Cyclosporine-inhibitable Blood–Brain Barrier Drug Transport Influences Clinical Morphine Pharmacodynamics

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ABSTRACT

Background: The blood–brain barrier is richly populated by active influx and efflux transporters influencing brain drug concentrations. Morphine, a drug with delayed clinical onset, is a substrate for the efflux transporter P-glycoprotein in vitro and in animals. This investigation tested whether morphine is a transporter substrate in humans.

Methods: Fourteen healthy volunteers received morphine (0.1 mg/kg, 1-h IV infusion) in a crossover study without (control) or with the infusion of validated P-glycoprotein inhibitor cyclosporine (5 mg/kg, 2-h infusion). Plasma and urine morphine and morphine glucuronide metabolite concentrations were measured by mass spectrometry. Morphine effects were measured by miosis and analgesia.

Results: Cyclosporine minimally altered morphine disposition, increasing the area under the plasma morphine concentration versus time curve to 100 ± 21 versus 85 ± 24 ng/ml·h ($P < 0.05$) without changing maximum plasma concentration. Cyclosporine enhanced (3.2 ± 0.9 *vs.* 2.5 ± 1.0 mm peak) and prolonged miosis, and increased the area under the miosis–time curve (18 ± 9 *vs.* 11 ± 5 mm·h), plasma effect-site transfer rate constant (k_{e0}, median 0.27 *vs.* 0.17 h^{-1}), and maximum calculated effect-site morphine concentration (11.5 ± 3.7 *vs.* 7.6 ± 2.9 ng/ml; all $P < 0.05$). Analgesia testing was confounded by cyclosporine-related pain.

Conclusions: Morphine is a transporter substrate at the human blood–brain barrier. Results suggest a role for P-glycoprotein or other efflux transporters in brain morphine access, although the magnitude of the effect is small, and unlikely to be a major determinant of morphine clinical effects. Efflux may explain some variability in clinical morphine effects.

What We Already Know about This Topic

- Considerable evidence suggests that morphine is a substrate for the blood–brain barrier efflux transporter P-glycoprotein *in vitro* and in animals, but little is known about blood–brain barrier transporters and morphine brain access in humans

What This Article Tells Us That Is New

- In 14 healthy volunteers, cyclosporine, an inhibitor of blood–brain barrier transporters, had minimal effects on circulating morphine concentrations, but increased the centrally mediated effect of morphine (miosis)
- These results suggest that transporter-mediated removal of morphine from the brain plays a role in morphine's pharmacodynamics after systemic administration

MORPHINE is a most peculiar and curiously acting opioid. Although there is well-described inter- and intraindividual variability in morphine disposition and effects, more perplexing is the unexplained disparity between plasma concentrations and clinical effect.[1] This disparity is exemplified by the long delay in onset of analgesia, miosis, and respiratory depression. Generally, delay between the time courses of plasma drug (opioid) concentration and

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clinical effect is explained by a hypothetical effect compartment with a half-life ($t_{½}k_{e0}$) characterizing first-order drug transfer from plasma to this compartment. Whereas the $t_{½}k_{e0}$ is 1 min for ultrafast-onset opioids (remifentanil, alfentanil) and 5–9 min for fast-onset opioids (sufentanil, fentanyl, methadone), it is 2–4 h for morphine.[1] Morphine effects and effect-site concentrations can increase while plasma concentrations decline.[1,2] The mechanism for delayed morphine effects is unknown.

The human blood–brain barrier has a variety of protective mechanisms, including both a structural barrier (endothelial cells with tight junctions, astrocytes, pericytes), and a functional barrier (numerous influx or efflux active transport systems). Drug efflux transporters of the adenosine triphosphate–binding cassette family are energy-dependent, membrane-bound proteins, including P-glycoprotein (P-gp, ABCB1, multidrug resistance protein 1, MDR1), breast cancer resistance protein (ABCG2), and multidrug resistance-related proteins (ABCC proteins). P-gp is expressed in brain capillary endothelial cells.[3,4]

Considerable evidence suggests that morphine is a P-gp substrate *in vitro* and in animals.[5,6] P-gp transported morphine out of bovine brain capillary endothelial cells, and P-gp inhibitors (cyclosporine, GF120918) impaired morphine efflux.[7] P-gp involvement in brain morphine disposition in animals was shown using genetic knockouts and chemical inhibitors. In mdr1a (murine MDR1 homologue) knockout mice, compared with wild-type mice, morphine brain uptake clearance was moderately (1.2-fold) increased,[8] microdialysis and *in-situ* brain perfusion confirmed significant contribution of mdr1 to morphine uptake,[9,10] morphine antinociception was significantly greater,[11,12] and the ED_{50} for morphine antinociception was reduced in half.[13] Among 16 strains of inbred mice, morphine hyperalgesia was most strongly associated with P-gp gene haplotype.[14] Wild-type animals pretreated with the P-gp inhibitor verapamil behaved like mdr1a-deficient animals.[13] Cyclosporine markedly increased morphine analgesia in wild-type but not mdr1a knockout mice.[12] In rats, GF120918 increased cerebral morphine uptake, the area under the morphine concentration–time curve in brain extracellular fluid and tissue, and increased antinociception approximately three-fold.[15,16]

In contrast to cellular and animal studies, there is less information on P-gp and morphine brain access in humans. Some P-gp inhibitors have been tested. PSC833 had no effect on morphine-related respiratory depression.[17] Quinidine did not alter IV morphine-dependent changes in pupil diameter (miosis) or respiratory depression or morphine concentration–effect relationships.[18,19] Although quinidine did increase miosis after oral morphine, this was attributed to intestinal P-gp inhibition, increased morphine absorption, and increased plasma concentrations rather than enhanced brain penetration and altered blood–brain barrier P-gp activity.[19] Quinidine, however, is a comparatively nonpotent P-gp inhibitor, and plasma quinidine concentrations may not have been sufficient to inhibit brain P-gp activity and P-gp-mediated morphine transport (if present).[19]

More recently, better clinical P-gp inhibitors have been identified. For example, cyclosporine has been shown to inhibit human blood–brain barrier P-gp activity.[20] Specifically, intracerebral concentrations of the P-gp substrate verapamil, quantified using positron emission tomography imaging, were increased 79% by cyclosporine.[21] This finding validated cyclosporine as an *in vivo* inhibitory P-gp probe in humans.

This investigation tested the hypothesis that morphine is a substrate for human blood–brain barrier drug transporters, such as P-glycoprotein, and that transport activity influences morphine plasma concentration–effect relationship (pharmacodynamics). Cyclosporine was used as a drug transport inhibitor. Morphine concentration–effect relationships were studied using pupil diameter as a primary measure of effect and analgesia as a secondary measure in a single-center, open-label, randomized crossover study in healthy volunteers.

Materials and Methods

Clinical Protocol

The protocol was a sequential open-label crossover study in healthy volunteers. It was approved by the Institutional Review Board of Washington University in St. Louis (St. Louis, Missouri), and all subjects provided written informed consent to participate. Men and women, aged 18–40 yr, in good general health with no remarkable medical conditions and a body mass index of 20–33 kg/m^2 were eligible for inclusion in this study. Exclusion criteria were a history of major medical problems, including a history of liver or kidney disease, use of prescription or nonprescription medications, herbals, or foods known to be substrates of P-glycoprotein or to affect its activity, pregnant or nursing women, and a known history of addiction to drugs or alcohol. Sixteen healthy volunteers (10 men and 6 women) were enrolled in the study. The subjects were asked to abstain from apples and citrus foods or juices for 5 days before the study day and on the study day because these may influence transporter function, and from alcohol or caffeine for 1 day before the study and on the study day, and to not ingest any food or liquid after midnight before each study day. On each study day, IV catheters were placed in one arm for blood sampling and in the contralateral arm for drug administration. Monitoring after opioid administration consisted of a standard electrocardiogram, blood pressure, and pulse oximetry. Subjects received supplemental oxygen if oxygen saturation decreased to less than 94%.

Subjects were familiarized with the test procedures, including drug administration, pupil measurements, and analgesia testing, at a prestudy visit. The first study session (control) consisted of a morphine infusion (0.1 mg/kg

over 1 h), given after baseline measurements. No placebo was infused *in lieu* of cyclosporine. Subjects were given antiemetic prophylaxis with ondansetron (4 mg IV) before morphine administration. Venous blood samples for morphine and morphine metabolite analysis were obtained just before and 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, and 10 h after the start of the morphine infusion. Plasma was separated and stored at −20°C for later analysis. Subjects were instructed to collect all their urine for 24 h after the morphine infusion. The volume collected was recorded, and an aliquot was stored at −20°C for later analysis. Subjects were given a standard breakfast 1 h after the end of the morphine administration and had free access to food and water thereafter. Subjects returned for a second (cyclosporine) study session after approximately 1 week. At this session, subjects received an IV infusion of cyclosporine (2.5 $mg \cdot kg^{-1} \cdot h^{-1}$; Bedford Laboratories, Bedford, OH) over 2 h, corresponding to the cyclosporine dose producing 79% P-gp inhibition for verapamil.[22] A 1-h morphine infusion (0.1 mg/kg) was administered during the second hour of the cyclosporine infusion. Any physicochemical incompatibilities between morphine and cyclosporine have not been described. Venous blood samples for morphine and metabolite analysis were obtained at the times described above. Venous samples were also obtained 1 (mid-infusion), 2 (end-infusion), and 4 h after the start of the cyclosporine infusion for determination of cyclosporine concentration. Additional blood samples were obtained before and the day after cyclosporine infusion for serum creatinine concentration measurement as a safety laboratory measure.

Morphine clinical effects were determined using miosis and response to thermal stimulus. Dark-adapted pupil diameters were measured in triplicate coincident with blood sampling using a hand-held infrared-based pupillometer (Neuroptics, Irvine, CA), as described previously.[23] Pupil diameter before the morphine infusion was the baseline value used to calculate pupil diameter change (miosis) at each time. Analgesia was assessed by response to thermal stimulus using both the maximum tolerated temperature and response to predetermined temperatures.[24,25] A hot water–based 3-cm^2 computer-controlled Peltier-type thermal stimulator (Pathway; Medoc Advanced Medical Systems, Ramat Yishai, Israel) was applied to the volar side of the forearm in which study drugs were infused. The thermode was set to a baseline of 32°C, and programmed to gradually increase the stimulus (0.5°C/s). Subjects pressed the button on a hand-held device when the thermode reached a maximum tolerable temperature to stop the temperature increase and initiate thermode cooling. Maximum thermode temperature was set to 52°C. If the subject tolerated this temperature without pressing the button, then 52°C was recorded as the maximum tolerable temperature. The maximum temperature testing was repeated twice, with the probe moved and cooled between stimuli, and the average of the three temperatures was recorded. Next, response to discrete heat stimuli was determined. Probe temperature was set to a baseline of 32°C and programmed to increase (0.5°C/s) to one of six predefined temperatures (41.0°, 43.0°, 44.8°, 46.5°, 48.2°, and 50.0°C) in random order, with the probe cooled and moved between stimuli. Subjective pain intensity was rated by the subject on a verbal analog scale ranging from 0 (no pain) to 100 (worst possible pain).

All 16 subjects completed the control arm of the study. Two subjects reported feelings of flushing and warmth after the beginning of the cyclosporine infusion and stopped the study session before the morphine infusion began. As a result, the final study cohort consisted of the 14 subjects completing both control and cyclosporine arms of the protocol (10 men and 4 women, weighing 75 ± 13 kg, body mass index 24 ± 3 kg/m^2). The average morphine dose was 7.5 ± 1.3 mg (range 5.8–10.2 mg) and that of cyclosporine was 420 ± 75 mg (range 326–574 mg). Samples were analyzed and data are reported for the 14 subjects completing both study arms.

Analytical Methods

Plasma and urine concentrations of morphine, morphine-3-glucuronide, and morphine-6-glucuronide were determined by high-performance liquid chromatography (HPLC)–tandem mass spectrometry, using deuterated internal standards. Subject plasma, quality control, or calibration samples (250 μl) were diluted with 750 μl of freshly prepared 2% (v/v) aqueous ammonium hydroxide containing internal standards (15 ng/ml morphine-d3, 24 ng/ml morphine-6-glucuronide-d3, and 75 ng/ml morphine-3-glucuronide-d3), processed with a 96-well solid-phase extraction plate (Strata-X, 30-mg; Phenomenex, Torrance, CA) through which 1 ml methanol and 1 ml water had been passed sequentially, rinsed with 1 ml of water, dried under vacuum, and eluted with methanol (4 × 0.25 ml). The samples were evaporated to dryness under nitrogen at 60°C and reconstituted in 100 μl of 10 mM aqueous ammonium formate with 10% methanol.

The mass spectrometer (4000 QTRAP; ABI Inc., Foster City, CA) was equipped with a Turbo Ion Spray ionization source operating in positive ionization mode and an 1100 series HPLC system (Agilent, Wilmington, DE). Chromatographic separation was performed on a T3 HPLC column (150 × 2.1 mm^2, 3.5 μm; Waters Corp., Milford, MA). The injection volume was 10 μl, and the oven temperature was 25°C. The HPLC mobile phase (0.3 ml/min) was (A) 10 mM ammonium formate in water and (B) 10 mM ammonium formate in methanol. The gradient program was 10% B for 0 min, linear gradient to 50% B between 0 and 1.0 min, linear gradient to 95% between 1.0 and 2.0 min, held at 95% B until 4 min, then reequilibrated to initial conditions (10% B) between 4.01 and 8.0 min. Under these conditions, retention times were 2.5,

3.7, and 6.0 min, respectively, for morphine-3-glucuronide, morphine-6-glucuronide, and morphine. Both Q1 and Q3 quadrupoles were optimized to unit mass resolution, and the mass spectrometer conditions were optimized for each analyte. The instrument was operated in positive ion mode with an ion spray voltage of 5,500 V. The curtain gas was set at 20, ion source gas 1 was 40, ion source gas 2 was 40, and collision gas was set at high. Multiple reaction monitoring transitions for each analyte and internal standard were *m/z* 286.2 → 152.3 and *m/z* 289.2 → 152.3 for morphine and morphine-d3, and *m/z* 462.5 → 286.2 for morphine-3- and -6-glucuronides, and *m/z* 465.5 → 289.2 for morphine-3- and -6-glucuronides-d3. Analytes were quantified using peak area ratios, and standard curves prepared using calibration standards in blank plasma. Calibration standards for morphine-3-glucuronide were 2, 4, 10, 20, 40, 200, 360, and 400 ng/ml, and morphine-6-glucuronide and morphine calibration standards were 0.5, 1, 2.5, 5, 10, 50, 90, and 100 ng/ml. Quality control samples for morphine-3-glucuronide were 10, 40, and 320 ng/ml, and morphine-6-glucuronide and morphine quality control samples were 2.5, 10, and 80 ng/ml. Interday variability of quality control samples (n = 22) for the entire study ranged from 2.9 to 8.4% (coefficient of variation) and accuracy ranged from 91 to 105%.

Morphine and morphine metabolite concentrations in urine were similarly determined. Calibration standards for morphine-3-glucuronide were 20, 100, 200, 1,000, 1,600, 2,000, 4,000, and 5,000 ng/ml, and morphine-6-glucuronide and morphine calibration standards were 5, 25, 50, 250, 400, 500, 1,000, and 5,000 ng/ml. All urine samples were evaluated in a single batch.

Cyclosporine blood concentrations were determined at the Barnes–Jewish Hospital Clinical Laboratory using HPLC–tandem mass spectrometry. Serum creatinine concentrations were quantified at the hospital laboratory using standard methods.

Noncompartmental Pharmacokinetic–Pharmacodynamic Analysis

Maximum plasma concentration (C_{max}), areas under the plasma concentration–time curve (AUC)s for morphine and morphine glucuronides during the measurement interval (0–10 h) and extrapolated to infinity, elimination clearance, and elimination half-life as well as maximum miosis, the area under the miosis–time curve (AUC), and time to maximum effect (T_{max}) were determined by noncompartmental analysis with WinNonlin (Pharsight, Palo Alto, CA). Urine morphine and metabolite clearance were determined as described previously.[19]

Compartmental Pharmacokinetic–Pharmacodynamic Modeling

Data from both the control and cyclosporine arms of a subject were modeled simultaneously. A standard two-stage sequential pharmacokinetic and pharmacodynamic analysis[26,27] was done using the SAAM II software system (SAAM Institute, Seattle, WA) implemented on a Windows-based computer. The SAAM II objective function used was the extended least-squares maximum likelihood function using data weighted with the inverse of the model-based variance of the data at the observation times. Systematic deviations of observed data from the calculated values were sought using the one-tailed one-sample runs test (results not shown), with *P* value less than 0.05, corrected for multiple applications of the runs test, as the criterion for rejection of the null hypothesis. Model misspecification was sought by visual inspection of the measured and predicted drug concentrations and effects *versus* time relationships.

Plasma morphine concentrations were first modeled with two-compartment pharmacokinetic models of morphine disposition under control and experimental conditions. All of the pharmacokinetic parameters describing morphine disposition under the two conditions were determined independently except the initial volume of distribution or central volume (V_C). The initial volume of distribution was constrained to be the same for both models, and therefore was codetermined by the data collected in both studies in a given individual. This was done because V_C is difficult to determine accurately with limited data and misestimation of V_C can lead to apparent differences in other model parameters.[28]

After finalizing the fit of the pharmacokinetic models to the morphine data, the parameters of the models were fixed and pharmacokinetic models were fit to the morphine-3-glucuronide and morphine-6-glucuronide data simultaneously for both the control study and the cyclosporine study. The formations of both morphine-3-glucuronide and morphine-6-glucuronide were modeled as a fraction of the elimination clearance of morphine in those models (*i.e.*, morphine elimination clearance was set equal to the sum of clearance by metabolism to morphine-3-glucuronide plus the clearance by metabolism to morphine-6-glucuronide plus the clearance by all other mechanisms). To model these data, the morphine dose was first converted to a molar amount, and the plasma morphine, morphine-3-glucuronide, and morphine-6-glucuronide concentrations were converted to molar concentrations. Metabolite formation was described using tanks-in-series delay elements to characterize the noninstantaneous appearance of the metabolite in the plasma. The steady-state volumes of distribution (V_{SS}) of both morphine-3-glucuronide and morphine-6-glucuronide were fixed at 0.2 × body mass (in kilograms), to approximate a total distribution volume equal to extracellular fluid space for each subject during both control and cyclosporine treatments.[29]

After finalizing the fit of the pharmacokinetic model to the morphine, morphine-3-glucuronide, and morphine-6-glucuronide data, all the pharmacokinetic parameters were fixed and the pharmacodynamic model was fit to the effect

data. The pupil diameter effect data were described as change from baseline (miosis) by a sigmoid E_{max} model:

$$E(t) = \left(\left(E_{max} \times C_E(t)^{\gamma} \right) \Big/ \left(C_E(t)^{\gamma} + EC_{50}{}^{\gamma} \right) \right) \quad (1)$$

where: $E(t)$ is the effect at time t; E_{max} is the maximum effect produced by morphine; $C_E(t)$ is the morphine concentration in the effect site at time t; C_{50} is the morphine biophase concentration at which the effect is half of maximum; and γ is the shape parameter that determines the steepness of the biophase concentration *versus* effect relationship. Because a maximum effect was not generally observed, it was assumed that the maximum observable morphine effect possible was a pupil diameter nadir of 2.5 mm, as described previously,[30] hence the maximum possible miosis (E_{max}) was estimated as the difference between the baseline pupil diameter and 2.5 mm. EC_{50} and γ were constrained to be the same for both sessions, and therefore were codetermined by the data collected in both studies in a given individual. This was done because we postulated that cyclosporine-inhibitable transport plays a role in determining morphine access to the brain, which would be reflected in differences in k_{e0} between control and cyclosporine studies in the same individuals.

The pharmacodynamic model did not include potential effects of morphine glucuronides. Morphine-3-glucuronide has no clinical effect and does not influence morphine effects.[31,32] Morphine-6-glucuronide is an active metabolite but crosses the blood–brain barrier slowly and is considered noncontributory to the short-term effects of morphine,[33–35] and the observed morphine-6-glucuronide concentrations were never more than 10% of the median EC_{50} for miosis reported previously.[30] Therefore, morphine-6-glucuronide was not included in the model, as described previously.[36]

Statistical Analysis

Normally distributed continuous data are reported as mean ± SD. Continuous data found not to be normally distributed by the Shapiro–Wilk normality test are reported as median and range. Within subject differences in normally distributed pharmacokinetic and pharmacodynamic data were assessed using the paired *t* test, whereas within subject differences in data that were not normally distributed were compared with the Wilcoxon signed-rank test (SigmaPlot; Systat Software, San Jose, CA). A two-tailed significance test was performed. The criterion for rejection of the null hypothesis was a *P* value of less than 0.05.

Results

Plasma Concentrations and Noncompartmental Pharmacokinetics

Plasma morphine and morphine glucuronides concentrations *versus* time are illustrated in figure 1, and pharmacokinetic parameters provided in table 1. Morphine concentrations peaked at the end of the infusion and were comparable in controls and cyclosporine-treated subjects. Morphine 3- and 6-glucuronide concentrations peaked 0.2 and 0.5 h, respectively, after the end of the morphine infusion. Cyclosporine had no or negligible effects on peak morphine glucuronide concentrations, but significantly delayed the time to peak concentrations (by 0.4 h for both). After peaking, plasma concentrations of morphine and both glucuronides in the cyclosporine arm were consistently higher than in controls. Areas under the curve ($AUC_{0\rightarrow\infty}$) of morphine, morphine-3-glucuronide, and morphine-6-glucuronide concentrations *versus* time in cyclosporine-treated volunteers were 17, 29, and 16% higher than in controls, respectively (table 1; $P < 0.05$). The increased morphine AUC reflects an 18% decrease in morphine elimination clearance by cyclosporine (table 1; $P < 0.05$).

Compartmental Pharmacokinetic Modeling

The best, median, and worst fits of the compartmental model to the morphine and glucuronide data are illustrated in figure 1. Pharmacokinetic parameters are presented in table 2. The initial distribution volume (V_C) of morphine did not differ between control and cyclosporine treatments because it was constrained to be the same, as indicated in Methods. Despite having the same initial distribution volume, the average peripheral volume (V_P) during cyclosporine treatment was approximately 11% less than control, and as a result, the average total volume of distribution (V_{SS}) was 10% less than control, although these differences were not statistically significant. Average intercompartmental clearance (CL_P) differed less than 10% between the two experimental conditions, but the average elimination clearance (CL_E) during the cyclosporine phase was 18% less than in controls ($P < 0.001$), similar to the noncompartmental analysis. The fraction of morphine elimination clearance represented by metabolism to morphine-3-glucuronide differed by less than 10% between control and cyclosporine sessions, but the fraction of morphine elimination clearance represented by metabolism to morphine-6-glucuronide during cyclosporine treatment was greater than 25% less than in controls ($P < 0.001$). The average morphine elimination half-life differed by less than 5% between the experimental conditions.

Pharmacokinetic parameters for morphine glucuronides are presented in table 2. The volumes of distribution of these metabolites were fixed at a total distribution volume (V_{SS}) equal to extracellular fluid space for each subject during both control and cyclosporine treatments (see Methods). Although the median fraction of morphine eliminated as morphine-3-glucuronide was approximately 40% and did not differ between treatments, the median fractions of morphine dose eliminated as morphine-6-glucuronide were 8.1% under control conditions and 7.4% during cyclosporine treatment ($P < 0.05$). Cyclosporine decreased the median elimination clearance of morphine-3-glucuronide

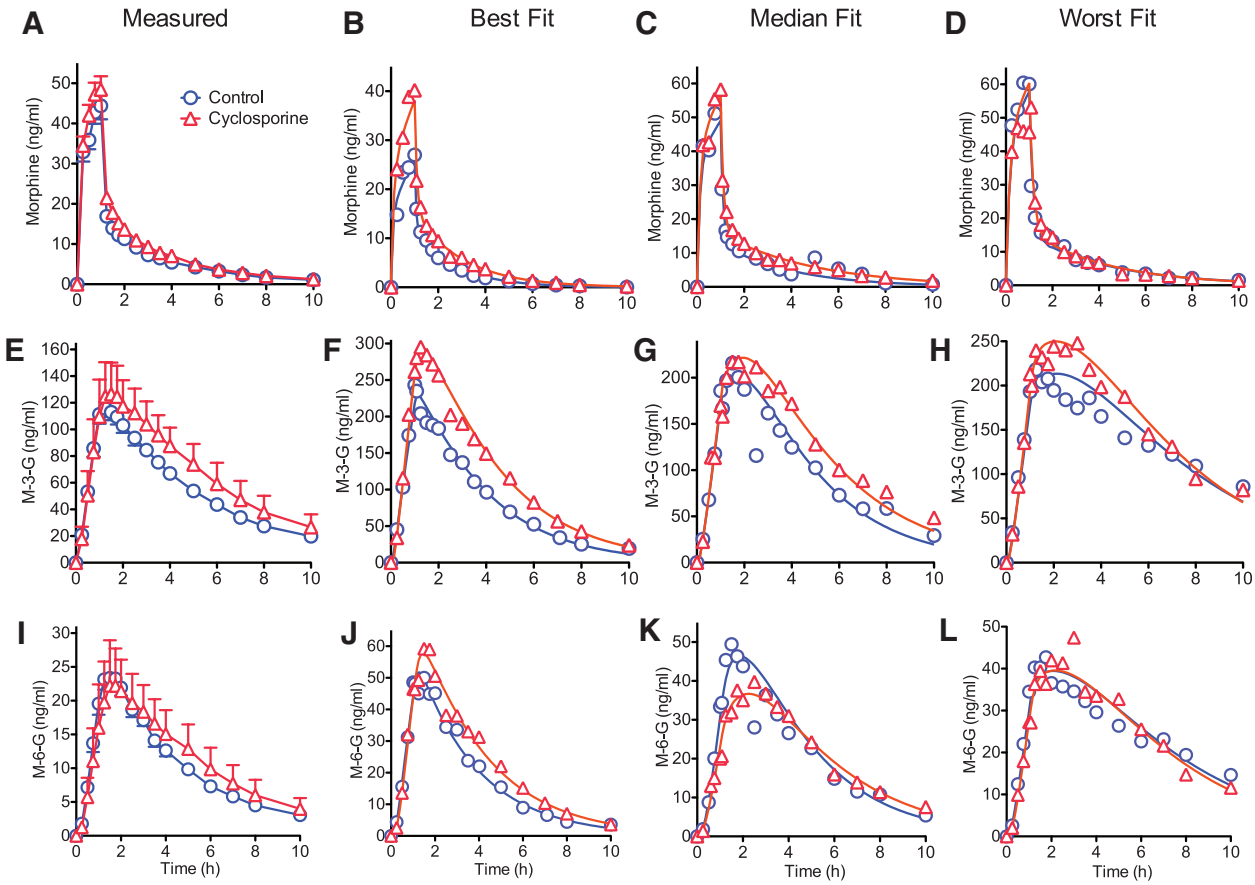

Fig. 1. Effects of cyclosporine on plasma concentrations of (*A*) morphine, (*E*) morphine-3-glucuronide (M-3-G), and (*I*) morphine-6-glucuronide (M-6-G) during and after a 1-h infusion of morphine (0.1 mg/kg) in subjects without (controls, *open circles*) or with a 2-h cyclosporine infusion (2.5 $mg \cdot kg^{-1} \cdot h^{-1}$, begun 1 h before the morphine infusion, *open triangles*). Times are relative to the start of the morphine infusion. Results are shown as the mean ± SD (N = 14). Pharmacokinetic model fits (best–median–worst, respectively) of a two-compartment pharmacokinetic model are shown for (*B–D*) morphine, (*F–H*) morphine-3-glucuronide (M-3-G), and (*J–L*) morphine-6-glucuronide (M-6-G) concentrations.

by slightly more than 10% ($P < 0.05$), and it decreased the median elimination clearance of morphine-6-glucuronide by approximately 25% ($P < 0.01$).

Pupillometry

Pupillometry results are given in figure 2, shown as measured dark-adapted pupil diameter (fig. 2A) and miosis (difference *vs.* predrug baseline; fig. 2B), and miosis parameters are provided in table 3. It is notable that maximum miosis did not occur until an average of 1.6 h after the end of the morphine infusion (T_{max}). Cyclosporine did not change this delay. Maximum miosis ($E_{max\ observed}$) was significantly greater in cyclosporine-treated subjects (3.2 ± 0.9 *vs.* 2.5 ± 1.0 mm; $P < 0.05$), and this difference in the cyclosporine-treated subjects persisted for the remainder of the observation period. The AUC for miosis during the 10-h observation period was significantly greater in the cyclosporine-treated subjects (17.7 ± 8.9 *vs.* 10.9 ± 5.1 mm·h). The relationship between miosis and morphine plasma concentration is shown in figure 2C. The delay in onset of morphine effect is apparent from the considerable and well-known hysteresis. Cyclosporine altered this hysteresis, specifically, increasing miosis on the portion of the curve representing the decline in plasma morphine concentrations.

Pharmacodynamic Modeling

Table 3 summarizes the pharmacodynamic parameters for pupillary effects for the effect model used in this study. The best, median, and worst fits of the E_{max} models to the pupillometry data are illustrated in figure 2, D–F. The median k_{e0} of the cyclosporine sessions was 59% larger than that during the control sessions ($P < 0.05$). Effect-site modeling using miosis and equation 1 were used to determine predicted biophase morphine concentrations and the influence of cyclosporine (fig. 3). The predicted maximum biophase concentration (41 ± 13 *vs.* 27 ± 11 ng/ml) and the $AUC_{0\text{-}12}$ (87 ± 20 *vs.* 64 ± 20 $ng \cdot ml^{-1} \cdot h^{-1}$) were significantly greater after cyclosporine infusion (both $P < 0.001$).

Analgesia

One testing paradigm evaluated maximally tolerated temperature on the volar side of the forearm. Maximally

Table 1. Morphine and Morphine Metabolite Noncompartmental Pharmacokinetic Parameters

		Control	Cyclosporine
Morphine	Plasma C_{max} (ng/ml)	46.4 ± 11.5	50.3 ± 11.4
	Plasma AUC_{∞} (ng/ml h)	85 ± 24	100 ± 21*†
	Plasma Cl (ml·kg^{-1}·min^{-1})	21.1 ± 6.9	17.4 ± 3.9*
	Plasma $t_{½}$ (h)	2.2 ± 0.6	2.3 ± 0.5
	Percentage dose eliminated in urine	6 ± 2	7 ± 2
	Urine clearance (ml·kg^{-1}·min^{-1})	1.2 ± 0.3	1.2 ± 0.4
Morphine-3-glucuronide	Plasma C_{max} (ng/ml)	123 ± 25	131 ± 25*
	Plasma T_{max} (h)	1.2 ± 0.2	1.6 ± 0.5*
	Plasma AUC_{∞} (ng/ml h)	667 ± 179	838 ± 165*‡
	Plasma AUC ratio (morphine glucuronide/morphine)	5.0 ± 1.2	5.3 ± 1.1
	Plasma $t_{½}$ (h)	3.3 ± 1.3	3.6 ± 1.0
	Percentage dose eliminated in urine	31 ± 4	35 ± 10
	Urine formation clearance (ml·kg^{-1}·min^{-1})	6.5 ± 1.8	6.2 ± 2.9
Morphine-6-glucuronide	Plasma C_{max} (ng/ml)	24.9 ± 5.2	23.6 ± 5.8
	Plasma T_{max} (h)	1.5 ± 0.2	1.9 ± 0.5*
	Plasma AUC_{∞} (ng/ml h)	117 ± 32	134 ± 32*§
	Plasma AUC ratio (morphine glucuronide/morphine)	0.88 ± 0.20	0.85 ± 0.20
	Plasma $t_{½}$ (h)	2.8 ± 1.2	3.2 ± 0.8
	Percentage dose eliminated in urine	7 ± 1	7 ± 2
	Urine formation clearance (ml·kg^{-1}·min^{-1})	1.5 ± 0.5	1.2 ± 0.5*

Urine data were not available for one control subject. All data are reported as mean ± SD except AUC ratios (cyclosporine/control), which are the geometric mean and 90% CI (n = 14).

*P < 0.01 *vs.* control. † AUC ratio (cyclosporine/control) geometric mean and 90% CI was 1.19 (1.11–1.27). ‡ AUC ratio (cyclosporine/control) geometric mean and 90% CI was 1.28 (1.20–1.36). § AUC ratio (cyclosporine/control) geometric mean and 90% CI was 1.15 (1.08–1.23).

AUC = area under the plasma concentration–time curve; C_{max} = peak plasma concentration; T_{max} = time to maximum concentration.

tolerated temperature before the start of the morphine infusion was comparable in control (48.8° ± 2.3°C) and cyclosporine (48.5° ± 2.6°C) sessions. Morphine increased the maximally tolerated temperature to only 49.1° ± 1.7°C after 1.5 h (0.5 h after the end of the infusion, which was not significantly different from baseline (fig. 4A). Cyclosporine actually decreased the maximally tolerated temperature to 47.5° ± 2.3°C at 1.5 h after the start of the cyclosporine infusion, and this was not significantly modulated by morphine.

A second testing paradigm used verbal analog scale scores in response to discreet temperatures, applied in a random order at each time (fig. 4, B–E). There was a clear stimulus–response relationship between temperature and pain rating (fig. 4, D and E). This response in both groups was essentially unaffected by morphine. There were no time- and morphine-dependent changes in verbal analog scale scores at any temperature (fig. 4, B and C). Pain scores were higher in cyclosporine-treated subjects, and these also were not affected by morphine. Thus, morphine (0.1 mg/kg) had negligible analgesic effects in this population, and cyclosporine clearly decreased thermal pain tolerance.

Cyclosporine

Cyclosporine concentrations were 3,411 ± 541 and 3,808 ± 604 ng/ml after 1 and 2 h of infusion (at the beginning and end of the morphine infusion), respectively, and 748 ± 183 ng/ml at 2 h after the cyclosporine infusion was stopped (4 h after starting cyclosporine infusion).

Adverse Events

Two subjects aborted the study after the first 10 min of cyclosporine infusion due to uncomfortable feelings of warmth and flushing of the face and trunk, which stopped after the infusion was aborted, and required no treatment. Other subjects also reported these effects, but did not consider them intolerable. These side effects resolved after morphine administration.

Serum creatinine concentrations were monitored as a safety assessment of renal function after cyclosporine infusion. Creatinine concentrations were 1.0 ± 0.1 and 0.9 ± 0.2 mg/dl, respectively, before and 1 day after the cyclosporine infusion. Three subjects had a postcyclosporine increase in creatinine of 0.1 mg/dl or less and five subjects had a decrease. Cyclosporine was therefore considered to have had no significant effect on renal function.

Discussion

This investigation tested the hypothesis that morphine is a substrate for drug transport at the human blood–brain barrier, and that transport activity influences morphine

Table 2. Morphine and Morphine Metabolite Compartmental Pharmacokinetic Parameters

		Control	Cyclosporine
Morphine	V_C, l*	21.5 ± 4.7	21.5 ± 4.7
	V_P, l	162 ± 28	143 ± 37
	V_{SS}, l	183 ± 28	165 ± 36
	CL_P, l	162 ± 82	149 ± 76
	CL_E, l	93.6 ± 22.0	77.1 ± 17.4#
	$t_{1/2\beta}$, h	2.2 (1.2–3.8)	2.2 (1.4–2.8)
Morphine-3-glucuronide	Fraction eliminated, %†	40.5 (27–52)	43.4 (21–73)
	$CL_{EM\text{-}3\text{-}G}$, l/h‡	39.0 ± 14.8	35.3 ± 13.4
	Delay time, h§	0.010 (0.003–0.09)	0.022 (0.003–0.13)**
	VSS, l‖	15.0 ± 2.5	15.0 ± 2.5
	Cl_E, l/h	8.4 (5.3–12.4)	7.5 (3.7–14.0)††
Morphine-6-glucuronide	Fraction eliminated, %†	8.1 (4.9–12.5)	7.4 (3.3–16.6)**
	$CL_{EM\text{-}6\text{-}G}$, l/h‡	8.3 ± 3.6	6.2 ± 3.1#
	Delay time, h	0.11 (0.04–0.34)	0.18 (0.06–0.37)
	V_{SS}, l‖	15.0 ± 2.5	15.0 ± 2.5
	Cl_E, l/h	9.6 (5.7–14.7)	7.3 (3.7–17.3)††

All data are reported as mean ± SD or median (range), n = 14.

* V_C was constrained to be the same for each subject during both control and cyclosporine treatments. † Percent of morphine dosage eliminated as the glucuronide metabolite. ‡ Elimination clearance represented by metabolism to morphine glucuronide, calculated as CL_E × percent eliminated as glucuronide. § When delay time for M-3-G could not be estimated (nine times for controls, six times for cyclosporine treatments), it was arbitrarily set at 0.01 h. ‖ V_{SS} of both morphine glucuronides were fixed at 0.2 × body mass (in kilograms), for each subject during both control and cyclosporine treatments, to approximate a total distribution volume equal to extracellular fluid space. #$P < 0.001$ *vs.* control. **$P < 0.05$ *vs.* control. ††$P < 0.01$ *vs.* control.

CL = clearance; V_C = central volume of distribution; V_p = peripheral volume of distribution; V_{SS} = steady-state volumes of distribution.

pharmacodynamics. More specifically, focus was on the efflux transporter, P-gp. Cyclosporine was used as a clinically validated inhibitory P-gp probe.[20] Previously, 2.5 mg·kg^{-1}·h^{-1} cyclosporine for 2 h (achieving a blood concentration of 2.8 ± 0.4 μM or 0.2 μM unbound) increased human brain uptake of the P-gp substrate verapamil by 79%, measured

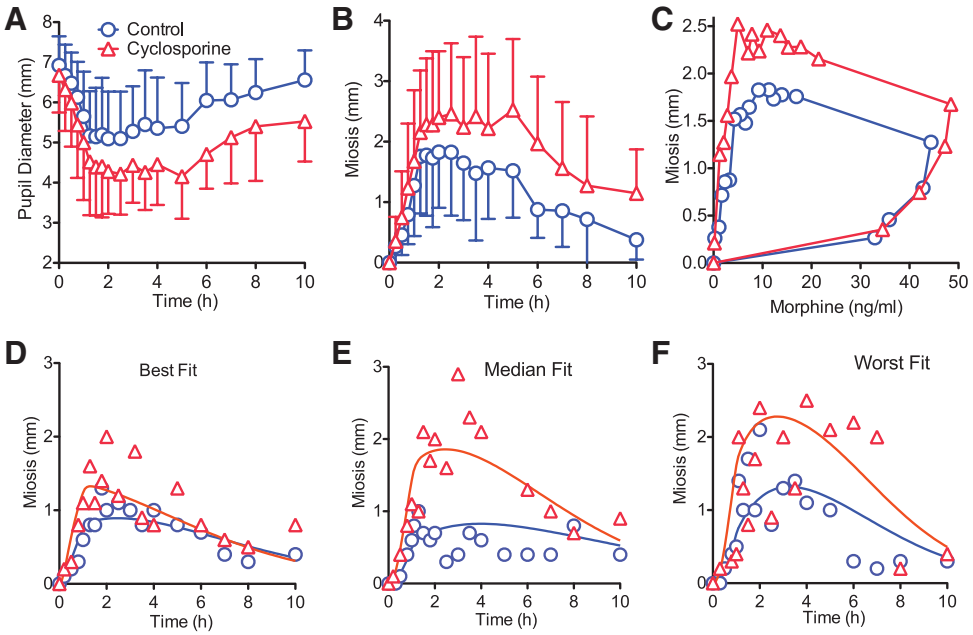

Fig. 2. Morphine effects on dark-adapted pupil diameter and influence of cyclosporine. Times are relative to the start of the morphine infusion. *Symbols* reflect controls (*circles*) and cyclosporine-treated subjects (*triangles*). Results are shown as the mean ± SD (N = 14) for (*A*) pupil diameter *versus* time, (*B*) pupil diameter change from baseline (miosis) *versus* time, and (*C*) miosis *versus* plasma morphine concentration (error bars omitted for clarity). Pharmacodynamic model fits for miosis using the E_{max} model (equation 1) are shown for the (*D*) best, (*E*) median, and (*F*) worst data fits.

Table 3. Morphine Pharmacodynamic Parameters

	Control	Cyclosporine
Noncompartmental		
$E_{max\ observed}$, mm*	2.5 ± 1.0	3.2 ± 0.9†
T_{max}, h	2.6 ± 1.8	2.7 ± 1.3
Miosis $AUC_{0\text{-}10}$, mm h	10.9 ± 5.1	17.7 ± 8.9†‡
Pharmacokinetic–pharmacodynamic§		
k_{e0}, h^{-1}	0.17 (0.07–0.57)	0.27 (0.12–0.45)#
$E_{max\ maximum\ possible}$, mm	4.4 ± 0.7	4.2 ± 0.9
EC_{50}, ng/ml (nM)	10.3 ± 5.6 (36 ± 20)	10.3 ± 5.6 (36 ± 20)
γ	2.0 ± 0.7	2.0 ± 0.7

All data are reported as mean ± SD or median (range) except AUC ratios (cyclosporine/control), which are the geometric mean and 90% CI (n = 14).

* $E_{max\ observed}$ represents the maximum observed miosis due to morphine. † $P < 0.01$ *vs.* control. ‡ AUC ratio (cyclosporine/control) geometric mean and 90% CI was 1.60 (1.37–1.87). § Determined using the E_{max} model for pupil diameter change from predrug baseline (miosis; equation 1). $E_{max\ maximum\ possible}$ represents the maximum possible miosis (difference between resting baseline diameter and the theoretical nadir of 2.5 mm). EC_{50} and γ were codetermined for both control and cyclosporine sessions in a given individual. # $P < 0.05$ *vs.* control.

AUC = area under the curve.

using positron emission tomography.[20,21] The blood EC_{50} for cyclosporine inhibition of P-gp was reported as 7 μM.[22,37] In the current investigation, using the same cyclosporine dosage, cyclosporine blood concentrations were 2.8 ± 0.4 and 3.2 ± 0.5 μM after 1 and 2 h of infusion, respectively (beginning and end of the morphine infusion), and 0.6 ± 0.2 μM at 2 h after cyclosporine was stopped. These concentrations were comparable with those previously shown to inhibit

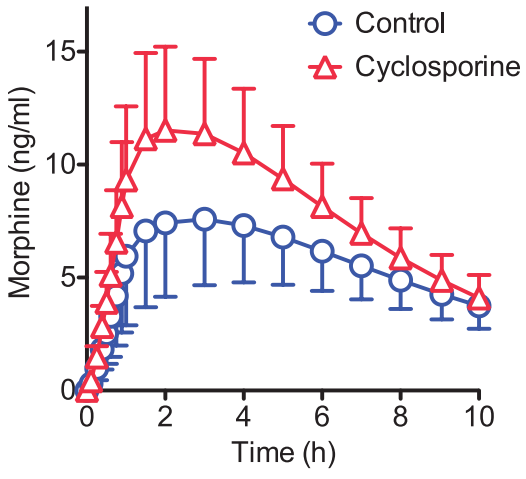

Fig. 3. Model-predicted biophase morphine concentrations during and after a 1-h infusion of morphine (0.1 mg/kg) in subjects without (controls, *open circles*) or with a 2-h cyclosporine infusion (2.5 $mg \cdot kg^{-1} \cdot h^{-1}$, begun 1 h before the morphine infusion, *open triangles*). Times are relative to the start of the morphine infusion. Results are shown as the mean ± SD (N = 14).

human brain P-gp activity by 79%, and were 40% of the EC_{50} for P-gp inhibition.[20,22,37] Thus, cyclosporine concentrations apparently sufficient to achieve effective P-gp inhibition were attained in the current investigation.

After initiating this study, it became apparent that cyclosporine also inhibits other transporters (multidrug resistance-related protein 2 and breast cancer resistance protein), although shown only *in vitro*,[38–41] and the cyclosporine IC_{50} for breast cancer resistance protein (26 μM)[40] is far greater than concentrations achieved in the current study. Nevertheless, we refer more broadly to cyclosporine-inhibitable, rather than specifically, to P-gp-dependent transport.

Morphine and morphine glucuronide pharmacokinetics in controls were similar to previous reports.[17,18,30,36] Cyclosporine slightly increased morphine plasma concentrations, largely due to an 18% decrease in morphine elimination clearance. One possible explanation is that cyclosporine inhibited morphine metabolism. A small fraction of morphine (approximately 4%) is *N*-demethylated by cytochrome P4503A (CYP3A),[42,43] and cyclosporine inhibits hepatic CYP3A activity.[44] The *in vitro* K_i for cyclosporine inhibition of hepatic microsomal CYP3A was 1.4 μM,[45] and clinically, 200 mg/day cyclosporine, which achieved a trough concentration of 119 ng/ml (0.1 μM), inhibited hepatic CYP3A activity by 24%.[44] Thus, cyclosporine concentrations in the current investigation (>3 μM peak) would be expected to inhibit greater than 90% of hepatic CYP3A activity. This might account for some, but not all, of the 17% increase in plasma morphine AUC. Cyclosporine may have also inhibited transporters mediating hepatic morphine uptake, as well as metabolism, further reducing morphine clearance.

Cyclosporine significantly increased plasma morphine glucuronide concentrations. Other P-gp inhibitors, quinidine and PSC833, also increased the AUC for morphine glucuronides.[17,18] This may simply reflect slightly higher morphine plasma concentrations, as cyclosporine had no apparent effect on morphine glucuronidation (based on the fraction of morphine eliminated as glucuronides, morphine metabolic clearance to glucuronides, glucuronide formation clearance, and plasma glucuronide/morphine AUC ratios). However cyclosporine did somewhat (10–25%) decrease glucuronide elimination clearance. Morphine glucuronides are eliminated renally.[42] Cyclosporine may inhibit one or more renal tubular efflux transporters (P-gp, breast cancer resistance protein, multidrug resistance-related protein) mediating luminal excretion, to reduce morphine glucuronides clearance. Some evidence also suggests hepatic excretion of morphine glucuronides, by multidrug resistance-related protein 2 and 3,[46] which may also be inhibitable by cyclosporine[41] In animals, absence of multidrug resistance-related protein 2 and 3 increased plasma morphine-3-glucuronide concentrations, potentially explained by reduced hepatic and renal efflux transport.[46] Together these considerations suggest a role for cyclosporine-inhibitable transporters in morphine glucuronide elimination in humans.

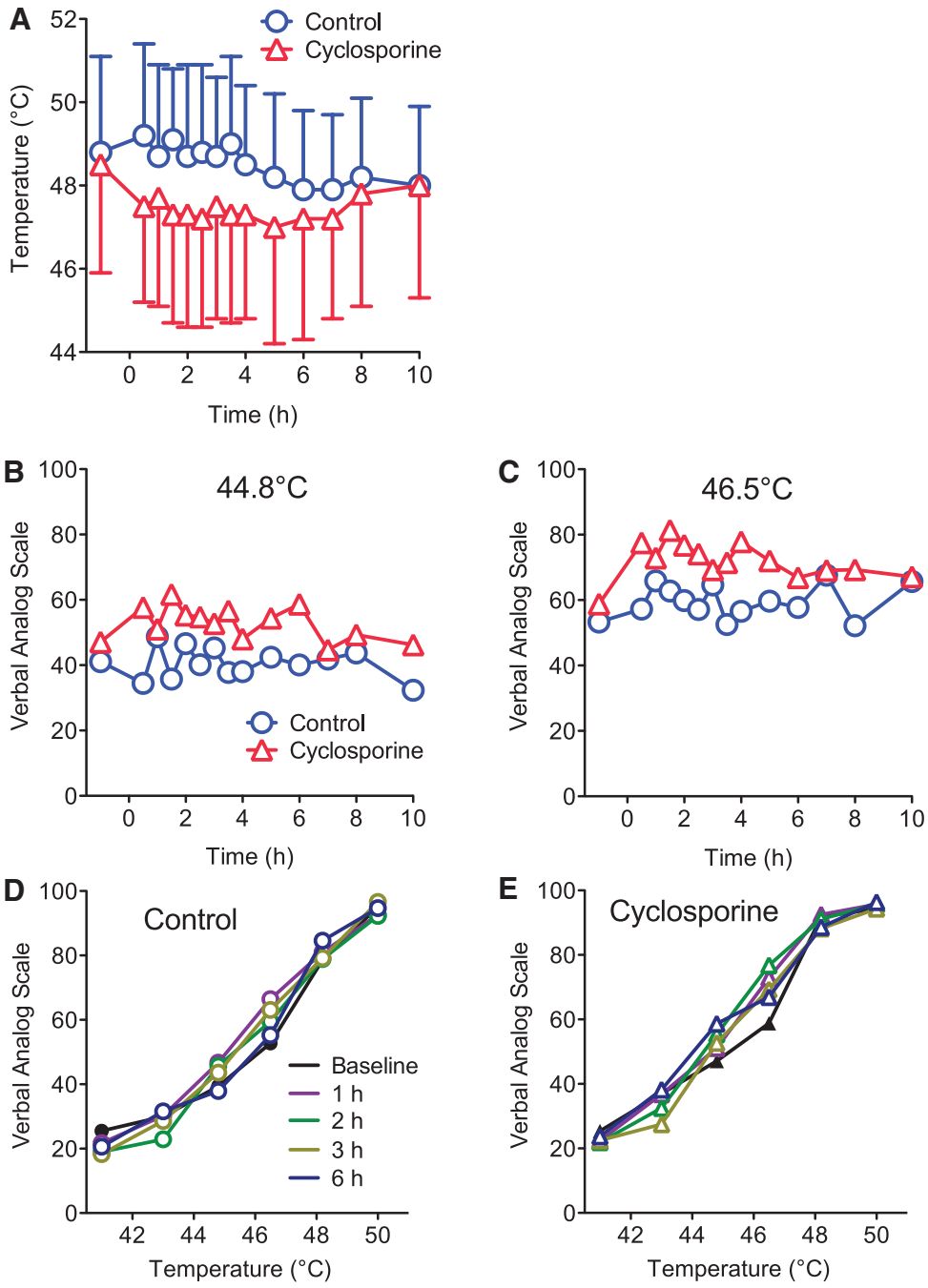

Fig. 4. Thermal pain perception before, during, and after a 1-h infusion of morphine. Times are relative to the start of the morphine infusion. The 2-h cyclosporine infusion (–1 to 1 h) was started 1 h before morphine (–1 to 0 h). Results are shown as the mean ± SD (N = 14) with some error bars omitted for clarity. (*A*) Maximally tolerated temperatures in control (*circles*) and cyclosporine (*triangles*) sessions. No time-specific maximally tolerated temperature was significantly greater than predrug baseline, in either controls or cyclosporine-treated subjects. (*B* and *C*) Verbal analog scores in response to specific thermal stimuli applied in random order at each time. Temperatures were 41.0°, 43.0°, 44.8°, 46.5°, 48.2°, and 50.0°C. (*B* and *C*) Results are shown for selected temperatures in controls (*circles*) and cyclosporine-treated subjects (*triangles*) at (*B*) 44.8°C and (*C*) 46.5°C. (*D* and *E*) Results are shown for all temperatures at selected times in (*D*) controls and (*E*) cyclosporine-treated subjects.

Morphine pharmacodynamics in controls was similar to that reported previously.[30] Miosis occurred after a substantial time delay, as observed previously.[19,36] Cyclosporine enhanced morphine-induced miosis, increasing maximum miosis and nearly doubling the miosis AUC. This increase in miosis occurred during the postinfusion phase. The 18% decrease in morphine elimination clearance by cyclosporine, resulting in a 17% increase in average morphine $AUC_{0-\infty}$, might not entirely explain the 62% increase in miosis AUC_{0-10}. However, the 59% increase in median k_{e0} produced by

cyclosporine, together with the slightly increased plasma morphine concentrations, offers a ready explanation of the increased miosis observed during the cyclosporine sessions. This combined effect is clearly apparent in the increased predicted morphine biophase concentrations after T_{max} (fig. 3). Thus cyclosporine increased morphine access to the brain. Theoretically, increased levels of intracerebral morphine could originate from enhanced uptake and/or delayed efflux. However, no uptake transporters for morphine have been identified, and cyclosporine has been shown to significantly inhibit morphine efflux *in vitro*.[12] Thus, the major conclusion of this investigation is that cyclosporine-inhibitable efflux transport at the blood–brain barrier measurably influences morphine access to the brain in humans. Moreover, P-glycoprotein may be a key element of this phenomenon. This investigation is the first to demonstrate a clinically measurable influence of efflux transport inhibition on morphine effects and pharmacodynamics.

Results of this investigation can be compared with previous studies on P-gp inhibition and morphine, in both humans and animals. Quinidine did not change morphine effects (pupil diameter, respiratory depression, and subjective self-assessments[18] or maximum miosis, AUC of miosis *versus* time, and subjective self-assessments)[19] in volunteers. Quinidine may have insufficient inhibitory potency for human P-gp. Quinidine IC_{50} was 34 μM in L-MDR1 cells expressing human P-gp, 36 μM in mouse brain,[8] and 3 μM in porcine brain capillary cells,[47] compared with 9 μM clinical plasma concentrations.[19] The P-gp inhibitor PSC833 did not significantly change morphine respiratory depression or drowsiness.[17] Therefore, differences between cyclosporine and other P-gp inhibitor effects on morphine pharmacodynamics may be attributable to differences in inhibitor concentrations relative to the K_i for transporter inhibition.

Results of this clinical investigation can be compared with previous studies of morphine and transporter inhibition in cells and animals. In general, there are marked interspecies differences in P-gp inhibitor effects *in vitro*.[48,49] Inhibition of bovine brain capillary cell P-gp-mediated transport by GF120918 or cyclosporine abolished basolateral to apical flux of morphine.[7] *In vivo*, inhibition of P-gp transport by GF120918 tripled cerebral morphine uptake in rats.[15] Mdr1 knockout mice exhibited five-fold increases in cerebral morphine concentration and analgesia.[12] Thus, effects of P-gp and transport inhibition on cerebral drug disposition appear greater in animals than humans.

Results of this investigation, showing a 60% increase in morphine effect on AUC by cyclosporine, can also be compared with studies of other P-gp substrates. Cyclosporine (10 mg/kg IV, approximately 5.6 μM in blood) in volunteers increased brain uptake of the P-gp substrate loperamide (assessed by positron emission tomography) by 110%,[37**] and when corrected for loperamide metabolism, increased 457%.[37] Loperamide respiratory depression was also increased by quinidine.[50] The most likely reason why quinidine influenced apparent brain uptake of loperamide,[50] but not morphine,[19] is that loperamide is a much better P-gp substrate, although there may also be differential sensitivity of the effect parameters (carbon dioxide response for loperamide and pupil diameter for morphine). Supporting this contention, loperamide has a higher efflux ratio than morphine (>20 *vs.* <10%) in P-gp-overexpressing cells,[47] and the transport ratio in mdr1 knockout mice *versus* control was 10.4 for loperamide and only 1.2 for morphine.[8] Thus, in humans, the quantitative consequence of transport inhibition was far less for morphine than for a much better P-gp substrate.

Although effects of transporter inhibition on morphine pharmacodynamics and clinical effects were statistically significant, the magnitude of effect was relatively small. Any clinical relevance to patients receiving cyclosporine therapeutically (where concentrations are well below 1 μM, and unlikely to influence morphine transport) is, therefore, probably negligible. More generally, given that cyclosporine concentrations were 40% of the EC_{50} for P-gp inhibition and comparable with those previously shown to inhibit human brain P-gp activity by 79%,[20] and this degree of transporter inhibition had only minor consequences for morphine brain uptake and clinical effects, it is unlikely that other brain transporter inhibitors (unless substantially more effective) would have clinically meaningful consequences for morphine effects and use.

The small clinical effects of efflux transport (P-gp) inhibition on morphine pharmacodynamics complement previous pharmacogenetic studies of P-gp and morphine. Although one investigation found greater pain relief in cancer pain patients who were homozygous for the P-gp C3435T single nucleotide polymorphism,[51] and another reported lower oral morphine requirements in C3435T homozygotes in a mixed chronic pain population,[52] neither the C3435T nor G2677T/A polymorphisms had any significant association with morphine dose requirements for postoperative or cancer pain.[53,54] These results are consistent with only a minor role for brain efflux transport in clinical morphine analgesia.

A most unexpected finding in this investigation was that cyclosporine caused cutaneous sensitization to touch and heat. This differs from the previously well-described cyclosporine pain syndrome (bilateral bone pain in the lower extremities)[55] and invalidated analgesia for measuring cyclosporine influence on morphine effects. Whether this sensitization in humans is analogous to reductions in thermal tail-flick latencies by cyclosporine in mice is unclear.[56] This appears to be the first report of acute cyclosporine sensitization in humans and was not described after previous cyclosporine use to inhibit P-gp.[20] The mechanism of sensitization is unknown. Further investigation as a potential experimental

** Passchier J, Comley R, Salinas C, Rabiner E, Gunn R, Cunningham V, Wilson A, Houle S, Gee A, Laruelle M: Blood brain barrier permeability of [11C]loperamide in humans under normal and impaired P-glycoprotein function. J Nucl Med 2008; 49:211P.

pain model[57] or source of mechanistic insights for acute sensitization and pain in humans may be appropriate.

There are potential limitations to the current investigation. Miotic effects of morphine-6-glucuronide were not incorporated into the pharmacodynamic model, but this was because morphine-6-glucuronide does not materially contribute the effects of single-dose morphine.[1] Previous studies characterized cyclosporine inhibitory potency using EC_{50} values, determined with the substrate verapamil,[20–22,37] rather than with K_i, which might affect the estimate of P-gp inhibition used in this investigation, given that a different substrate was used.

In summary, this investigation showed that cyclosporine, used as an *in vivo* inhibitor probe for blood–brain barrier P-gp and other transporters, moderately enhanced morphine-induced miosis and nearly doubled the area under the miosis–time curve. Effects were mostly explained by an increase in morphine k_{e0} and apparent effect-site morphine concentrations. This suggests a role for P-gp or other efflux transporters in brain morphine access, although the magnitude of the effect is small, and unlikely to be a major determinant of morphine clinical effects.

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References

1. Lötsch J: Pharmacokinetic-pharmacodynamic modeling of opioids. J Pain Symptom Manage 2005; 29(5 suppl):S90–103
2. Kharasch ED: Intraoperative methadone: Rediscovery, reappraisal, and reinvigoration? Anesth Analg 2011; 112:13–6
3. Cordon-Cardo C, O'Brien JP, Casals D, Rittman-Grauer L, Biedler JL, Melamed MR, Bertino JR: Multidrug-resistance gene (P-glycoprotein) is expressed by endothelial cells at blood-brain barrier sites. Proc Natl Acad Sci U S A 1989; 86:695–8
4. Bendayan R, Ronaldson PT, Gingras D, Bendayan M: *In situ* localization of P-glycoprotein (ABCB1) in human and rat brain. J Histochem Cytochem 2006; 54:1159–67
5. Tournier N, Declèves X, Saubaméa B, Scherrmann JM, Cisternino S: Opioid transport by ATP-binding cassette transporters at the blood-brain barrier: Implications for neuropsychopharmacology. Curr Pharm Des 2011; 17:2829–42
6. Mercer SL, Coop A: Opioid analgesics and P-glycoprotein efflux transporters: A potential systems-level contribution to analgesic tolerance. Curr Top Med Chem 2011; 11:1157–64
7. Letrent SP, Polli JW, Humphreys JE, Pollack GM, Brouwer KR, Brouwer KL: P-glycoprotein-mediated transport of morphine in brain capillary endothelial cells. Biochem Pharmacol 1999; 58:951–7
8. Dagenais C, Graff CL, Pollack GM: Variable modulation of opioid brain uptake by P-glycoprotein in mice. Biochem Pharmacol 2004; 67:269–76
9. Xie R, Hammarlund-Udenaes M, de Boer AG, de Lange EC: The role of P-glycoprotein in blood-brain barrier transport of morphine: Transcortical microdialysis studies in mdr1a (−/−) and mdr1a (+/+) mice. Br J Pharmacol 1999; 128:563–8
10. Cisternino S, Rousselle C, Debray M, Scherrmann JM: *In situ* transport of vinblastine and selected P-glycoprotein substrates: Implications for drug-drug interactions at the mouse blood-brain barrier. Pharm Res 2004; 21:1382–9
11. Hamabe W, Maeda T, Fukazawa Y, Kumamoto K, Shang LQ, Yamamoto A, Yamamoto C, Tokuyama S, Kishioka S: P-glycoprotein ATPase activating effect of opioid analgesics and their P-glycoprotein-dependent antinociception in mice. Pharmacol Biochem Behav 2006; 85:629–36
12. Thompson SJ, Koszdin K, Bernards CM: Opiate-induced analgesia is increased and prolonged in mice lacking P-glycoprotein. Anesthesiology 2000; 92:1392–9
13. Zong J, Pollack GM: Morphine antinociception is enhanced in mdr1a gene-deficient mice. Pharm Res 2000; 17:749–53
14. Liang DY, Liao G, Lighthall GK, Peltz G, Clark DJ: Genetic variants of the P-glycoprotein gene Abcb1b modulate opioid-induced hyperalgesia, tolerance and dependence. Pharmacogenet Genomics 2006; 16:825–35
15. Letrent SP, Pollack GM, Brouwer KR, Brouwer KL: Effects of a potent and specific P-glycoprotein inhibitor on the blood-brain barrier distribution and antinociceptive effect of morphine in the rat. Drug Metab Dispos 1999; 27:827–34
16. Letrent SP, Pollack GM, Brouwer KR, Brouwer KL: Effect of GF120918, a potent P-glycoprotein inhibitor, on morphine pharmacokinetics and pharmacodynamics in the rat. Pharm Res 1998; 15:599–5
17. Drewe J, Ball HA, Beglinger C, Peng B, Kemmler A, Schächinger H, Haefeli WE: Effect of P-glycoprotein modulation on the clinical pharmacokinetics and adverse effects of morphine. Br J Clin Pharmacol 2000; 50:237–46
18. Skarke C, Jarrar M, Erb K, Schmidt H, Geisslinger G, Lötsch J: Respiratory and miotic effects of morphine in healthy volunteers when P-glycoprotein is blocked by quinidine. Clin Pharmacol Ther 2003; 74:303–11
19. Kharasch ED, Hoffer C, Whittington D, Sheffels P: Role of P-glycoprotein in the intestinal absorption and clinical effects of morphine. Clin Pharmacol Ther 2003; 74:543–54
20. Sasongko L, Link JM, Muzi M, Mankoff DA, Yang X, Collier AC, Shoner SC, Unadkat JD: Imaging P-glycoprotein transport activity at the human blood-brain barrier with positron emission tomography. Clin Pharmacol Ther 2005; 77:503–14
21. Hsiao P, Bui T, Ho RJ, Unadkat JD: *In vitro*-to-*in vivo* prediction of P-glycoprotein-based drug interactions at the human and rodent blood-brain barrier. Drug Metab Dispos 2008; 36:481–4
22. Hsiao P, Sasongko L, Link JM, Mankoff DA, Muzi M, Collier AC, Unadkat JD: Verapamil P-glycoprotein transport across the rat blood-brain barrier: Cyclosporine, a concentration inhibition analysis, and comparison with human data. J Pharmacol Exp Ther 2006; 317:704–10
23. Kharasch ED, Walker A, Hoffer C, Sheffels P: Intravenous and oral alfentanil as *in vivo* probes for hepatic and first-pass cytochrome P450 3A activity: Noninvasive assessment by use of pupillary miosis. Clin Pharmacol Ther 2004; 76:452–66
24. Cortinez LI, Hsu YW, Sum-Ping ST, Young C, Keifer JC, Macleod D, Robertson KM, Wright DR, Moretti EW, Somma J: Dexmedetomidine pharmacodynamics: Part II: Crossover comparison of the analgesic effect of dexmedetomidine and remifentanil in healthy volunteers. Anesthesiology 2004; 101:1077–83

25. Olofsen E, Romberg R, Bijl H, Mooren R, Engbers F, Kest B, Dahan A: Alfentanil and placebo analgesia: No sex differences detected in models of experimental pain. ANESTHESIOLOGY 2005; 103:130–9
26. Sheiner LB, Beal SL: Evaluation of methods for estimating population pharmacokinetic parameters. II. Biexponential model and experimental pharmacokinetic data. J Pharmacokinet Biopharm 1981; 9:635–51
27. Zhang L, Beal SL, Sheiner LB: Simultaneous *vs.* sequential analysis for population PK/PD data I: Best-case performance. J Pharmacokinet Pharmacodyn 2003; 30:387–4
28. Avram MJ, Krejcie TC: Using front-end kinetics to optimize target-controlled drug infusions. ANESTHESIOLOGY 2003; 99:1078–86
29. van Dorp EL, Morariu A, Dahan A: Morphine-6-glucuronide: Potency and safety compared with morphine. Expert Opin Pharmacother 2008; 9:1955–61
30. Lötsch J, Skarke C, Schmidt H, Grösch S, Geisslinger G: The transfer half-life of morphine-6-glucuronide from plasma to effect site assessed by pupil size measurement in healthy volunteers. ANESTHESIOLOGY 2001; 95:1329–38
31. Penson RT, Joel SP, Clark S, Gloyne A, Slevin ML: Limited phase I study of morphine-3-glucuronide. J Pharm Sci 2001; 90:1810–6
32. Penson RT, Joel SP, Bakhshi K, Clark SJ, Langford RM, Slevin ML: Randomized placebo-controlled trial of the activity of the morphine glucuronides. Clin Pharmacol Ther 2000; 68:667–76
33. Lötsch J, Kobal G, Stockmann A, Brune K, Geisslinger G: Lack of analgesic activity of morphine-6-glucuronide after short-term intravenous administration in healthy volunteers. ANESTHESIOLOGY 1997; 87:1348–58
34. Lötsch J, Kobal G, Geisslinger G: No contribution of morphine-6-glucuronide to clinical morphine effects after short-term administration. Clin Neuropharmacol 1998; 21:351–4
35. Lötsch J, Weiss M, Ahne G, Kobal G, Geisslinger G: Pharmacokinetic modeling of M6G formation after oral administration of morphine in healthy volunteers. ANESTHESIOLOGY 1999; 90:1026–38
36. Dershwitz M, Walsh JL, Morishige RJ, Connors PM, Rubsamen RM, Shafer SL, Rosow CE: Pharmacokinetics and pharmacodynamics of inhaled *versus* intravenous morphine in healthy volunteers. ANESTHESIOLOGY 2000; 93:619–28
37. Hsiao P, Unadkat JD: P-glycoprotein-based loperamide-cyclosporine drug interaction at the rat blood-brain barrier: Prediction from *in vitro* studies and extrapolation to humans. Mol Pharm 2012; 9:629–33
38. Kobayashi M, Saitoh H, Kobayashi M, Tadano K, Takahashi Y, Hirano T: Cyclosporin A, but not tacrolimus, inhibits the biliary excretion of mycophenolic acid glucuronide possibly mediated by multidrug resistance-associated protein 2 in rats. J Pharmacol Exp Ther 2004; 309:1029–35
39. Qadir M, O'Loughlin KL, Fricke SM, Williamson NA, Greco WR, Minderman H, Baer MR: Cyclosporin A is a broad-spectrum multidrug resistance modulator. Clin Cancer Res 2005; 11:2320–6
40. Xia CQ, Liu N, Miwa GT, Gan LS: Interactions of cyclosporin a with breast cancer resistance protein. Drug Metab Dispos 2007; 35:576–82
41. Westley IS, Brogan LR, Morris RG, Evans AM, Sallustio BC: Role of Mrp2 in the hepatic disposition of mycophenolic acid and its glucuronide metabolites: Effect of cyclosporine. Drug Metab Dispos 2006; 34:261–6
42. Yeh SY: Urinary excretion of morphine and its metabolites in morphine-dependent subjects. J Pharmacol Exp Ther 1975; 192:201–10
43. Projean D, Morin PE, Tu TM, Ducharme J: Identification of CYP3A4 and CYP2C8 as the major cytochrome P450 s responsible for morphine N-demethylation in human liver microsomes. Xenobiotica 2003; 33:841–54
44. de Jonge H, de Loor H, Verbeke K, Vanrenterghem Y, Kuypers DR: *In vivo* CYP3A activity is significantly lower in cyclosporine-treated as compared with tacrolimus-treated renal allograft recipients. Clin Pharmacol Ther 2011; 90:414–22
45. Niwa T, Yamamoto S, Saito M, Shiraga T, Takagi A: Effect of cyclosporine and tacrolimus on cytochrome p450 activities in human liver microsomes. Yakugaku Zasshi 2007; 127:209–16
46. van de Wetering K, Zelcer N, Kuil A, Feddema W, Hillebrand M, Vlaming ML, Schinkel AH, Beijnen JH, Borst P: Multidrug resistance proteins 2 and 3 provide alternative routes for hepatic excretion of morphine-glucuronides. Mol Pharmacol 2007; 72:387–94
47. Wandel C, Kim R, Wood M, Wood A: Interaction of morphine, fentanyl, sufentanil, alfentanil, and loperamide with the efflux drug transporter P-glycoprotein. ANESTHESIOLOGY 2002; 96:913–20
48. Tang-Wai DF, Kajiji S, DiCapua F, de Graaf D, Roninson IB, Gros P: Human (MDR1) and mouse (mdr1, mdr3) P-glycoproteins can be distinguished by their respective drug resistance profiles and sensitivity to modulators. Biochemistry 1995; 34:32–9
49. Suzuyama N, Katoh M, Takeuchi T, Yoshitomi S, Higuchi T, Asashi S, Yokoi T: Species differences of inhibitory effects on P-glycoprotein-mediated drug transport. J Pharm Sci 2007; 96:1609–18
50. Sadeque AJ, Wandel C, He H, Shah S, Wood AJ: Increased drug delivery to the brain by P-glycoprotein inhibition. Clin Pharmacol Ther 2000; 68:231–7
51. Campa D, Gioia A, Tomei A, Poli P, Barale R: Association of ABCB1/MDR1 and OPRM1 gene polymorphisms with morphine pain relief. Clin Pharmacol Ther 2008; 83:559–66
52. Lötsch J, von Hentig N, Freynhagen R, Griessinger N, Zimmermann M, Doehring A, Rohrbacher M, Sittl R, Geisslinger G: Cross-sectional analysis of the influence of currently known pharmacogenetic modulators on opioid therapy in outpatient pain centers. Pharmacogenet Genomics 2009; 19:429–36
53. Coulbault L, Beaussier M, Verstuyft C, Weickmans H, Dubert L, Trégouet D, Descot C, Parc Y, Lienhart A, Jaillon P, Becquemont L: Environmental and genetic factors associated with morphine response in the postoperative period. Clin Pharmacol Ther 2006; 79:316–24
54. Klepstad P, Fladvad T, Skorpen F, Bjordal K, Caraceni A, Dale O, Davies A, Kloke M, Lundström S, Maltoni M, Radbruch L, Sabatowski R, Sigurdardottir V, Strasser F, Fayers PM, Kaasa S; European Palliative Care Research Collaborative (EPCRC); European Association for Palliative Care Research Network: Influence from genetic variability on opioid use for cancer pain: A European genetic association study of 2294 cancer pain patients. Pain 2011; 152:1139–45
55. Prommer E: Calcineurin-inhibitor pain syndrome. Clin J Pain 2012; 28:556–9
56. Sato Y, Onaka T, Kobayashi E, Seo N: The differential effect of cyclosporine on hypnotic response and pain reaction in mice. Anesth Analg 2007; 105:1489–93
57. Olesen AE, Andresen T, Staahl C, Drewes AM: Human experimental pain models for assessing the therapeutic efficacy of analgesic drugs. Pharmacol Rev 2012; 64:722–79