Significance of Trough Monitoring for Tacrolimus Blood Concentration and Calcineurin Activity in Adult Patients Undergoing Primary Living-Donor Liver Transplantation

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Running title: Tacrolimus pharmacokinetics and calcineurin activity

Abstract

Purpose Tacrolimus pharmacokinetics and calcineurin activity in peripheral blood mononuclear cells (PBMC) was investigated in adult patients undergoing primary living-donor liver transplantation (LDLT) in order to clarify the significance of trough monitoring of blood tacrolimus concentration during the early post-transplantation period.

Methods Fourteen patients were enrolled in this study, and time-course data after oral administration of a conventional tacrolimus formulation twice a day were obtained at 1 and 3 weeks after transplantation. The concentration of tacrolimus in whole blood and calcineurin activity in PBMC was measured.

Results The apparent clearance of tacrolimus significantly increased at 3 weeks compared with 1 week after transplantation, although the trough concentration did not significantly differ at 1 and 3 weeks after transplantation. The concentration at each sampling time, except at 1 h post-dose, was well correlated with the area under the concentration-time curve from 0 to 12 h ($AUC_{0–12}$). Neither the concentration at the trough time point nor $AUC_{0–12}$ was correlated with the area under the calcineurin activity-time curve from 0 to 12 h; calcineurin activity at the trough time point, however, was strongly correlated (r^2>0.92).

Conclusions Trough concentration monitoring was appropriate for routine tacrolimus dosage adjustment in adult LDLT patients. In addition, monitoring of calcineurin activity at the trough time point could be useful to predict the immunological status during the dosing interval of tacrolimus.

Key words: LDLT, pharmacodynamics, pharmacokinetics, therapeutic drug monitoring

Introduction

Tacrolimus, a calcineurin (CN) inhibitor, has been widely used to prevent acute rejections after liver transplantation, and therapeutic drug monitoring (TDM) of this drug is recommended to adjust dosages because of its narrow therapeutic index [1, 2]. Despite the large inter-individual variation in tacrolimus pharmacokinetics, the area under the concentration-time curve (AUC) *versus* the trough blood concentration (C_0) has a nearly linear relationship [3, 4], and C_0 of tacrolimus is usually monitored in patients receiving this drug. However, in some cases of renal transplantation, the correlation between C_0 and the AUC of tacrolimus is not adequate [5]. With cyclosporine, another CN inhibitor, C_0 does not correlate well with systemic drug exposure, and blood concentrations at 2 h post-dose (C_2) have been shown to be good predictors for the absorption profile [6]. Levy et al. [7] reported that a new monitoring strategy based on C_2 levels was superior to traditional C_0 monitoring for liver transplant recipients in reduction of the incidence and severity of acute rejections. Therefore, the relationship between C_0 and AUC of tacrolimus should be clarified in adult LDLT patients, because the pharmacokinetics of tacrolimus during the early post-transplantation period may fluctuate widely, according to the regeneration of grafted liver [8, 9].

The measurement of CN phosphatase activity in circulating blood is a pharmacodynamic approach for evaluating the immunosuppressive effect of CN inhibitors [10]. We found that tacrolimus and cyclosporine had different inhibitory effects on CN activity in peripheral blood mononuclear cells

(PBMCs) in *de novo* LDLT patients [11]. CN activity at trough time points represents a surrogate predictor for overall CN activity throughout the dosing intervals after cyclosporine administration in LDLT patients [12]. However, there is little information about the relationship between the overall CN activity throughout the dosing intervals and blood tacrolimus concentrations, and CN activity at trough time points, after oral administration of tacrolimus in this population.

This study was designed to evaluate pharmacokinetic profiles in parallel with CN activity in PBMCs at 1 and 3 weeks after LDLT in adult patients. Our aim was to evaluate the relationship between blood tacrolimus concentration at each sampling time and drug exposure during the dosing intervals, as well as CN activity during the dosing intervals, to clarify the significance of trough monitoring of tacrolimus blood concentration during the early post-transplantation phase.

Patients and methods

Study design

Patients more than 18 years old and who underwent primary LDLT between November 2007 and February 2009 at the Department of Transplantation and Immunology, Kyoto University Hospital were included in this study. Patients who suffered from fulminant hepatitis or were co-administered medications incompatible with tacrolimus were excluded. The study was discontinued when the administration of tacrolimus was stopped. The study protocol conformed to the ethical guidelines of the Declaration of Helsinki as reflected in *a priori* approval by the Kyoto University Graduate School and the Faculty of Medicine Ethics Committee. Written informed consent was obtained from each patient.

Within 12 h after LDLT, we started immunosuppression with a conventional tacrolimus formulation (Prograf®; Astellas Pharma Inc., Tokyo, Japan) and low-dose corticosteroids. The initial oral dose of tacrolimus was 0.05 mg/kg twice daily (0900 hours and 2100 hours), and the dose was adjusted to target blood tacrolimus concentrations according to the trough measurements during the 3 weeks after transplantation. The target C_0 was set between 10 and 15 ng/ml on postoperative days (PODs) 1–7, between 8 and 12 ng/ml on PODs 8–14, and between 6 and 10 ng/ml after POD 15, using a microparticle enzyme immunoassay (MEIA) method with an IMx® analyzer (Abbott Japan Co. Ltd., Tokyo, Japan). Corticosteroids were administered according to a protocol described previously [11].

Blood samples (2 ml) were taken before and at 1, 2, 4, 8, and 12 h after the morning administration on POD 6 or 8 (at 1 week) and POD 20 or 22 (at 3 weeks) in order to evaluate the effects of time after transplantation on pharmacokinetics and pharmacodynamics of tacrolimus. The concentration of tacrolimus in whole blood was measured using three analytical methods: high-performance liquid chromatography with tandem mass spectrometry (LC/MS/MS), as previously reported [13]; the MEIA method; and the enzyme-multiplied immunoassay instrument (EMIT) method, using the Viva-E® System (Siemens Healthcare Diagnostics, Tokyo, Japan). Samples were assayed as soon as possible after blood collection and preserved at -20°C before the assay if necessary.

CN phosphatase activity in PBMCs was measured using the remainder of the blood sample after blood concentration measurements, as an index of the pharmacological effects of tacrolimus. The assay of CN phosphatase activity in PBMCs was performed by use of〔ϒ-phosphorus32〕regulatory subunit type II (RII) phosphopeptide as a substrate, according to a procedure described previously [11]. On the day of transplantation, we obtained a blood sample to determine the baseline CN activity (CN_{base}) before the administration of tacrolimus in each patient.

Pharmacokinetic and pharmacodynamic analysis

The AUC from 0 to 12 h (AUC_{0-12}) after tacrolimus administration was calculated according to the trapezoidal rule. The highest observed concentration and associated time point were defined as the

maximum drug concentration (C_{max}) and the time at which the maximum concentration occurs (t_{max}), respectively. The apparent clearance (CL/F) was calculated by dividing the morning dose on each study day with the $AUC_{0–12}$. The area under the CN activity-time curve from 0 to 12 h ($AUA_{0–12}$) after administration was calculated according to the trapezoidal rule. The greatest observed CN inhibition, which caused a nadir of enzyme activity, and its associated time points were defined as the maximum CN inhibition (CN_{nadir}) and the corresponding time (t_{nadir}), respectively. The relationship between the blood tacrolimus concentration and CN activity in PBMCs was analyzed using the following maximum inhibitory effect (E_{max}) model:

$$CN = E_{max} - E_{max} \bullet C/(EC_{50} + C),$$

where CN is the CN activity at blood concentration C; E_{max} is the maximum inhibitory effect attributable to the drug, which is assumed to be the same as the baseline activity; and EC_{50} is the blood concentration that gives a half-maximal effect. The fixed parameters (θ) for E_{max} and EC_{50}, were estimated by use of the nonlinear mixed effects modeling program NONMEM version 6.2 (ICON Development Solutions, Ellicott City, MD), and inter-individual variability (η) for E_{max} and EC_{50} and residual variability (ε) were assumed to be log-normally distributed [11].

Statistical analysis

Data are presented as the mean ± standard deviation (SD). Statistical analyses were performed using the statistical software package GraphPad Prism 5 (GraphPad Software, Inc., San Diego, CA). The statistical significance of differences in mean values between 2 groups was analyzed using the paired *t* test. Pearson's correlation coefficient (*r*) was used to estimate correlations between 2 factors. A value of $P < 0.05$ was considered statistically significant.

Results

Measurement of blood tacrolimus concentrations by 3 methods

We routinely measured blood tacrolimus concentrations by the MEIA method and compared these measurements and those obtained using the EMIT assay with LC/MS/MS data. Although the MEIA or EMIT measurements were correlated with those obtained with the LC/MS/MS method, r^2 values were relatively poor in EMIT measurements (Fig. 1). We used LC/MS/MS data in the following analyses, because it is the most reliable method and because the MEIA method using an IMx® analyzer will not be commercially available after 2010.

Pharmacokinetic and pharmacodynamic profiles of tacrolimus

We included 14 primary LDLT patients in this study. The patients' demographic characteristics are summarized in Table 1. Figure 2 shows the time-course profiles of the blood tacrolimus concentration and CN activity at 1 and 3 weeks after LDLT. Table 2 shows the corresponding pharmacokinetic and pharmacodynamic parameters for tacrolimus. We could not obtain time-course data for 1 patient at 3 weeks after LDLT because of the decease from infection. The blood concentration profile at 3 weeks after LDLT changed gradually compared with that at 1 week, and the blood concentration at 1 h post-dose at 3 weeks was significantly lower than at 1 week (Fig. 2a). The $AUC_{0–12}$ was significantly smaller at 3 weeks than at 1 week after LDLT ($P < 0.05$), although the morning dose tended to increase from 0.020

mg/kg at 1 week to 0.026 mg/kg at 3 weeks (Table 2). Eleven of 13 patients showed an increase of CL/F at 3 weeks compared with that at 1 week, and this difference was statistically significant (Table 2, $P<0.05$). Thirteen patients would yield an 82% power to detect a 0.121 l/h/kg difference in CL/F (0.147 *versus* 0.268 l/h/kg at 1 and 3 weeks, respectively) with a significant level of 0.05 (one-tailed test).

The CN activity changed slightly and in parallel with the blood concentration, and returned to the pre-dose levels by 12 h post-dose at both 1 and 3 weeks after LDLT (Fig. 2b). The CN activity at the trough time point (CN_0) was suppressed to approximately 65% of the baseline value at 1 week, and CN_0 at 1 and 3 weeks after LDLT were not statistically significant (Table 2; Fig. 2).

Correlation between blood concentration and AUC of tacrolimus

The trough blood concentration before the morning dose (C_0) and before the evening dose (C_{12}) showed a high correlation with the $AUC_{0–12}$ (Fig. 3; $r^2 = 0.767$ to 0.888), although the correlation of C_0 at 1 week after LDLT was not so high ($r^2 = 0.530$). The blood concentrations at 2, 4, and 8 h post-dose also showed strong correlations with the $AUC_{0–12}$, and the correlation with the blood concentration at 1 h post-dose was weak ($r^2 = 0.411$ or 0.498).

Relationship between blood concentration and CN activity

The CN activity in PBMCs was inhibited in a concentration-dependent manner by tacrolimus, but the inhibition was not complete even at blood tacrolimus concentrations more than 20 ng/ml (Fig. 4). Through the application of the E_{max} model to data from the 14 patients, we calculated the EC_{50} as 20.9 ng/ml (95% confident interval: 11.6–30.2) and the E_{max} as 64.6 pmol/min/mg protein (95% confident interval: 56.3–72.9) by using the nonlinear mixed effects model.

Correlation between tacrolimus exposure and pharmacodynamic response

Both pharmacodynamic parameters CN_0 and $AUA_{0–12}$ did not correlate with C_0 (Figs. 5a and b). The correlation between the $AUA_{0–12}$ and the $AUC_{0–12}$ was also weak (Fig. 5c). However, the $AUA_{0–12}$ showed a strong correlation with CN_0 activity (r^2 = 0.919 or 0.931, Fig. 5d), as did CN activity at other time points (data not shown).

Discussion

LDLT and subsequent immunosuppressive therapy provide excellent results and are usually used in combination with a deceased donor organ-transplant program [14, 15]. Although the prevention of immunological reactions with sufficient immunosuppression prolongs graft and patient survival rates, the large inter-individual variation in tacrolimus pharmacokinetics interferes with treatment [16]. We previously reported that the probability of acute cellular rejection during the first 10 days after surgery was significantly associated with the average trough concentration of tacrolimus between PODs 2 and 4 [17]. However, we had no clear evidence of the trough monitoring or AUC-based monitoring of tacrolimus blood concentration. In this study, we confirmed that the trough blood concentration was a good surrogate marker for tacrolimus exposure during the dosing interval in LDLT patients.

In the time-course study at 3 weeks after LDLT, t_{max} was prolonged and the difference between peak and trough concentrations was smaller compared with that at 1 week, indicating the delayed and poor absorption of tacrolimus at 3 weeks after LDLT (Fig. 2). Although we cannot completely explain this phenomenon, the first-pass effects in the intestine and/or liver by cytochrome 3A and P-glycoprotein may be increased at 3 weeks after LDLT compared with at 1 week. In addition, the apparent clearance of tacrolimus at 3 weeks after LDLT was approximately twice that at 1 week (Table 2). We previously reported that the total-body clearance of tacrolimus in LDLT patients was increased according to the POD because of the regeneration of grafted liver [8, 9]. According to the previously estimated population

pharmacokinetic parameters [8], a typical adult LDLT recipient in this study (grafted liver weight of 611 g, normal hepatic and renal function, and body weight of 67.1 kg during week 1 and 63.5 kg during week 3) would have a CL/F of 0.186 L/h/kg on POD 7 and 0.241 L/h/kg on POD 21; these values are comparable to the mean CL/F in this study.

We examined the correlation between $AUC_{0–12}$ and blood concentration at each sampling point (Fig. 3). Although the correlation between the blood concentration at 1 h post-dose and the $AUC_{0–12}$ was weak, other blood concentrations showed reasonable or strong correlations with the $AUC_{0–12}$. Since the blood concentration at 12 h post-dose (C_{12}) will correlate with AUC_{0-12} for this dose and that C_0 should correlate with AUC_{0-12} for the previous dose, C_{12} showed higher correlation than C_0. The relatively weak correlation found in C_0 at 1 week after LDLT was considered due to a large variability in the pharmacokinetics of tacrolimus immediately after LDLT, similar to the findings in renal transplant recipients [5]. A good correlation between AUC from 0 to 24 h and trough concentrations for both twice-daily and once-daily prolonged tacrolimus formulations were reported in *de novo* kidney transplantation [18]. According to the previous report by Scholten et al. [5], Bayesian forecasting with a 2-point sampling strategy, a trough level and a second sample obtained between 2 and 4 h post-dose, might improve the correlation with $AUC_{0–12}$. Taking these finding into consideration, we concluded that a single-trough concentration before the morning dose is sufficient to provide an index of blood tacrolimus exposure during the dosing interval in LDLT patients, even during the early post-transplantation period.

The CN activity changed in parallel with the blood tacrolimus concentration, and showed a similar flat time profile at 1 and 3 weeks after LDLT (Fig. 2). These results indicated that unlike cyclosporine [12], tacrolimus partially suppressed CN activity throughout the dosing interval, probably because of the limited amount of active FK506-binding protein 12 in PBMCs [19]. The relationship between CN activity and blood tacrolimus concentration was analyzed using an E_{max} model with an EC_{50} of 20.9 ng/mL (Fig. 4), which is higher than the upper limit of the therapeutic range of tacrolimus, as discussed in our previous report [11]. Additionally, Fig. 4 showed a large inter-individual variability in the relation between tacrolimus exposure and CN activity. This phenomenon may be explained by the inter-individual variability of expression level of P-glycoprotein in PBMCs [20] or variation in PBMC subset concentrations [21].

We next examined the correlation between pharmacokinetic and pharmacodynamic parameters. A single C_0 did not correlate with CN_0 or AUA_{0-12} (Figs. 5a, b). In addition, as in our previous study of cyclosporine [12], the AUC_{0-12} of tacrolimus showed no relationship with AUA_{0-12} (Fig. 5c). These results indicate a large inter-individual variability in the relationship between tacrolimus blood exposure and CN activity; monitoring of only tacrolimus blood concentrations does not adequately maintain CN activity at a targeted level, as reported by Blanchet et al. [22]. However, CN_0 activity was strongly correlated with the AUA_{0-12} (Fig. 5d, $r^2 > 0.92$). We recently reported that CN activity rapidly increased a few days before the onset of acute rejection in 2 patients after living-donor kidney transplantation [23].

Therefore, monitoring CN activity at the trough time point would be useful for predicting the overall CN activity in LDLT patients administered tacrolimus. In this study, we could not clarify the relationship between calcineurin activity and clinical outcomes, nor therapeutic range of calcineurin activity. Significance of measurements of calcineurin activity remains to be clarified in a large cohort of liver transplant recipients.

In conclusion, we have shown that C_0 monitoring of tacrolimus can be used to evaluate drug exposure in LDLT patients during the early post-transplantatation period, and that monitoring of CN activity at the trough time point could be useful to predict the immunological status during the dosing interval of tacrolimus.

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Figure Legends

Fig. 1 Correlation between the blood tacrolimus concentration by high-performance liquid chromatography with tandem mass spectrometry (LC/MS/MS) and microparticle enzyme immunoassay (MEIA) (a) or enzyme-multiplied immunoassay instrument (EMIT) (b) methods. Each point shows a time-course datum from 14 patients at 1 week and 13 patients at 3 weeks after living-donor liver transplantation. Solid and dotted lines show the linear regression line and the line of identity, respectively

Fig. 2 Time course of blood tacrolimus concentration and calcineurin (CN) phosphatase activity in peripheral blood mononuclear cells at 1 week (*open circles*) and 3 weeks (*closed circles*) after living-donor liver transplantation. Each symbol represents the mean ± standard deviation (n = 14 and 13 for 1 and 3 weeks after transplantation, respectively). *$P < 0.05$, significantly different from 1 week after transplantation

Fig. 3 Correlation between area under the concentration-time curve from 0 to 12 h ($AUC_{0\text{-}12}$) and blood tacrolimus concentration at pre-dose and 1, 2, 4, 8, and 12 h after the morning administration (C_0, C_1, C_2, C_4, C_8, and C_{12}, respectively). Each point shows a datum from 14 patients at 1 week (*open circles*) and 13 patients at 3 weeks (*closed circles*) after living-donor liver transplantation. Each solid and dashed line

represents the linear regression line at 1 and 3 weeks, respectively

Fig. 4 Relationship between blood tacrolimus concentration and calcineurin (CN) activity in living-donor liver transplant patients. Each point shows a time-course datum from 14 patients at 1 week (*open circles*) and 13 patients at 3 weeks (*closed circles*) after living-donor liver transplantation. Solid line shows the predicted calcineurin phosphatase activity *versus* the blood tacrolimus concentration profile according to the maximum inhibitory effect model by use of the nonlinear mixed effects modeling program

Fig. 5 Correlation between pharmacokinetic and pharmacodynamic parameters (a, b, and c) and between pharmacodynamic parameters (d) of tacrolimus in 14 patients at 1 week (*open circles*) and 13 patients at 3 weeks (*closed circles*) after living-donor liver transplantation. Calcineurin activity at the trough time point (CN_0, panel a) or the area under the calcineurin activity-time curve from 0 to 12 h ($AUA_{0–12}$, panel b) *versus* blood concentration pre-dose (C_0). Panel c: $AUA_{0–12}$ *versus* area under the concentration-time curve from 0 to 12 h ($AUC_{0–12}$). Panel d: $AUA_{0–12}$ *versus* CN_0 activity. Each solid and dashed line represents the linear regression line at 1 and 3 weeks, respectively

Table 1 Demographic characteristics of the study population

Characteristic	Number or mean ± standard deviation
Gender (male/female)	8/6
Age (years)	58 ± 6
Grafted liver weight (g)	611 ± 156
GRWR (%)	0.955 ± 0.184
ABO blood group match	
identical	7
compatible	5
incompatible	2
Primary disease	
Hepatitis B virus infection	3
Hepatitis C virus infection	6
Primary biliary cirrhosis	3
Alcoholic liver cirrhosis	1
Autoimmune hepatitis	1

GRWR, graft-to-recipient weight ratio.

Table 2 Pharmacokinetic and pharmacodynamic parameters of tacrolimus

Parameters	Week1 (n = 14)	Week3 (n = 13)
Body weight (kg)	67.1 ± 15.2	63.5 ± 10.1
Morning dose (mg/kg)	0.020 ± 0.015	0.026 ± 0.017
Pharmacokinetic parameters		
C_0 (ng/ml)	9.8 ± 2.6	7.7 ± 2.7
t_{max} (h)	2 (1-8)	2 (0-4)
C_{max} (ng/ml)	16.0 ± 5.4	12.5 ± 4.9
AUC_{0-12} (ng h/ml)	140 ± 38	110 ± 40*
CL/F (l/h/kg)	0.147 ± 0.110	0.268 ± 0.220*
Pharmacodynamic parameters		
CN_{base} (pmol/min/mg protein)	73.8 ± 16.2[a]	-[b]
CN_0 (pmol/min/mg protein)	47.9 ± 14.5	47.0 ± 11.2
t_{nadir} (h)	2	4
CN_{nadir} (mg/min/mg protein)	40.6 ± 15.4	39.2 ± 9.7
AUA_{0-12} (pmol h/min/mg protein)	537 ± 188	512 ± 114

Data are given as the mean ± SD or median (minimum-maximum). [a]n = 10. [b]Only measured on the day of transplantation. *Significantly different from the mean value at week 1 ($P < 0.05$).

C_0, blood concentration pre-dose; C_{max}, maximum blood concentration; t_{max}, time corresponding to C_{max}; AUC_{0-12}, area under the concentration-time curve from 0 to 12 h; CL/F, apparent clearance; CN_{base}, calcineurin activity at baseline measured before tacrolimus administration on the day of transplantation; CN_0, calcineurin activity pre-dose; CN_{nadir}, calcineurin activity at maximum inhibition; t_{nadir}, time corresponding to CN_{nadir}; AUA_{0-12}, area under the calcineurin activity-time curve from 0 to 12 h.

Fig.1

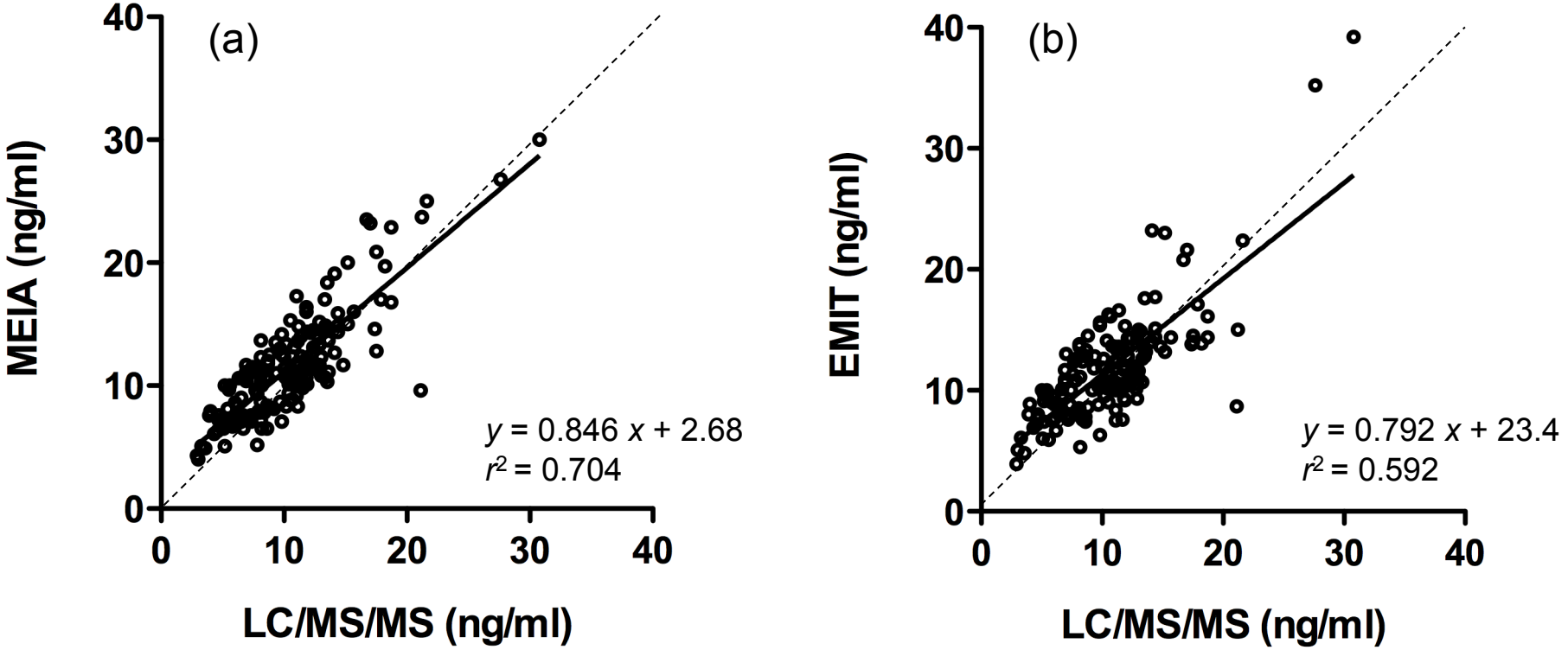

(a)
MEIA (ng/ml)
LC/MS/MS (ng/ml)
y = 0.846 x + 2.68
r2 = 0.704
0
10
20
30
40
(b)
EMIT (ng/ml)
LC/MS/MS (ng/ml)
y = 0.792 x + 23.4
r2 = 0.592

Fig. 2

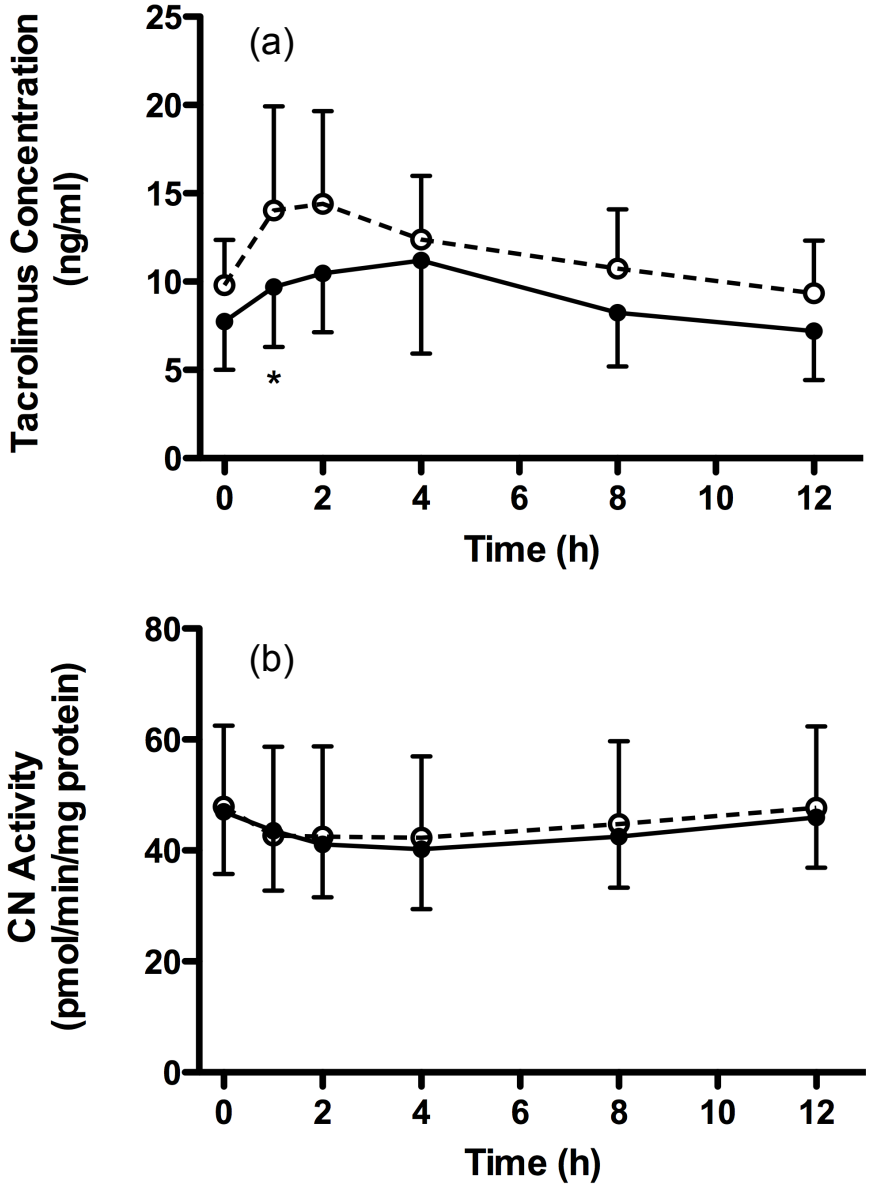

(a)
Tacrolimus Concentration (ng/ml)
25
20
15
10
5
0
*
0
2
4
6
8
10
12
Time (h)
(b)
CN Activity (pmol/min/mg protein)
80
60
40
20
0
0
2
4
6
8
10
12
Time (h)

Fig.3

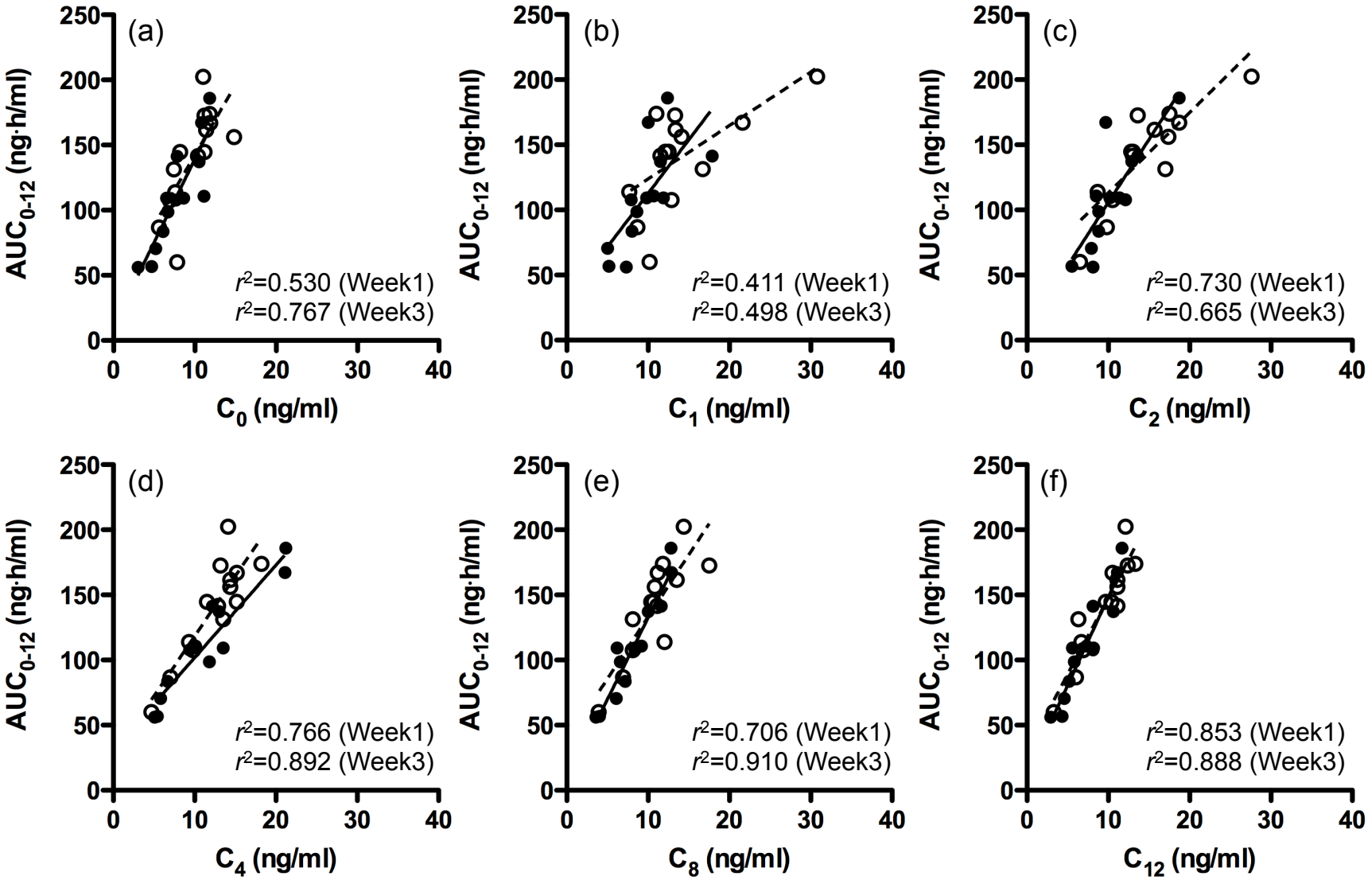

(a)
AUC0-12 (ng·h/ml)
C0 (ng/ml)
r2=0.530 (Week1)
r2=0.767 (Week3)
(b)
AUC0-12 (ng·h/ml)
C1 (ng/ml)
r2=0.411 (Week1)
r2=0.498 (Week3)
(c)
AUC0-12 (ng·h/ml)
C2 (ng/ml)
r2=0.730 (Week1)
r2=0.665 (Week3)
(d)
AUC0-12 (ng·h/ml)
C4 (ng/ml)
r2=0.766 (Week1)
r2=0.892 (Week3)
(e)
AUC0-12 (ng·h/ml)
C8 (ng/ml)
r2=0.706 (Week1)
r2=0.910 (Week3)
(f)
AUC0-12 (ng·h/ml)
C12 (ng/ml)
r2=0.853 (Week1)
r2=0.888 (Week3)

Fig.4

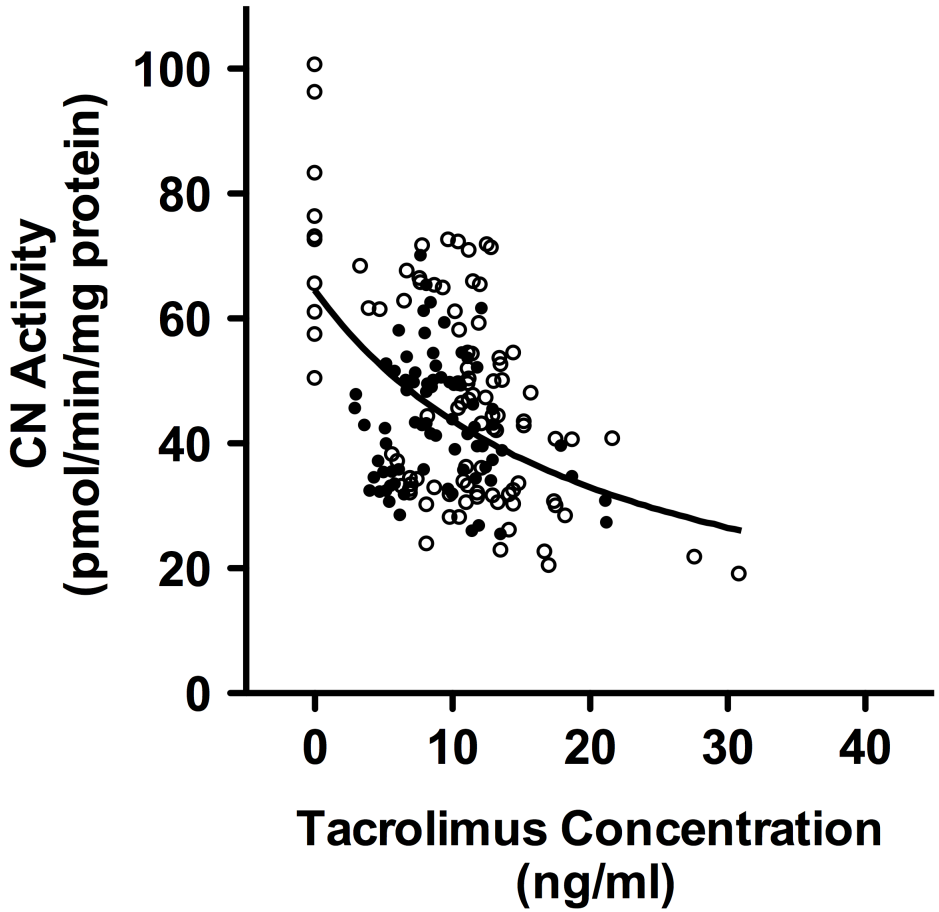
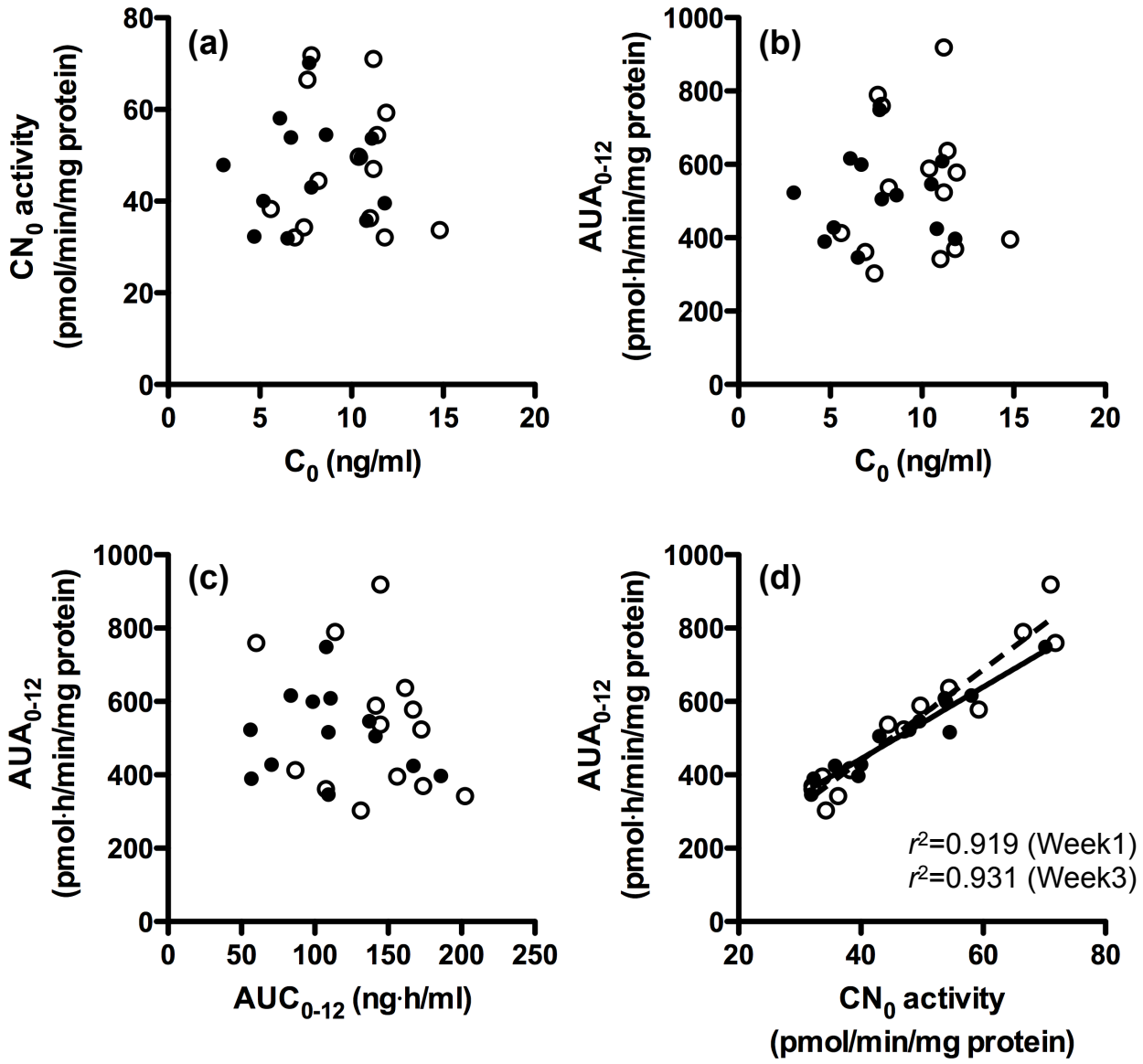

CN Activity
(pmol/min/mg protein)
100
80
60
40
20
0
0
10
20
30
40
Tacrolimus Concentration
(ng/ml)

Fig. 5


(a)
CN0 activity
(pmol/min/mg protein)
C0 (ng/ml)
(b)
AUA0-12
(pmol·h/min/mg protein)
C0 (ng/ml)
(c)
AUA0-12
(pmol·h/min/mg protein)
AUC0-12 (ng·h/ml)
(d)
AUA0-12
(pmol·h/min/mg protein)
r2=0.919 (Week1)
r2=0.931 (Week3)
CN0 activity
(pmol/min/mg protein)