxel $\geq$ 0.375 μg/mL × hour (P = 0.095) were identified as being potential factors for peripheral neuropathy development. In a Cox regression analysis, only $T_{>0.05} \geq$ 10.6 hours remained as an independent risk factor (relative risk, 18.43; P = 0.036) after adjusting for prior vincamycin (relative risk, 11.28; P = 0.038).

Conclusions: From the results obtained in this study, it is concluded that exposure to paclitaxel but not Cremophor EL is associated with peripheral neuropathy development.

Neurotoxicity has emerged as one of the most important and often dose-limiting toxicities associated with weekly paclitaxel therapy (1–6). Severe hematologic toxicities have become less frequent in short infusions over 1 or 3 hours, compared with former 24-hour applications, and can be managed with growth factors (1–5, 7). Paclitaxel is well known to cause both sensory and motor peripheral neuropathy by inducing axonal degeneration and demyelination (8–12). We have previously conducted a randomized clinical trial focusing on the development of a peripheral neuropathy as the primary end point in weekly paclitaxel infusions over 1- or 3-hour duration. However, a prediction of whether it would be of advantage to infuse over 1- or 3-hour was complicated by the fact that a reduction of infusion time decreases the area under the curve (AUC) of both total and unbound paclitaxel but increases the AUC of its vehicle Cremophor EL, which is known to have its neurotoxic potential as well (13, 14). In this prior trial, we could show that after 12 weeks of therapy the majority of our patients had developed a peripheral neuropathy without significant differences between the two infusion groups (6). Prior pharmacodynamic investigations already revealed that the AUC of total paclitaxel (15–17) and unbound paclitaxel (15) and the time above total paclitaxel concentrations of 0.05 μmol/L ($T_{>0.05}$; refs. 17, 18) might be associated with the extent of granulocytopenia, but the relations of paclitaxel pharmacokinetics with neurotoxicity are poorly understood. The question whether a fixed dosing of paclitaxel might be of advantage compared with the common body surface area–based administration in the context of efficacy and toxicity has not been answered consistently (19, 20). Taken together, this leads to a strong demand for a further optimization of paclitaxel dosing and scheduling. Using the clinical (6) and pharmacokinetic (15) data acquired in our prior trial, the present investigation

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addressed the question whether and to what extent pharmacologic variables contributed to the development of a peripheral neuropathy as the most important nonhematologic toxicity.

Patients and Methods

Study design and patients. The subset of 24 patients investigated in this pharmacodynamic study was obtained from a pharmacokinetic analysis group (n = 29; ref. 15) from a larger prospective and randomized multicenter trial designed to investigate the effects of weekly 1- or 3-hour paclitaxel infusions on cumulative peripheral neuropathy as the primary end point in patients with locally advanced or metastatic cancer for whom a monotherapy with paclitaxel was a therapeutic option (n = 121; ref. 6). It was the aim of the present study to analyze the influence of the obtained paclitaxel administration's pharmacokinetic variables on cumulative peripheral neuropathy development.

Eligibility criteria and randomization. Patients with histologically proven, locally advanced or metastatic cancer, for whom paclitaxel as monotherapy was a therapeutic option, were candidates for this study. Exclusion criteria included age <18 years or >75 years with Eastern Cooperative Oncology Group performance status of >2; life expectancy of <3 months; preexisting peripheral neuropathy (peripheral neuropathy score before therapy of >3; Table 1); significant heart disease; known anaphylaxis against Cremophor EL, chemotherapy, or radiotherapy in the last 4 weeks, chemotherapy with taxanes in the last year; simultaneous anticancer treatment with hormone or immunotherapy; significant renal (serum creatinine > 1.5 × upper limit of normal), hepatic (total serum bilirubin > 1.5 × upper limit of normal), or hematologic insufficiency (absolute neutrophil count < 1.5×10^9/L and platelet count < 75×10^9/L); as well as bidimensionally nonmeasurable tumor. In fertile women, a negative test for pregnancy was required. Eligible patients were reported to the general study headquarters by facsimile, using a standard form in which they were assigned a serial number and allocated to the 1- or 3-hour infusion group by reference to a randomization list created by the Department of Biostatistics of Bristol-Myers Squibb (Munich, Germany). All patients gave informed consent according to the local ethics committee requirements and were monitored and treated at the participating center.

Treatment plan and delivery. All patients were scheduled to receive a total of six weekly infusions of paclitaxel (100 mg/m^2). Paclitaxel formulated in a mixture of Cremophor EL and ethanol USP (1:1, v/v; Taxol) was purchased from Bristol Myers Squibb and diluted in 500 mL of 5% (w/v) dextrose in water and given to the patient using a motor-driven programmable infusion pump over a 1- or 3-hour period. Premedication consisted of dexamethasone, an H1 histamine blocker and an H2 histamine blocker. After 6 weeks of therapy defined as one cycle, response was evaluated and responding patients received further 6 weeks of therapy, which was given continuously without a break, provided toxic effects were not prohibitive. Treatment should be delivered continuously and not exceed an interruption of 14 days between two paclitaxel applications. After a maximal therapy duration of two cycles, response was reevaluated and patients were taken off protocol therapy.

General toxicity assessment. Briefly, clinical examination, hematologic diagnostics with a complete blood cell count, as well as the assessment of symptoms and toxicity had to be done weekly while patients were on therapy. Before therapy, and if possible after one and after two cycles, these examinations had to be supplemented by the evaluation of the peripheral neuropathy score, clinical chemistries (serum creatinine, aspartate aminotransferase, alanine aminotransferase, alkaline phosphatase, and bilirubin), ECG analysis, and the performance status. Hematologic requirements for paclitaxel administration were an absolute neutrophil count of $\geq 1.5 \times 10^9$/L and platelet count of $\geq 75 \times 10^9$/L. Toxicities other than peripheral neuropathy were graded according to the National Cancer Institute common toxicity criteria guidelines, version 2.0. In leukopenia grade 4 and/or febrile neutropenia as well as thrombocytopenia grade 4, a dose reduction of 25% for all further administrations was demanded.

Assessment of neurotoxicity. For the assessment of neurotoxicity, we used primarily a standardized clinical peripheral neuropathy scoring system questioning patients' symptoms and requiring a clinical examination based on a tuning fork test and an evaluation of strength and peripheral reflexes (Table 1), as previously reported (6). This individual clinical score could range from 0 (best) to 12 (worst) points; based on the inclusion criteria of this trial, a peripheral neuropathy was defined as an event when the peripheral neuropathy score exceeded 3 for the first time. The score had to be obtained, as a minimum, before and after 6 and 12 weeks of therapy provided that therapy was not interrupted due to significant toxicity or disease progression before the evaluation. With regard to patients' safety, we decided in the early period of the study to extend the protocol and to require weekly evaluations of the peripheral neuropathy score to ensure an optimal monitoring for neurotoxicity. An amendment was written and approved by the department of ethics. Patients experiencing a peripheral neuropathy score from 4 to 6 received a 25% dose reduction and could continue therapy, whereas patients with a peripheral neuropathy score from 7 to 12 were removed from the trial at that time. Dose reductions due to peripheral neuropathy were only permitted based on this score.

Pharmacokinetics of paclitaxel and Cremophor EL. The exact methodologies and results of the pharmacokinetic study used for this analysis have been reported in an individual publication (15). Briefly, blood samples were obtained from the treating center (exclusively the Tumor Biology Center of Freiburg and the University Medical Center of

Table 1. Scoring system employed for the graduation of paclitaxel-induced peripheral neuropathy as previously published (6) and modified after Berger *et al.* (12) and Chaudhry *et al.* (11)

Score	0	1	2	3
A. Sensory symptoms	None	Numbness/paraesthesia in the feet	Numbness/paraesthesia in feet and fingers	Functionally disabling numbness/paraesthesia
B. Strength	Normal	Weak toe extension	Weak toe extension and weak finger abduction	General/diffuse weakness
C. Tendon reflexes	Normal	Single reflexes reduced	Single reflexes absent	all reflexes absent
D. Vibratory sense*	Normal (8/8)	‹6/8	‹4/8	None (0/8)

NOTE: The individual score was obtained as the sum of the areas A to D and could therefore range from 0 (best) to 12 (worst). Clinically significant peripheral neuropathy was defined as an event when the peripheral neuropathy score exceeded the value 3 the first time (6).
*Vibratory sense had to be obtained by the tuning fork test.

Freiburg, Germany) during and until 48 hours after the end of paclitaxel administration (14 time points for 3-hour infusion and 12 time points for 1-hour infusions) and delivered to the Tumor Biology Center of Freiburg as the study center responsible for these analyses. All samples were collected in 10-mL polypropylene tubes containing 75 IU of ammonium-heparinate (Sarstedt, Germany), separated by centrifugation (10 minutes at 2,000 × *g*), aliquoted in 1.5-mL fractions and stored at −20°C until analysis. Concentrations of total paclitaxel were determined by reversed-phase high-performance liquid chromatography, whereas Cremophor EL analyses were based on a colorimetric dye-binding microassay. For measurement of unbound paclitaxel plasma concentrations, equilibrium dialysis using a [*G*-^{3}H]paclitaxel tracer was employed.

Statistical analysis. For the statistical evaluation of the effect of the pharmacokinetic variables AUC and C_{max} of paclitaxel, unbound paclitaxel, and Cremophor EL as well as $T_{>0.05}$ on peripheral neuropathy development, which were obtained at the first drug application, the assumption was made that these variables remained constant during the whole course of therapy. As an initial analysis, to determine if there were differences in pharmacokinetic variables between patients with or without peripheral neuropathy development when viewed simply as a dichotomous variable, we created scatter plots and applied an unpaired two-tailed *t* test after confirming normality. *P*s ≤ 0.05 were considered to be significant and are presented without adjustment for multiple comparisons in this exploratory analysis. Furthermore, we calculated the overall systemic drug exposure as a product of AUC_{tot} and weeks of therapy (overall systemic drug exposure = AUC_{tot} × weeks of therapy) and checked again for group differences. The nonparametric Mann-Whitney test was used to check for group differences in therapy duration and $T_{>0.05}$ because these particular variables were not normally distributed.

As a more rigorous analysis, because the development of a peripheral neuropathy in course of paclitaxel therapy may be treated as an event with probability increasing as a function of weeks of therapy, another evaluation was done to determine if the pharmacokinetic variables AUC, C_{max}, and $T_{>0.05}$ could be used to describe the probability of developing a peripheral neuropathy as a function of weeks of therapy. To do so, exploratory analyses using the Kaplan-Meier method and the log-rank test to determine the degree to which individual pharmacokinetic variables might be associated in a univariate fashion with time to development of a peripheral neuropathy were done first (21). Values obtained for AUC, C_{max}, and $T_{>0.05}$ were divided into quartiles to determine their association with the primary outcome peripheral neuropathy, to identify if these results were consistent in a linear fashion with the outcome, or if dichotomizing at a quartile or the median may be more useful. For this univariate analysis, we employed the log-rank test to examine for group differences. All of the resulting *P*s are two tailed and because this is interpreted as an exploratory analysis, have not been adjusted for multiple comparisons. Finally, those factors that seemed to have potential effect in the univariate analyses were then evaluated in a Cox proportional hazards model to determine if they were associated with the outcome when considered jointly (22). All graphs presented in this publication have been plotted employing Prism 4.00 for Windows software (Graph Pad Software, San Diego, CA).

Results

Participants and treatment delivery. Pharmacokinetic data were available for 29 patients. Five of them were not assessable for this analysis due to incorrect infusion durations (n = 2), unallowed dose reductions (n = 2), and an incomplete follow-up evaluation of the peripheral neuropathy score (n = 1). Thus, this pharmacodynamic analysis was ultimately based on 24 patients. Their characteristics at baseline are displayed in Table 2. Four of these patients experienced a single event of delayed (>14 days) treatment delivery (in particular 15, 17, 19, or 21 days) but were still considered eligible for this analysis. One patient refused further therapy after one completed cycle, so that only the first 6 weeks of therapy could be considered for this analysis. Within the maximum therapy duration of 12 weeks, 10 of 24 patients developed a clinically significant peripheral neuropathy. No group differences (P = 0.63) between 1- and 3-hour infusions could be observed (Fig. 1A), but patients with peripheral neuropathy development received more paclitaxel infusions than those without (Fig. 1B). A single patient with 1-hour infusions exceeded the peripheral neuropathy score of 6 at week 8 and had to be taken off protocol therapy. In course of their therapy 5 of 24 patients received dose reduction of 25% on week 3 (3-hour infusion), 7 (1-hour infusion), 7 (3-hour infusion), 11 (3-hour infusion), or 12 (1-h infusions) due to a peripheral neuropathy score from 4 to 6. No dose reduction due to other causes were done, so that all 24 patients received the same dose of paclitaxel until they developed a peripheral neuropathy or were taken off protocol therapy. Univariate unadjusted log rank analyses showed age (60-72 versus 42-59 years; P = 0.006) and prior therapy with

Table 2. Patient characteristics at baseline

Characteristics	All	No PNP	PNP
Assessable patients	24	14	10
Male/female	12/12	7/7	5/5
Age (y)			
Median	59.5	58	62
Range	42-72	42-72	52-70
Infusion duration (randomized)			
1-h infusion	14	8	6
3-h infusion	10	6	4
Performance status (ECOG)			
ECOG 0	5	4	1
ECOG 1	16	7	9
ECOG 2	2	2	0
ECOG ≤ 2	1	1	0
Site of primary tumor			
Breast	6	2	4
Lung	7	3	4
Ovary	3	3	0
Bladder or ureter	2	2	0
Esophagus	2	0	2
Head/neck	2	2	0
Penis	1	1	0
Kidney	1	1	0
Prior therapy	22	14	8
Chemotherapy containing *Vinca*	7	3	4
Chemotherapy containing platinum	13	9	4
Radiation therapy	10	6	4

NOTE: A total of 24 patients were assessable for both pharmacokinetics and toxicity. Patients had been randomized to receive either 1- or 3-h paclitaxel infusions. Based on the clinical peripheral neuropathy score, 10 patients developed a peripheral neuropathy during the course of their therapy, whereas 14 patients remained free of peripheral neuropathy.

Abbreviations: PNP, peripheral neuropathy; ECOG, Eastern Cooperative Oncology Group.

vincamycin ($P = 0.033$) to be potentially related to peripheral neuropathy development (data not shown).

Pharmacodynamics of paclitaxel and Cremophor EL. This pharmacodynamic analysis was based on the variables AUC and C_{max} which have been obtained for total paclitaxel, unbound paclitaxel and Cremophor EL at the first paclitaxel application. For 23 patients, the $T_{>0.05}$ was available. As a first step, we tested to see if there were group differences between patients with and without peripheral neuropathy development regardless of when their peripheral neuropathy development took place over time. No differences could be found for the peak concentrations of total paclitaxel, unbound paclitaxel, and Cremophor EL (Fig. 2A-C), but patients with peripheral neuropathy development showed a higher average of systemic exposure to total paclitaxel and unbound paclitaxel but not to Cremophor EL than those without peripheral neuropathy (Fig. 2D-F). However, none of these group differences was significant. In a second analysis, we considered the effects of therapy duration by calculating the overall systemic drug exposure and found that patients with peripheral neuropathy had significantly higher overall systemic drug exposures for total paclitaxel ($P = 0.002$) and unbound paclitaxel ($P = 0.003$) but not for Cremophor EL ($P = 0.1$) than those without peripheral neuropathy development (Fig. 2G-I).

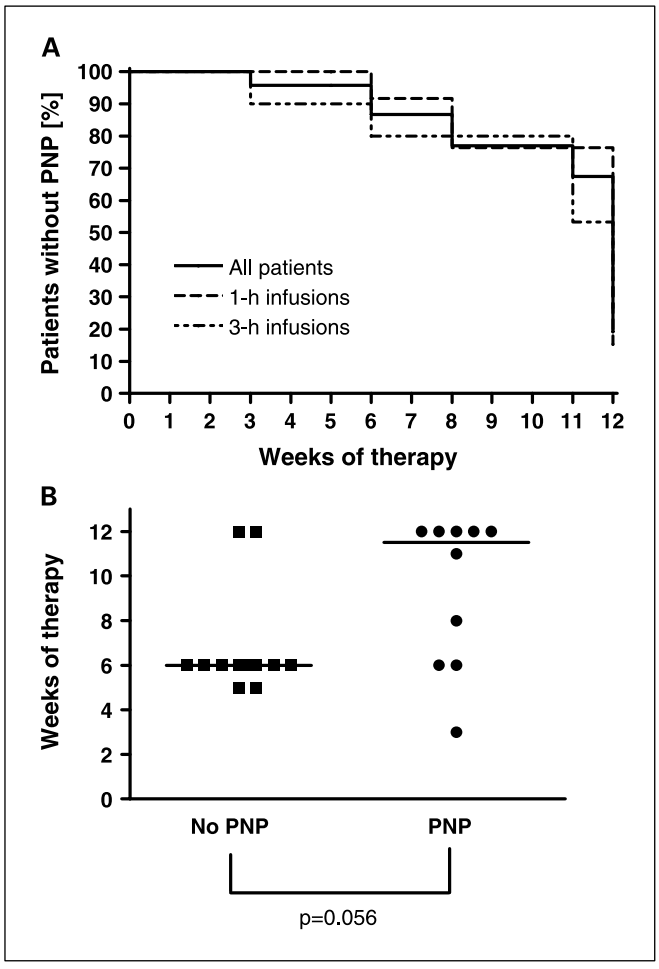

Fig. 1. Effect of therapy duration on the development of a peripheral neuropathy (*PNP*). *A*, Kaplan-Meier analysis of peripheral neuropathy – free outcome in the course of therapy for all patients evaluable for both pharmacokinetics and toxicity ($n = 24$) and for the subgroups of patients receiving 1-hour ($n = 14$) and 3-hour infusions ($n = 10$). No significant group differences ($P = 0.63$) were detected between these two infusion groups. *B*, scatter plots and the median (*horizontal bar*) of finally assessable weeks of therapy (until patients exceeded peripheral neuropathy score 3 or were taken off protocol therapy) in 14 patients without (■) and 10 patients with (●) peripheral neuropathy development. Applying a two-tailed Mann-Whitney test, this group difference approached statistical significance.

Considering the duration of therapy, we did Kaplan-Meier analyses investigating the probability of developing a peripheral neuropathy over time. To do this analysis, initially values obtained for the AUC or C_{max} for total paclitaxel, unbound paclitaxel, and Cremophor EL were divided into one lower and one higher level subgroup and compared with each other. These exploratory analyses showed that patients with AUC levels of $\geq$4.7μg/mL × hour for total paclitaxel and $\geq$0.375 μg/mL × hour for unbound paclitaxel had a higher probability of developing peripheral neuropathy than those with levels of <4.7 μg/mL × hour ($P = 0.047$; Fig. 3A) or <0.375 μg/mL × hour ($P = 0.095$; Fig. 3B). However, only the group difference for total paclitaxel was statistically significant. For Cremophor EL, no group differences could be observed ($P = 0.70$; Fig. 3C). A similar analysis was done for the peak concentrations but failed to provide significant group differences (data not shown).

Patients with peripheral neuropathy showed significantly ($P = 0.022$) higher $T_{>0.05}$ than those without peripheral neuropathy (Fig. 4A). For one patient, no value for $T_{>0.05}$ was available, so that this particular analysis was based on a subset of 23 patients. Subdividing this group at tertiles and applying the Kaplan-Meier method, patients with $T_{>0.05} \geq 10.6$ hours had a higher ($P = 0.023$) probability of developing a peripheral neuropathy than those with times below 10.6 hours (Fig. 4B).

Cox regression analysis. Based upon the prior exploratory analyses, prior vincamycin, age (60-72 versus 42-59 years), an AUC of total paclitaxel of $\geq$4.7 μg/L, an AUC of unbound paclitaxel of $\geq$ 0.375 μg/L, and a $T_{>0.05} \geq 10.6$ hours have been found to be potentially promising factors for a Cox regression analysis. Initial models showed that age could be discarded as a factor because of its relative unimportance compared with the other variables. Models without $T_{>0.05}$ could be based on 24 patients, whereas a model that included this variable was based on 23 assessable patients. Prior therapy with vincamycin remained an independent variable in both models. The relative risks, confidence intervals, and *P*s of the Cox analysis are presented in Table 3. In particular, when all three variables are considered simultaneously, model 1 shows no significant effect of AUC of total paclitaxel or unbound paclitaxel when taking prior vincamycin into account, whereas model 2 suggests that the $T_{>0.05} \geq 10.6$ hours threshold remains significant after adjusting for prior vincamycin (Table 3).

Discussion

Both the clinical availability of growth factors and the fact that the reduction of infusion time from 24 to 3 hours diminished severe hematologic toxicities by reducing the AUC of paclitaxel contributed mainly to patient safety in current paclitaxel schedules (2, 7, 23). Nevertheless, neurotoxicity, predominantly seen as cumulative peripheral neuropathy (6, 8–10, 23), has resulted in demands for further improvement, especially as treatment options are rare or nonexistent and the application of neuroprotective agents such as

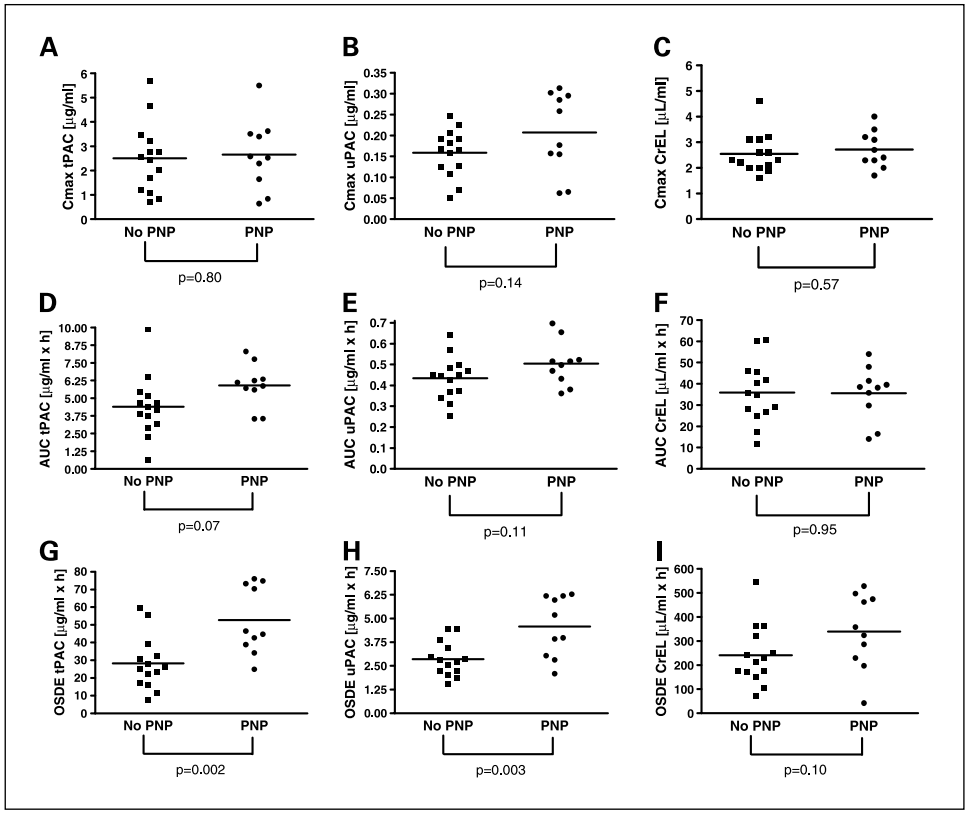

Fig. 2. Scatter plots of pharmacokinetic variables as obtained during the first drug application in 14 patients without (■) and 10 patients with (●) peripheral neuropathy (*PNP*) development in course of their therapy. *Horizontal bars*, mean of each group. A two-tailed, two-sample *t* test was applied to examine for differences between these two groups. *A-C*, peak concentrations (C_{max}) of total paclitaxel (*tPAC*), unbound paclitaxel (*uPAC*), and Cremophor EL (*CrEL*). *D-F*, systemic drug exposure (AUC_{tot}) to total paclitaxel, unbound paclitaxel, and Cremophor EL. *G-I*, overall systemic drug exposure (*OSDE*) to total paclitaxel, unbound paclitaxel, and Cremophor EL as estimated by calculating the product of the AUC_{tot} and the number of drug applications given by weeks of therapy (OSDE = AUC_{tot} × weeks of therapy).

amifostine seem to lack definite benefit thus far (24). For all these reasons, the present study was undertaken to focus primarily on neurotoxicity and contributes in at least a preliminary fashion to the understanding of the complex interplay between pharmacokinetic variables and peripheral neuropathy development in infusions of 1- or 3-hour duration, which have meanwhile become a widely used standard. From previous experience, we found the applied scoring system based on patient symptoms and a clinical examination to be a valuable instrument for providing reliable information on peripheral neuropathy development especially when acquired weekly (6). However, the addition of neurophysiologic testing for peripheral neuropathy evaluation can be of predictive value as recently shown for patients treated with a combination paclitaxel and cisplatin (25).

Whereas various other studies have already discussed the association between paclitaxel pharmacokinetic variables and hematologic toxicity (15–18), this is to our knowledge the first comprehensive evaluation of pharmacodynamic effects of paclitaxel on peripheral neuropathy development. Considering the cumulative nature of peripheral neuropathy development, it was critical for this analysis to investigate the influence of the obtained pharmacokinetic variables using a statistical approach incorporating the time to peripheral neuropathy development. Selecting Kaplan-Meier analyses as the statistical tool, we found that mainly the AUCs of total paclitaxel and unbound paclitaxel contributed to the peripheral neuropathy development in univariate analyses, although these variables were not found to be independently contributing in the Cox model. This effect was also noted when estimating the overall systemic drug exposure as a product of AUC and the number of chemotherapy applications. As pharmacokinetic analyses of paclitaxel in plasma are complicated by the nonlinear behavior of this drug, which is most likely based on interactions with its vehicle Cremophor EL (26), it was important for these analyses to determine also unbound, pharmacologically active drug concentrations of paclitaxel (15). Nevertheless, at a dose level of 100 mg/m^2 paclitaxel as it has been given in this trial, it is likely that the AUC of total paclitaxel remained in the linear range of the dose-exposure relationship (15, 27–29).

Physiologically relevant concentrations of Cremophor EL are known to cause axonal swelling, vesicular degeneration, and demyelization in preclinical models, suggesting that increased exposure to this vehicle could lead to more treatment-related neurotoxicity (13). Interestingly, in the current analysis, no effects of Cremophor EL exposure measures on peripheral neuropathy development could be observed. This is despite the fact that the AUC for Cremophor EL is increased by the reduction of infusion time, in contrast to that of paclitaxel (15). Furthermore, we could not detect any influence of the Cremophor EL peak concentrations, which also differs significantly between 1- and 3-hour infusions, on the neurotoxic outcome. These findings are in contrast to results obtained in animal models (14, 30) but coincide with recent observations from two phase I clinical trials showing that peripheral neuropathy remained an important and often dose-limiting toxicity after administration of Cremophor EL–free, albumin-stabilized nanoparticle (31) or polymeric micellar (32) paclitaxel formulations. This altogether provides further evidence of the conjecture that the intrinsic toxic effects of paclitaxel are more important than those of Cremophor EL

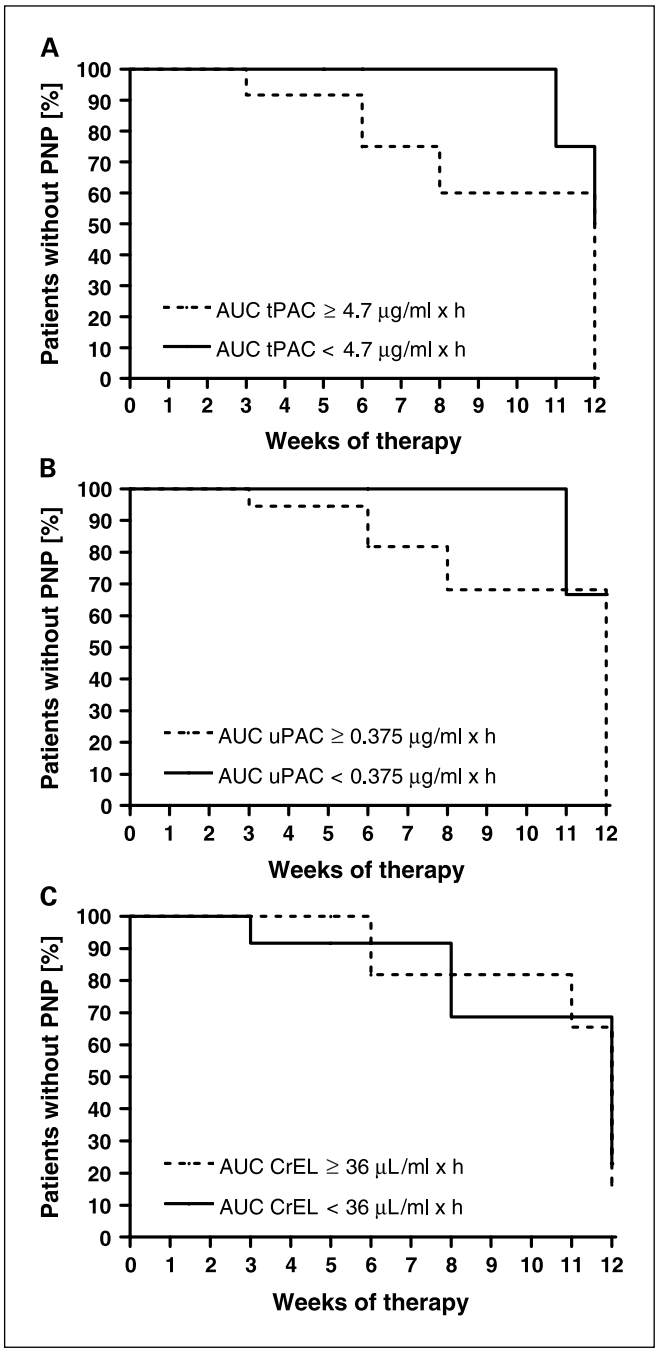

Fig. 3. Kaplan-Meier analyses of peripheral neuropathy (*PNP*) – free outcome in the course of PAC therapy and systemic exposure (AUC) to total paclitaxel (*tPAC*), unbound paclitaxel (*uPAC*), and Cremophor EL (*CrEL*) as obtained at the first drug application in 24 patients. The unadjusted univariate two-tailed log-rank test showed the (*A*) AUC of total paclitaxel (≥4.7 μg/mL × h [*n* = 12] versus <4.7 [*n* = 12]; *P* = 0.047) and the (*B*) AUC of unbound paclitaxel (≥0.375 μg/mL × h [*n* = 18] versus <0.375 [*n* = 6]; *P* = 0.095) as potentially promising variables for inclusion in the Cox regression when dichotomized as described. *C*, no differences could be detected for Cremophor EL (≥36 μL/mL × h [*n* = 12] versus <36 [*n* = 12]; *P* = 0.70).

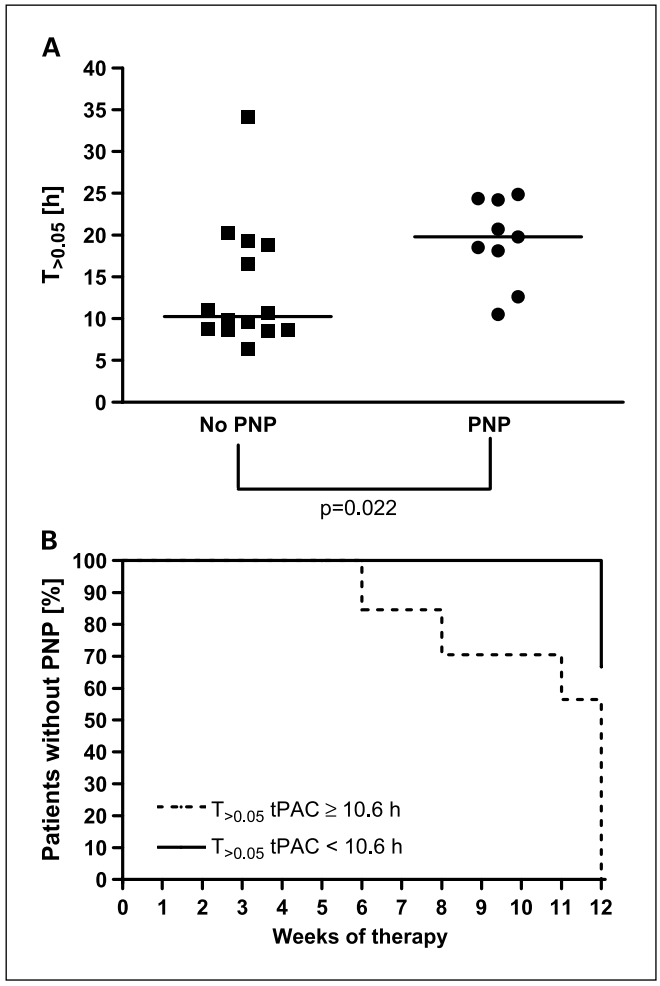

Fig. 4. Time of concentrations of total paclitaxel (*tPAC*) above 0.05 μmol/L ($T_{>0.05}$) as obtained at the first drug application and peripheral neuropathy (*PNP*) development in 23 patients. *A*, scatter plots and the median (*horizontal bar*) of $T_{>0.05}$ in 14 patients without (■) and nine patients with (●) peripheral neuropathy. Applying a nonparametric Mann-Whitney test, this group difference was significant (*P* = 0.022). *B*, Kaplan-Meier type analyses of peripheral neuropathy – free outcome in this group. Splitting the variables into a group of 15 patients with $T_{>0.05} \geq$ 10.6 hours and eight patients with $T_{>0.05}$ < 10.6 hours, the unadjusted two-tailed log-rank test *P* was 0.023.

with regard to peripheral neuropathy development. Both of these phase I studies described an association between observed neuromuscular grade 3 toxicities and increased AUC or C_{max} levels of paclitaxel; however, these differences were based on very limited number of incidents (31, 32). It should be pointed out that we investigated the pharmacodynamic effects of Cremophor EL and paclitaxel separately from each other, whereas future models simultaneously considering measures of exposure to both paclitaxel and Cremophor EL could further refine the observed associations.

Based on previously published data reporting the association between concentrations of paclitaxel exceeding a particular threshold of 0.05 μmol/L ($T_{>0.05}$) and the extent of granulocytopenia (17, 18), we included this variable into our analysis as well. We found $T_{>0.05}$ to contribute to peripheral neuropathy development in the univariate analyses but also an independent factor in the Cox model. The hazard ratio of peripheral neuropathy development for patients experiencing concentrations of paclitaxel above 0.05 μmol/L for 10.6 hours or longer was estimated to be 18, although with very wide confidence intervals. Other studies failed to find a relation between pharmacokinetics and neurotoxicity (17, 33, 34), which could be likely because of the fact that neurotoxicity

Table 3. Cox regression analysis considered age (60-72 versus 42-59 y), previous therapy with vincamycin, AUC total paclitaxel $\geq$ 4.7 μg/mL $\times$ h, AUC unbound paclitaxel $\geq$ 0.375 μg/mL $\times$ h, and $T_{>0.05}$ total paclitaxel $\geq$ 10.6 h as promising variables influencing peripheral neuropathy development (peripheral neuropathy score of >3), as found in univariate analyses

Effect on PNP development	Hazard ratio (95% confidence interval)	*P*
Model 1		
Previous Vincamycin	11.46 (1.26-104.11)	0.03
AUC tPAC $\geq$4.7 μg/mL $\times$ h	2.18 (0.27-17.73)	0.47
AUC uPAC $\geq$0.375 μg/mL $\times$ h	7.40 (0.26-213.02)	0.24
Model 2		
Previous Vincamycin	11.28 (1.14-111.52)	0.038
$T_{>0.05}$ tPAC $\geq$10.6 h	18.43 (1.20-279.90)	0.036

NOTE: Model 1 is based on 24 patients and Model 2 on 23 patients each being assessable for this particular analysis. Both models have been adjusted for prior vincamycin as an independent factor in this analysis but not for age, which could be discarded as a factor relative to the other parameters.
Abbreviations: PNP, peripheral neuropathy; tPAC, total paclitaxel; uPAC, unbound paclitaxel.

was not a primary end point in these trials. Further models used concentrations of paclitaxel above 0.1 μmol/L ($T_{>0.1}$) as a threshold and found it to be related to hematologic toxicity (18, 35) and therapeutic efficacy (36). As our findings are based on a relatively limited number of patients, the conduction of further clinical studies investigating pharmacodynamic effects on peripheral neuropathy as primary end point would be desirable. In this context, further both empirically based (17, 18, 35) and mechanism-based estimates (37) that remained unstudied in our analysis should be investigated for their potential effects on peripheral neuropathy development.

The delivery of docosahexaenoic acid-paclitaxel, a fatty acid–conjugated form of paclitaxel that was primarily developed to enhance the drug uptake into solid tumors, revealed no moderate or severe neurotoxicity (38). The administration of docosahexaenoic acid-paclitaxel increased the half-life of paclitaxel significantly resulting in concentrations above 0.01 μmol/L ($T_{>0.01}$) for 6 to 7 days (38). Our data suggests that peripheral neuropathy development is associated with a particular threshold of drug exposure. Thus, the extended exposure to these low concentrations of paclitaxel associated with the administration of docosahexaenoic acid-paclitaxel might not have reached the threshold required for affecting peripheral nerves. Another, more simple explanation for these findings could be again the fact that neurotoxicity was not the primary end point of this study.

An unexpectedly identified variable with moderate statistical significance in both Cox models was prior therapy with vincamycin, which exclusively appeared as a factor potentially associated with development of peripheral neuropathy in this particular subset of patients but not in our primary clinical trial (6). One explanation for this discrepancy could be the fact that only two study centers were allowed to participate in the present substudy, which could have increased the reliability and validity of the acquired data.

In this study, $T_{>0.05}$ was the most important pharmacokinetic variable affecting the final outcome of our patients. As 1- and 3-hour infusions do not significantly differ in their $T_{>0.05}$ (15), this study contributes to the explanation why no significant differences in terms of peripheral neuropathy development have been seen in the primary clinical trial (6). From these experiences, we conclude that both 1- and 3-hour infusions are equally safe with respect to neurotoxicity. Furthermore, we believe that a further optimization in paclitaxel scheduling by adapting the infusion duration alone does not seem achievable. We strongly encourage further research in this area, which should include the development and investigation of neuroprotective agents accompanying paclitaxel therapy. Recent data revealed a decrease of nerve growth factor levels in plasma to be related to and predictive for peripheral neuropathy development (39), which could also be a target for a clinical application.

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