

Comparison of the hypothalamic–pituitary–adrenal axis susceptibility upon single-dose i.m. depot versus long-acting i.v. triamcinolone acetonide therapy: a direct pharmacokinetic correlation

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Abstract

The effects of single injections of glucocorticoid (GC) depot suspension and of long-acting GC were studied in conscious dogs. Both the depot suspension GC triamcinolone-16,17- α -acetonide (TAA) and the long-acting triamcinolone acetonide-21-dihydrogen phosphate (TAA-DHP) decreased basal and ACTH-stimulated cortisol levels and in a specific time-dependent way. Before treatment, all dogs had normal basal and peak cortisol responses to ACTH challenge (13–15 and >120 nmol/l at 1 h respectively). Intravenous TAA-DHP reduced cortisol levels for 12 h, i.m. TAA reduced cortisol levels as of 1.5 h and the effect lasted for at least 4 weeks. Both treatments blunted the peak response to ACTH. ACTH elevated cortisol levels to or above baseline values within

10 days following TAA-DHP treatment, but the TAA treatment suppressed an ACTH response for at least 4 weeks. Kinetic analysis of both the preparations demonstrated rapid absorption (t_{\max} , 0.6–1.5 h) and low maximum plasma concentrations (peak C_{\max} , 2.99–5.51 nmol/l) of the steroids; indeed, the terminal half-life of TAA-DHP (13.9 ± 1.3 h) was very much shorter than that of TAA (125.9 ± 15.8 h). In addition, the mean residence time differed very much (11 vs 160 h for TAA-DHP and TAA respectively), in line with a delayed elimination of the depot compared with the long-acting formulation. Application of these TAA formulations needs careful evaluation for their surprisingly different effects on endocrine stress axis activity.

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Introduction

Triamcinolone acetonide (TAA), a synthetic glucocorticoid (GC; 9 α -fluoro-16 α -hydroxyprednisolone), is a more potent intermediate-acting derivative of triamcinolone and has eight times more potency than prednisone. The intravenously used long-acting TAA is available as water-soluble phosphate ester, e.g. triamcinolone acetonide-21-dihydrogen phosphate (TAA-DHP), which is supposed to be hydrolysed rapidly in the body to form the free corticoid alcohol (Möllmann *et al.* 1985). The depot i.m. formulation of triamcinolone acetonide, e.g. triamcinolone-16,17- α -acetonide (TAA), is available as a sterile crystalline suspension. This formulation is practically insoluble in water, and hence provides a depot effect with constant release of the active agent from the injection site over a long period of time.

In general, GCs are potent anti-inflammatory drugs used for the treatment of a variety of disorders. When given systemically, they are known to induce many side effects. To avoid multiple dosing of short-acting GCs, long-acting GCs, including TAA are preferred formulations for the treatment of several autoimmune diseases, such as in systemic lupus erythematosus and multiple sclerosis and/or serious inflammatory diseases as well as in diabetic retinopathy (Scher 1964, Heun *et al.* 1992, Doggrel 2001,

Jonas *et al.* 2001, Massin *et al.* 2004, Hoffmann *et al.* 2006). Moreover, depot formulation of injectable TAA is effective in GC-resistant asthma which is poorly controlled by β_2 -adrenoceptor agonists (Doggrel 2001). The most common and best studied use of this drug formulation is for the treatment of joint disorders (Roberts *et al.* 1996, Kumar *et al.* 2004) and several exsudative diseases of the eye (Gillies *et al.* 2003, Jonas *et al.* 2003).

Suppression of the hypothalamic–pituitary–adrenal (HPA) axis function has been well documented as one of the most important potential complications upon repeated systemic GC therapy (Tuft *et al.* 1971, Miyamoto *et al.* 1972, Mikhail *et al.* 1973, Dallman *et al.* 1994), a paradigm based in part upon administration of high non-physiological doses of GCs (Baxter 2000, Zaloga & Marik 2001). This drawback is associated with decreased production of the hypothalamic corticotrophin-releasing hormone (CRH) and the pituitary adrenocorticotrophic hormone (ACTH; Keller-Wood & Dallman 1984, Antoni 1986, Dallman *et al.* 1987). Many studies have demonstrated that repeated and high dosing treatment with short- or long-acting GCs adversely affect the vulnerability of the HPA axis activity and adrenal function with a consequent decrease in plasma cortisol levels. Only a few studies addressed single-dose depot TAA administration and the risk to induce long-term adverse effects. Recently,

a case of acute iatrogenic Cushing's syndrome and HPA axis suppression which persisted 8 months has been reported in humans after a single-dose i.m. depot TAA administration (Iglesias *et al.* 2005). However, in another study on dogs, the adrenocortical responsiveness recovered within 2 weeks after i.m. TAA injection (Kemppainen *et al.* 1982). Such delayed HPA axis and adrenal responses after the single-dose depot, TAA seem to be associated with the delayed pharmacokinetics of the drug, but direct evidence is lacking so far. Few studies have focussed merely on the pharmacokinetics of the long-acting TAA and its water-soluble phosphate ester (TAA-DHP) after i.v. administration, and showed that TAA exhibits a high clearance, high volume of distribution and short half-life (Möllmann *et al.* 1985, Derendorf *et al.* 1995, Rohatagi *et al.* 1995).

Since repeated administration of GCs eventually suppresses HPA axis activity, we were interested to compare two long-acting GC formulations for their effect on HPA axis activity. We have determined the time dependence of the effects of TAA and TAA-DHP treatment (single injections) on basal and ACTH-stimulated cortisol levels and assessed the pharmacokinetics of the TAA formulations.

Materials and Methods

Chemicals

Triamcinolone acetonide-21-dihydrogen phosphate (TAA-DHP; volon A soluble 40 mg) was purchased from Mibe GmbH Arzneimittel (Brehna, Germany), and the depot formulation of TAA was a kind gift of AniMedica GmbH (Senden-Bösensell, Germany). Triamcinolone acetonide was purchased from Sigma. The ELISA Kit was obtained from Bio-X Diagnostics (Jemelle, Belgium). ^3H -cortisol (specific activity, 50–90 Ci/mmol) was purchased from Amersham Biosciences, and ACTH (Synacthen) from Novartis. All other chemicals were obtained at pro-analysis quality from commercial sources.

Animals

In these studies, ten castrated adult beagle dogs (four males and six females) between 4 and 5 years of age, weighing between 11 and 16 kg, were used. The animals were housed in solid bottom cages and were fed with commercial diet food and received water *ad libitum*. They were clinically healthy and received no steroid therapy at least 3 months prior to this experiment, except a routine vaccination and deworming. Each dog served as its own control.

Animal experiments were approved by the local ethical committee for animal welfare and were carried out in accordance with the guidelines of the German law relating to animal welfare.

Experimental design

All animals were investigated on two consecutive occasions with a 2-week washout period in a single-blind, crossover and random order. First, animals received a single dose of the long-acting formulation TAA-DHP (0.2 mg/kg) intravenously; the response of basal cortisol was measured in blood plasma samples taken at 0 h (control and baseline) and at 0.5, 1, 1.5, 2, 4, 8, 12, 24, 36, 48, 72 and 96 h, and at days 8 and 10 after injection. The ACTH-stimulated cortisol response at this occasion was determined on 0 h (baseline) as well on 48 h and day 10 after treatment. Secondly, 2 weeks after TAA-DHP when the animals had recovered as indicated by normalised plasma cortisol levels, the animals received the TAA formulation (i.m.). Sampling was at 0, 0.5, 1, 1.5, 2, 4, 8, 12, 24, 36, 48, 72 and 96 h, and at days 8, 10, 15, 17, 22 and 29, to cover a full 4-week period. ACTH-stimulated cortisol levels were assessed at 0 h (baseline) and 48 h, and at days 10 and 29. All tests and blood sampling were started between 0800 and 1000 h. The dogs were fasted overnight before experiments.

HPA axis activity was tested by a bolus injection of synthetic ACTH (synacthen, 250 μg per animal, not corrected for body weight) at 0800 h and blood was taken 1 h after this ACTH challenge.

For the analysis of basal and ACTH-stimulated cortisol levels as well as for the pharmacokinetic analysis of both substances, blood samples were usually collected at 0800 h from the cephalic vein by venipuncture in EDTA-containing tubes (Sarstedt, Hamburg, Germany). Plasma samples were obtained after centrifugation of the whole blood (4000 g, 10 min, 4 °C), and the aliquots were stored at -20 °C until analysis.

Assay of cortisol

Cortisol was assayed by RIA using commercially available ^3H -cortisol (specific activity, 50–90 Ci/nmol) as recently described (Abraham *et al.* 2005). The detection limit was 0.3 nmol/l; coefficient of variations were 8.1% (intra-assay) and 10.2% (interassay; $N=6$) at plasma cortisol levels measured in the animals. All samples were determined in duplicate, and all samples from a single study were run in the same assay. In brief, perturbing components were separated by precipitating the blood plasma with an absolute alcohol (99.98%). For this purpose, 100 μl thawed blood plasma were mixed with 900 μl ethanol and centrifuged at 4000 g for 15 min at 4 °C. Thereafter, 100 μl supernatant were transferred to new incubation tubes, and samples were dried overnight at 37 °C in a drying closet. After drying the samples, 100 μl phosphate buffer were added to each sample. Samples were incubated after the addition of aliquots of 100 μl ^3H -cortisol at a final concentration of 1.4–2.5 nM (≈ 125 nCi/ml) and 100 μl polyclonal antibody (raised in rabbits against cortisol) at final volumes of 300 μl for 4 h at 4 °C. Non-specific binding was determined in the absence of antibody. The separation of bound and unbound tracers was achieved by adsorption of the free nucleotide on to active charcoal, followed by centrifugation at 1500 g for 15 min at 4 °C. An aliquot of the supernatant was

removed for liquid scintillation analysis (Perkin–Elmer Life Sciences, Freiburg, Germany). Sample cortisol was estimated from comparison with standards run in triplicate; cortisol concentrations are expressed in nanomolar per litre. Samples from individual dogs were always run in the same assay.

Assay of TAA

Plasma concentrations of TAA were measured using a commercially available enzyme immunoassay (ELISA). This kit is designed for screening of TAA in milk, urine, tissue and feed samples. A calibration line was generated for each analysis by assaying TAA standards (0.02–0.46 nmol/l). The limit of quantification (LOQ) was calculated in 18 representative blank samples (plasma samples without TAA). The LOQ was calculated as the apparent content corresponding to the value of the mean plus three times the S.E.M. for the blank determinations. The LOQ was 0.14 nmol/l plasma. The coefficient of variance for the interassay precision was <11%. The assay was carried out according to the manufacturer's instruction. In brief, plasma (100 µl) was extracted with 4 ml diethyl ether after adding 400 µl distilled water. After agitation of the samples for 20 min at room temperature, they were centrifuged at 1000 *g* for 10 min. The organic phase was then evaporated to dryness, and each sample was dissolved in 1 ml phosphate buffer (34 mM, pH 7.4). Samples (50 µl) were added to each sheep anti-rabbit IgG-coated microplate wells (96-well plate) with 100 µl conjugate solution (TAA plus peroxidase) and 100 µl anti-TAA antibody solution. Then the wells were incubated for 2 h at 4 °C. After washing the well plates, 150 µl substrate (tetramethylbenzidine) were added to each well, and incubation was carried out light protected for 30 min at room temperature for colour development. The reaction was terminated by adding 50 µl sulphuric acid (3 M) and the optical density for each well was determined at 450 nm (TECAN Deutschland GmbH, Crailsheim, Germany; Spectra Thermo). Blank plasma and a positive control were included in each strip when analysing samples.

Pharmacokinetic data for plasma concentrations of TAA in each animal were analysed using least-squares non-linear regression analysis (Heinzel *et al.* 1993). The calculated highest plasma concentration of TAA was designated C_{max} , and the time this value was reached designated T_{max} . The area under the curve (AUC) was calculated using the trapezoidal rule. The total body clearance (CL) was calculated as dose divided by AUC. Mean residence time (MRT) was determined as area under the first moment curve divided by AUC.

Statistical analysis

Data presented in figures and tables are means \pm S.E.M. ($N=10$). Statistical analysis of the data obtained with the RIA (basal and ACTH-induced cortisol levels) was performed using GraphPad prism software (version 4.0; GraphPad Software, San Diego, CA, USA). Statistical significance of differences was analysed by unpaired two-tailed Student's *t*-test

or, if appropriate, by repeated measures ANOVA followed by *t*-test using Bonferroni corrections for multiple comparisons. A *P* value <0.05 was taken to indicate significance of differences. The statistical evaluation was performed using GraphPad prism software as mentioned earlier.

Results

Basal and ACTH-stimulated cortisol levels

Figure 1A and B shows the results of *in vivo* experiments from two consecutive occasions, i.e. after a single i.v. and i.m. injection of TAA-DHP and TAA respectively. A significant interaction between time and treatment ($P<0.01$) for the plasma cortisol was observed. One and a half hours after

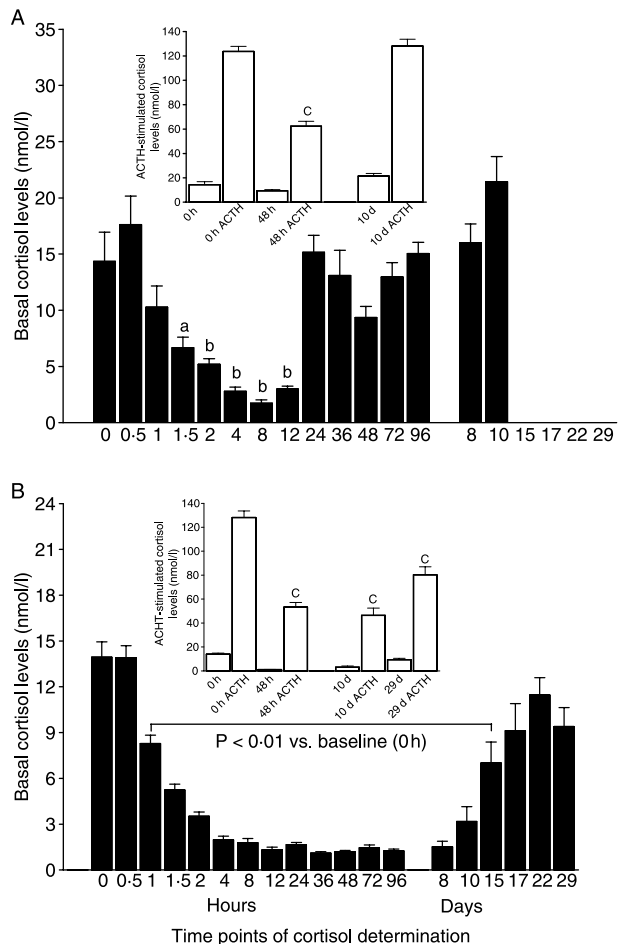


Figure 1 Mean plasma cortisol values (\pm S.E.M., $N=10$) (A) before treatment and after a single-dose i.v. administration of the long-acting-GC (TAA-DHP) and (B) before and after a single-dose i.m. administration of depot TAA. Insets. Mean baseline and maximum cortisol levels (\pm S.E.M.) after ACTH stimulation before and after (A) TAA-DHP and (B) depot TAA. ^a $P<0.05$ vs baseline (0 h); ^b $P<0.01$ vs baseline (0 h); ^c $P<0.01$ vs baseline ACTH-stimulated cortisol (before TAA-DHP injection); in the insets, d represents day.

TAA-DHP injection, basal cortisol had decreased below baseline values (14.35 ± 2.60 vs 6.67 ± 0.94 nmol/l; $P < 0.05$; Fig. 1A). The largest response (inhibition of basal cortisol) following TAA-DHP was observed at 8 h following injection (1.73 ± 0.94 nmol/l; $P < 0.01$). Even though basal cortisol had recovered after 24 h, the ACTH response was still blunted at 48 h after the injection of TAA-DHP (Fig. 1A, inset; 62.37 ± 4.01 vs 123.66 ± 4.15 nmol/l; $P < 0.01$ vs time 0), but reached baseline values after 10 days.

In contrast, as shown in Fig. 1B, the depot i.m. GC formulation (TAA) declined significantly ($P < 0.01$) the baseline (0 h) cortisol concentrations (13.94 ± 1.01) until day 15. The lowest cortisol concentrations were steady between 4 h and day 8 after injection. Here, the cortisol rise towards the baseline values was markedly delayed when compared with TAA-DHP, and baseline values were achieved only after about 3 weeks (day 22). On average, after the injection of 250 µg ACTH, maximum cortisol concentrations had decreased by approximately 58, 64 and 37% respectively, below values of pre-treatment stimulation after 48 h, 10 and 29 days of single TAA dose (Fig. 1B, inset; $P < 0.01$ vs time 0); this formulation consistently delayed the HPA axis recovery.

Gender did not affect basal cortisol levels (males 14.76 ± 2.26 nmol/l, $n = 4$ vs females 13.39 ± 0.89 nmol/l, $n = 6$) and cortisol responses after ACTH challenge (males 126.02 ± 8.01 nmol/l, $n = 4$ vs females 122.09 ± 4.96 nmol/l, $n = 6$).

Plasma TAA following TAA and TAA-DHP injection

The mean plasma concentration (\pm s.e.m.) of TAA measured over 36 h after i.v. administration of a single-dose TAA-DHP (0.2 mg/kg) indicated rapid decline of the GC reaching values at or below the limit of quantification after 8 h. Figure 2A depicts the mean plasma concentration–time profile after i.v. administration. The mean pharmacokinetic parameters calculated by non-compartmental methods are given in Table 1. The t_{max} of TAA after a single i.v. dose occurred at 0.6 ± 0.1 h, reaching a C_{max} value of 5.8 ± 0.2 nmol/l. The total body clearance was 0.5 ± 0.1 ml/min per kg. The terminal half-life was 13.9 ± 1.3 h, and the MRT 10.7 ± 1.3 h, indicating a relatively fast elimination of the active substance. The volume of distribution at steady-state level was 0.6 ± 0.1 l/kg.

The mean plasma concentrations of TAA after i.m. depot single dose (0.2 mg/kg) are depicted in Fig. 2B, and the mean pharmacokinetic data are listed in Table 1. At t_{max} 1.5 ± 0.1 h, the maximum plasma concentrations (C_{max}) of TAA were 3.1 ± 0.3 nmol/l, amounting about 50% of the initial concentration observed after i.v. administration (5.8 ± 0.2 nmol/l; peak levels of TAA occurred 30 min after i.v. injection). Subsequently, TAA levels decreased, but were still detectable 29 days after a single-dose i.m. depot injection. The area under the plasma concentration curve (AUC) was larger than the AUC after i.v. TAA-DHP injection (134.2 ± 8.4 vs 17.9 ± 1.7 nmol/h per l). The total body clearance for the depot formulation was 0.1 ml/min per kg. The terminal half-life for the depot TAA was

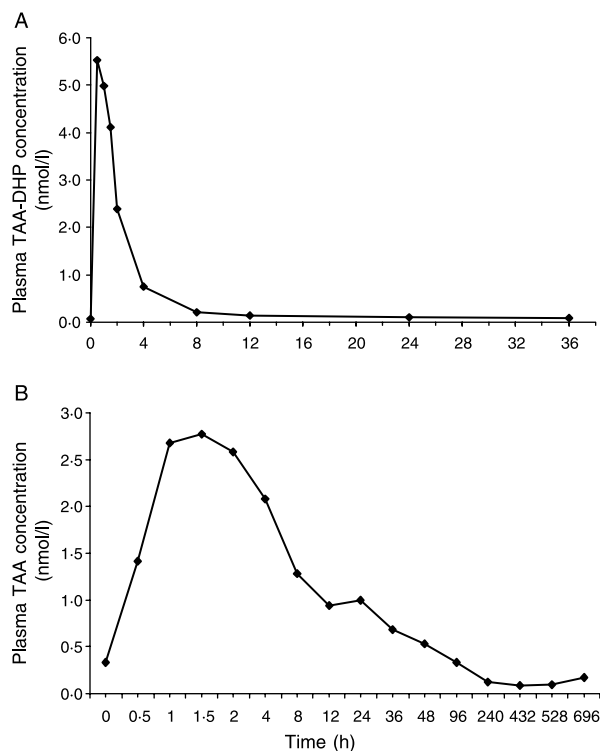


Figure 2 Mean plasma concentration profiles for TAA (\pm s.e.m., $n = 10$) (A) after a single-dose i.v. administration of the long-acting GC (0.2 mg/kg) and (B) single-dose i.m. administration of the depot GC (0.2 mg/kg).

125.9 ± 15.8 h, and the MRT 159.8 ± 21.2 h, which strongly explains the delayed elimination time for this GC preparation.

Discussion

A single dose of i.m. depot TAA has far longer lasting (up to 4 weeks) effects on HPA axis activity than the similar i.v. dose of TAA-DHP (effect lasting < 72 h). This was confirmed by reduced basal cortisol levels as well as by cortisol responses to

Table 1 Pharmacokinetic parameters (means \pm s.e.m., $n = 10$) for TAA after a single-dose (0.2 mg/kg) long-acting i.v. versus i.m. depot TAA administration

Parameter	TAA-DHP (i.v.)	TAA (i.m.)
C_{max} (nmol/l)	5.8 ± 0.2	3.1 ± 0.3
t_{max} (h)	0.6 ± 0.1	1.5 ± 0.1
$t_{1/2}$ (h)	13.9 ± 1.3	$125.9 \pm 15.8^*$
AUC $_{0-\infty}$ (nmol/h/l)	17.9 ± 1.7	$134.2 \pm 8.4^*$
MRT $_{0-\infty}$ (h)	10.7 ± 1.3	$159.8 \pm 21.2^*$
CL/f (ml/min/kg)	0.5 ± 0.1	0.1 ± 0.0
V_z (l/kg)	0.6 ± 0.1	0.6 ± 0.1

C_{max} , maximum plasma concentration; t_{max} , time of C_{max} ; $t_{1/2}$, terminal elimination half-life; AUC $_{0-\infty}$, area under the plasma concentration–time curve; MRT $_{0-\infty}$, mean residence time; CL, clearance; V_z , volume of distribution. $^*P < 0.001$ vs intravenous TAA-DHP.

ACTH challenge. Indeed, the pharmacokinetic profiles of the two TAA formulations corroborate this finding.

The observed depot TAA-induced decrease in basal and ACTH-stimulated cortisol levels over a month can be explained by a reduced function of the adrenal cortex to synthesise and secrete cortisol. Upstream suppressed CRH and ACTH release by feedback through elevated cortisol is well known (Livanou *et al.* 1967, Gulliver & Eid 2005) and we predict that injections of TAA formulations may have similar feedback effects. Another explanation for the prolonged suppressive effect of the single-dosed depot TAA on HPA axis activity is possibly the systemic accumulation of the drug as the pharmacokinetic observations clearly point to this phenomenon. First, the MRT of the i.m. TAA was about 15-fold longer than that of i.v. TAA-DHP. Secondly, the half-life of TAA after i.m. administration (130 h) was longer than the i.v. (14 h) administration. TAA was detectable in plasma over 4 weeks after i.m. administration, suggesting that the less soluble depot formulation is absorbed for a longer period of time than the soluble i.v. TAA formulation, as suggested also for the intra-articular depot TAA administration (Kumar *et al.* 2004). Moreover, and thirdly, the AUC after a single i.m. depot TAA was 7.3-fold larger than after i.v. TAA-DHP administration, indicating the significant prolonged absorption rate of the i.m. depot TAA due to a 'flip-flop' pharmacokinetic scenario. This means that the ascending phase of the curve (0–2 h) represents the disposition of TAA, and the descending part the rate-limiting process of TAA release from the muscle into the circulation system (Fig. 2B). Therefore, because of this higher AUC value, one may predict that the suppressed response of the HPA axis is strongly associated with the prolonged effects of the depot formulation of TAA. Fourthly, the total body clearance was low in the depot form (Table 1), the distribution volume for either TAA formulation was not different, and these observations combined suggest a saturation of the elimination pathway at a similar single dose of TAA (0.2 mg/kg). The absolute bioavailability could not be calculated because of the depot effect of the i.m. suspension. In contrast, in one study, the corticosteroid TAA could not be detected in plasma after a single i.m. injection (0.2 mg/kg) and the data were not sufficient for pharmacokinetic analysis (French *et al.* 2000).

This systemic effect of the depot TAA on HPA axis was in part in line with an earlier study on dogs (Kempainen *et al.* 1982), where normal adrenocortical function was observed within 2 weeks. In patients, long-term i.m. administration of TAA (for 1–5 years at 3–6-week interval) caused a complete suppression of the HPA axis and adrenal function (Mikhail *et al.* 1969, 1973, Carson *et al.* 1975, Morimoto *et al.* 1980). However, these data can only be partly compared, because TAA treatment has been carried out repeatedly at a certain time interval over a year, where the cumulative systemic effect increased upon multiple dosing for markers of pharmacodynamic activity, e.g. cortisol.

On the contrary, the single-dose i.v. administration of TAA-DHP acutely reduced basal and ACTH-stimulated cortisol levels, which recovered to baseline over 24 and 48 h respectively. The latter suggests still an impeded capacity of the HPA axis to achieve full function. In line with our findings,

it was shown that high-dose i.v. methylprednisolone (1 g per patient) can immediately reduce the peak cortisol levels (Trotter & Garvey 1980, Levic *et al.* 1996). But in contrast to our data, presumably because of the large dose applied, full recovery needed here about 9 days after the last dose, but a symptom of prolonged HPA axis suppression was not seen. Our data are more consistent with the acute HPA suppressive effect of single i.v. prednisolone administration, which indeed was mild and lasted for 24 h when doses as high as 30 mg were given (Morimoto *et al.* 1980). The rapid absorption, the shorter half-life and MRT as well as the rapid elimination observed after TAA-DHP in the present study were in agreement with the i.v. TAA pharmacokinetics in human studies (Möllmann *et al.* 1985, Derendorf *et al.* 1995, Rohatagi *et al.* 1995).

With regard to topical administration of TAA and its effect on HPA axis function, there are some discrepancies. For example, a repeated local intra-articular administration of TAA (40 mg) caused in paediatric patients signs of Cushing's syndrome that appeared 4–6 weeks after TAA delivery and lasted 4–6 months after the last dose of TAA (Kumar *et al.* 2004). TAA was still detectable in the plasma and urine for 4–5 months after the last dose of the steroid, which was much longer than in our study, perhaps due to drug accumulation, but the distinct patterns of the pharmacodynamic and pharmacokinetic profiles support in part our findings obtained from the single-dose i.m. depot TAA injection. But in contrast to the intra-articular TAA adverse effects, the intraspinal TAA administration which is beneficial in patients with multiple sclerosis did not seem to affect the adrenocortical cortisol release (Neu *et al.* 1978, Hoffmann *et al.* 2006); indeed, the metabolic fate of the intraspinal TAA is presently not well known. In addition, it was shown that a repeated intranasal administration of high-dose aqueous depot TAA does not seem to be absorbed and is unlikely to cause clinically relevant HPA axis suppression in asthmatic patients (Sorkness *et al.* 1999, Skoner *et al.* 2003, Bachert *et al.* 2004).

In summary, our findings indicate that after a single equivalent dose of the i.m. depot TAA or the i.v. long-acting TAA-DHP, there was an excellent correlation between the pharmacokinetic and pharmacodynamic profiles. The HPA axis and the adrenocortical activity were more persistently impaired by the depot formulation than by the long-acting i.v. TAA-DHP, indicating a cumulative effect of TAA on the adrenal refractoriness over at least 1 month. In conclusion, the regular clinical use, for example, at weekly intervals, of depot GCs may necessarily worsen the conditions of adrenal crisis; thus, in patients who are in need of corticosteroid therapy careful re-estimation of the pharmacokinetics and pharmacodynamics of depot GC formulations should be considered.

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