Renal Function in a Rat Model of Analgesic Nephropathy: Effect of Chloroquine

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ABSTRACT
The antimalaria drug chloroquine is often taken against a background of analgesic nephropathy caused by nonsteroidal anti-inflammatory drugs such as paracetamol (acetaminophen). Chloroquine has marked effects on the normal kidney and stimulates an increase in plasma vasopressin via nitric oxide. The aim of this study was to determine the renal action of chloroquine in a model of analgesic nephropathy. Sprague-Dawley rats (n = 6–8/group) were treated with paracetamol (500 mg kg⁻¹ day⁻¹) for 30 days in drinking water to induce analgesic nephropathy; control rats received normal tap water. Under intravenous anesthesia (100 mg kg⁻¹) rats were infused with 2.5% dextrose for 3 h to equilibrate and after a control hour they received either vehicle, chloroquine (0.04 mg h⁻¹), N⁶-nitro-L-arginine methyl ester (l-NAME, nitric-oxide synthase inhibitor, 60 μg kg⁻¹ h⁻¹) or combined chloroquine and l-NAME over the next hour. Plasma was collected from a parallel group of animals for vasopressin radioimmunoassay. Long-term paracetamol treatment resulted in a decrease in glomerular filtration rate (p < 0.05), sodium excretion (p < 0.001), and urine osmolality (p < 0.001), but no change in urine flow rate compared with untreated animals. Chloroquine administration in paracetamol treated rats induced a significant reduction (p < 0.05) in urine flow rate and a significant increase in plasma vasopressin (p < 0.001). These effects were blocked by coadministration of l-NAME and thus seem to be mediated by a pathway involving nitric oxide. However, these responses contrast with the chloroquine-induced diuresis previously observed in untreated rats, possibly reflecting paracetamol inhibition of renal prostaglandin synthesis and consequent moderation of vasopressin’s action.

Paracetamol (known as acetaminophen in the United States) is one of the most commonly used nonsteroidal anti-inflammatory drugs (NSAIDs) (Hardman et al., 2001). It is a rapid, reversible, noncompetitive inhibitor of cyclooxygenase activity and thus products of the arachidonic acid cascade. In addition to its analgesic properties, paracetamol also has direct actions on the kidney. Colletti et al. (1999) demonstrated that administration of paracetamol to dogs fed either a normal or low sodium diet (renal prostaglandin-dependent state) resulted in a decrease in renal blood flow, glomerular filtration rate (GFR), and prostaglandin E₂ (PGE₂) excretion. In the isolated perfused rat kidney, administration of paracetamol resulted in a decrease in GFR and PGE₂ (Trumper et al., 1998). Similarly, in normal human volunteers treated with paracetamol for 3 days, a reduction in urinary PGE₂ and sodium excretion was observed. In addition, paracetamol induced a delay in the onset of diuresis after an acute water load (Prescott et al., 1989).

Paracetamol also exerts acute and chronic nephrotoxic effects. Acute ingestion of large doses (10–15 g) is characterized by necrosis and damage to the proximal tubule. However, it is recognized from both clinical and experimental studies that much lower doses (500–1000 mg) can produce renal damage, especially in patients with hepatic disease or those taking enzyme inducer drugs (carbamazepine and phenytoin) or in the malnourished (Blantz, 1996). Chronic ingestion of paracetamol results in analgesic nephropathy. This is defined as habitual ingestion of an analgesic, which after an insidious onset, leads to renal papillary necrosis and chronic interstitial nephritis with progressive renal failure (Henrich, 1998). Epidemiological studies show that long-term regular consumption of paracetamol increases the relative risk of chronic renal disease to 3.2 (Sandler et al., 1989), whereas the odds ratio for end stage renal disease was 2.1 for the heaviest annual intake of paracetamol and 2.4 for cumulative lifetime intake of more than 5000 tablets containing paracetamol (Perneger et al., 1994). Burrell et al. (1990) found that paracetamol (380 mg kg⁻¹ b.wt. day⁻¹) and aspirin (230 mg kg⁻¹ b.wt. day⁻¹) given for 21 weeks to female Fischer-344 rats resulted in papillary necrosis and impaired ability to concentrate urine, although a lower dose of parac-
etamol alone (120 mg kg\(^{-1}\) b.wt. day\(^{-1}\)) did not induce significant renal damage. Paracetamol and other NSAIDs are often prescribed as antipyretic agents to reduce fever associated with malaria. Hence, people living in regions where malaria is prevalent are likely to ingest paracetamol on a regular basis over a long period. Indeed, there is evidence of widespread chronic paracetamol ingestion in many developing countries (Chada, 1998; Eddleston, 2000). The consequences of clinical and subclinical analgesic nephropathy may be exacerbated in these populations by antimalarial drugs, which can also affect renal function.

We have shown (Ahmed et al., 2003) that one such drug, chloroquine, causes a marked increase in GFR, urine flow rate, and urinary sodium excretion in the rat. These effects were reversed by L-NAME, suggesting that nitric oxide mediates, at least in part, these renal effects of chloroquine. Because chronic paracetamol ingestion impairs urinary concentration ability in the rat (Burrell et al., 1990), chloroquine administration against a background of analgesic nephropathy might be expected to cause a pronounced diuresis which may be of clinical significance in patients suffering from dehydration or electrolyte imbalance. Accordingly, the aims of this study were to develop a subclinical model of paracetamol-induced analgesic nephropathy in the rat without overt renal dysfunction or gross kidney morphological changes and then to determine the effects of chloroquine on renal function in this model. The rationale for choosing a subclinical level was to model the more common level of renal impairment seen with long-term NSAID use in both Western and tropical countries. This would allow the subsequent study of the confounding effects of chloroquine against a background of a moderately damaged kidney in which capacity to adapt fluid and ion balance may be impaired. Because we have previously shown that chloroquine’s actions on renal function and vasopressin secretion are mediated, at least in part, by nitric oxide (Ahmed et al., 2003), we have also studied the effect of nitric oxide inhibition by L-NAME on the responses to chloroquine administration in paracetamol-treated rats.

**Materials and Methods**

All experiments were performed under the authority of a UK Home Office Project License and received local ethical approval.

**Induction of Analgesic Nephropathy.** Male Sprague-Dawley rats (345–400 g) were purchased from Charles River UK Limited (Margate, Kent, UK) and were held in the School of Biological Sciences where they had free access to food (Beekay Rat and Mouse Standard Diet, Bantin and Kingman Ltd., Hull, UK) and water, with a 12-h light and 12-h dark cycle before experimentation. Paracetamol (4-acetaminophenol; Sigma-Aldrich, Poole, Dorset, UK) was dissolved in drinking water (500 mg kg\(^{-1}\) b.wt. day\(^{-1}\)), and the pH was adjusted to 6.7 by addition of NaOH (Burrell et al., 1991b). Rats received paracetamol for 30 days before renal function studies were performed specifically to collect blood for vasopressin radioimmunoassay. Blood samples (0.6 ml) were collected from the carotid artery and a similar volume of dextrose solution was replaced. Plasma was separated by centrifugation and stored at 4°C before analysis. Parallel groups of animals (n = 6/group) equivalent to those used for renal studies were prepared specifically to collect blood for vasopressin radioimmunoassay. Blood samples were taken from animals undergoing servo-controlled fluid replacement midway through the drug (chloroquine, L-NAME, or in combination) treatment period. Animals were decapitated and trunk blood (5–7 ml) was collected into tubes held on ice containing 100 μl of 0.125 mol EDTA (Sigma-Aldrich) and 250 μl of ammonium heparin (BDH, Poole, Dorset, UK). Plasma was separated after centrifugation for 10 min and stored at −20°C before measurement of plasma vasopressin concentration by radioimmunoassay as described previously (Warne et al., 1994).
Analysis. Urine and plasma sodium concentrations were measured by flame photometry (Corning 480; Corning Ltd., Halstead, Essex, UK) and osmolality by freezing point depression (Roehling osmometer; LH Roehling, Berlin, Germany). [3H]Insulin was determined using a 1900CA Tri-Carb liquid scintillation analyzer (Canberra Industries, Meriden, CT) beta-counter.

Statistical Analysis. Data are presented as the mean ± S.E.M. Statistical analysis was performed using SPSS for Windows (standard version 10.1.0; SPSS UK Ltd., Woking, Surrey, UK). Comparisons between paracetamol-treated and untreated rats were by Student’s unpaired t test. In paracetamol-treated rats receiving chloroquine ± L-NAME comparisons over time were by repeated measures ANOVA and comparisons within groups between control, treatment and recovery periods were by ANOVA followed by Student-Newman-Keuls (SNK) test. Significance was ascribed at the 5% level.

Results

Baseline Renal Function in Paracetamol-Treated Rats

Data presented in Table 1 represent renal excretion rates over the control hour immediately after the equilibration period and before subsequent drug administration (chloroquine or L-NAME). Paracetamol treatment resulted in a significant reduction in GFR (p < 0.05) compared with untreated animals. Urine flow rate tended to be higher in paracetamol-treated rats, which was associated with a significant reduction in urine osmolality (p < 0.001) and sodium excretion rate (p < 0.001). Despite these marked effects on renal concentrating ability, paracetamol treatment at the dose used in this study had no significant effect on the gross histological morphology of the kidney compared with untreated rats (data not shown). Mean arterial blood pressure did not differ between paracetamol-treated rats and untreated rats (untreated, n = 8, 121 ± 3 mm Hg; paracetamol-treated, n = 24, 126 ± 4 mm Hg). Mean arterial blood pressure remained stable in all four paracetamol-treated groups over the course of the whole experiment and did not differ between groups (paracetamol 126 ± 4, paracetamol/chloroquine 126 ± 2, paracetamol/L-NAME 127 ± 4, paracetamol/chloroquine/L-NAME 123 ± 7 mm Hg).

Chloroquine Administration in Paracetamol-Treated Rats

Urine Flow Rate. The urine flow rates of paracetamol-treated rats infused with chloroquine ± L-NAME are shown in Fig. 1. Repeated measures ANOVA revealed significant differences both over time (F4,80 = 25.6, p < 0.001) and between drug treatments (F3,24 = 3.1, p < 0.05). Urine flow was stable and similar in all groups of animals immediately before chloroquine or L-NAME infusion. During the hour of chloroquine infusion in paracetamol-treated rats there was a significant reduction in urine flow rate (post hoc SNK test vehicle versus chloroquine, p < 0.05), followed by a significant diuresis in the recovery hour (p < 0.05) (Fig. 1A). Coinfusion of L-NAME with chloroquine completely abolished the antidiuresis seen with chloroquine infusion alone (Fig. 1B). The urine flow rate in paracetamol/chloroquine/L-NAME rats started to increase immediately upon the infusion of chloroquine and L-NAME (p < 0.05) and continued to rise even after chloroquine administration ceased (p < 0.05; Fig. 1B). The same pattern was also observed in the paracetamol-treated rats receiving L-NAME alone.

There were no differences in GFR (Fig. 2; ANOVA 1st h, F3,24 = 0.86, p = 0.48) and urine osmolality (Fig. 4; F3,24 = 0.52, p = 0.67) during the initial postequilibration control period between the four groups, although Na+ excretion was somewhat lower in the group due to receive chloroquine and L-NAME (Fig. 3; F3,24 = 4.9, p = 0.01). Thus, for ease of comparison, in subsequent graphs the mean values are presented for the control, postequilibration hour (1st h), the hour of drug treatment (2nd h) and the recovery hour (3rd h).

Glomerular Filtration Rate. The GFR, as determined from the clearance of inulin, is shown in Fig. 2. During the hour of chloroquine administration, no significant differences were seen between the groups. In the subsequent hour, rats that had been infused with chloroquine showed a significant increase in GFR (ANOVA 3rd h, F3,24 = 6.86, p = 0.002; post hoc SNK test vehicle versus chloroquine, p < 0.01) compared with vehicle infused paracetamol-treated rats. L-NAME alone induced a significant increase in GFR during the 3rd h.

Table 1

Table 1 presents the renal excretion rates, standardized to 100 g b.wt. over 1 h. Statistical analysis was by Student’s unpaired t test.

### TABLE 1

<table>
<thead>
<tr>
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<th>Untreated (n = 8)</th>
<th>Paracetamol-Treated (n = 24)</th>
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<tbody>
<tr>
<td>Glomerular filtration rate (ml min⁻¹)</td>
<td>0.74 ± 0.07</td>
<td>0.50 ± 0.06*</td>
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<tr>
<td>Urine flow rate (ml h⁻¹)</td>
<td>0.23 ± 0.03</td>
<td>0.51 ± 0.17</td>
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<tr>
<td>Sodium excretion rate (µmol h⁻¹)</td>
<td>9.9 ± 1.2</td>
<td>4.1 ± 0.4***</td>
</tr>
<tr>
<td>Urine osmolality (mOsm kg⁻¹ H₂O)</td>
<td>543 ± 46</td>
<td>174 ± 10***</td>
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* p < 0.05, *** p < 0.001 untreated vs. paracetamol-treated rats.

![Graphs showing changes in urine flow rate over time](https://via.placeholder.com/150)
(p < 0.001). However, when infusion of chloroquine was combined with L-NAME there was no effect on sodium excretion. Sodium excretion continued to increase after cessation of chloroquine infusion in the chloroquine only group (ANOVA 3rd h, F_3,23 = 86.6, p < 0.001; post hoc SNK test vehicle versus chloroquine, p < 0.001). Animals receiving L-NAME alone also showed elevated sodium excretion in the 2nd and 3rd h (vehicle versus L-NAME, p < 0.001). Sodium excretion remained at baseline levels over the 3rd h in rats receiving the combined chloroquine and L-NAME infusion, which was significantly lower than that in rats receiving chloroquine alone (p < 0.001).

**Urine Osmolality.** Urine osmolality is shown in Fig. 4 as a measure of urine concentrating ability. During chloroquine infusion there was a significant increase in urine osmolality (ANOVA 2nd h, F_3,23 = 7.39, p < 0.01; post hoc SNK test vehicle versus chloroquine, p < 0.01) compared with vehicle-infused, paracetamol-treated rats, which is consistent with the associated fall in urine flow rate (Fig. 1A). The combination of chloroquine and L-NAME returned urine osmolality to baseline values. Over the following hour, after the cessation of chloroquine infusion, osmolality remained elevated in the chloroquine-infused group (ANOVA 3rd h, F_3,23 = 3.79, p < 0.05; post hoc SNK test vehicle versus chloroquine, p < 0.05), but this was lower than during the preceding hour. L-NAME, with or without chloroquine, had no effect on urine osmolality by comparison with vehicle-infused, paracetamol-treated rats.

**Plasma Vasopressin.** The sensitivity of the vasopressin assay was 1.2 fmol ml⁻¹; coefficients of variation were determined using a pool of plasma with a measured vasopressin concentration of 4 pg ml⁻¹, interassay variation was 8.2 ± 0.8% (n = 5), and intra-assay variation was 11.4 ± 1.5% (n = 10).

Samples for the measurement of plasma vasopressin were taken from a parallel group of animals midway through the
hour of chloroquine infusion (Fig. 5). This corresponded with the maximum reduction in urine flow rate (Fig. 1A) and increase in urine osmolality (Fig. 4) when chloroquine was infused in paracetamol-treated rats. Chloroquine infusion was associated with a significant increase in plasma vasopressin (ANOVA; $F_{3,23} = 20.95$, $p < 0.001$; post hoc SNK test vehicle versus chloroquine, $p < 0.001$) compared with vehicle-infused, paracetamol-treated rats. The administration of L-NAME with or without chloroquine induced a significant reduction in plasma vasopressin compared with vehicle-infused paracetamol-treated rats ($p < 0.01$) and rats receiving chloroquine ($p < 0.001$).

Figure 6 depicts a model that could explain the differing actions of chloroquine on water reabsorption by collecting duct cells in (A) untreated and (B) paracetamol-treated rats.

**Discussion**

Establishing a Model of Analgesic Nephropathy. The paracetamol treatment regime used in this study induced changes in the renal excretion of water and ions, suggesting that a subclinical level of analgesic nephropathy had been achieved. The administration of paracetamol for 30 days had no effect on gross kidney morphology, nor on the growth or general health of the animals. The dose of 500 mg kg$^{-1}$ day$^{-1}$ is considerably higher than the normal adult dose of 14.3 mg kg$^{-1}$ (Hardman et al., 2001), which is likely to shift this balance in favor of vasoconstriction and a reduction in GFR. GFR is regulated, in part, by angiotensin II, which stimulates both afferent and efferent arteriolar constriction and by PGE$_2$ and prostaglandin I$_2$, which, in conjunction with nitric oxide, stimulate vasodilatation (Schlondorff, 1986). Paracetamol inhibits prostaglandin synthesis (Hardman et al., 2001), which is likely to shift this balance in favor of vasoconstriction and a reduction in GFR. Prostaglandin I$_2$ and PGE$_2$ are also found within the mesangium (Klahr et al., 1988) where they act to relax mesangial cells, thereby increasing GFR. Inhibition of these prostaglandins may lead to contraction of the mesangium and a reduction in GFR (Navar, 1998). Tubuloglomerular feedback is also dependent on prostaglandins and may be impaired during inhibition of prostaglandin synthesis, leading to an inappropriate GFR (Zenser et al., 1981).

An inhibitory effect on prostaglandin synthesis may also account for the effects of paracetamol on sodium excretion. Paracetamol inhibits PGE$_2$ synthesis, which is the primary prostaglandin affecting medullary hemodynamics and sodium and water handling (Dunn, 1998). Prostaglandins increase renal blood flow, reducing proximal reabsorption of sodium (Ichikawa and Brenner, 1980), while directly inhibiting sodium reabsorption by the thick ascending limb (Kaojarern et al., 1983). Thus, inhibition of PGE$_2$ synthesis is likely to cause a reduction in sodium excretion, as was observed in paracetamol-treated rats.

Paracetamol treatment also resulted in a reduction in urine osmolality, which may reflect an additional failure in the ability of the paracetamol-treated rat kidney to concentrate urine. Humans with analgesic nephropathy have been reported to have lower urine osmolality than control subjects, even after administration of desamino-d-arginine vasopressin (Wambach et al., 1989). This did not seem to be mediated by a reduction in AVP-induced cAMP, because urinary excretion rates were comparable between the two groups. During the early stages of analgesic treatment in rats (Burrell et al., 1990), the changes in urinary concentrating ability were reversible, but after prolonged analgesic treatment, maximum urinary concentrating ability failed to recover, suggesting that papillary damage was permanent (Burrell et al., 1991b).
Fig. 6. Proposed model of chloroquine’s actions on water reabsorption by collecting duct cells in untreated (A) and paracetamol-treated (B) rats. NO, nitric oxide; V₁, type 1 vasopressin receptor; V₂, type 2 vasopressin receptor; PG, prostaglandins; AQP, aquaporin 2.
**Chloroquine Administration in Paracetamol-Treated Rats.** Administration of chloroquine in rats previously treated for 30 days with paracetamol led to a reduction in urine flow rate of over 50% by comparison with vehicle-infused rats. The urine flow rate decreased steadily and reached its lowest level 30 min after the onset of chloroquine infusion, before rising again to a maximum after 80 min. This contrasts with our previous observation in nonparacetamol-treated rats in which chloroquine had no antidiuretic effect. Indeed, chloroquine induced a significant diuresis despite concurrently stimulating an increase in plasma vasopressin (Ahmed et al., 2003).

One explanation for this lies in the observation that NSAID treatment enhances the sensitivity of the kidney to the action of vasopressin. Stimulation of arginine vasopressin V₁ receptors leads to increased prostaglandin synthesis, which inhibits cAMP production in the collecting duct and diminishes the antidiuretic effect mediated by the V₂ receptor. Paracetamol, by inhibiting prostaglandin synthesis, may potentiate the antidiuretic effect of arginine vasopressin in the collecting duct (Fejes-Toth et al., 1977; Walker et al., 1994). Against this background, the chloroquine-induced increase in vasopressin may be sufficient to overcome the diuretic influences of chloroquine and thus result in antidiuresis. The subsequent reversal in urine flow rate upon cessation of chloroquine infusion may reflect a fall in plasma vasopressin concentration, however, we did not measure plasma vasopressin at this time.

Nitric oxide seems to play an important role in mediating these actions of chloroquine, although its effects seem to be moderated by the actions of paracetamol. In our previous study (Ahmed et al., 2003), chloroquine induced a diuresis and an increase in plasma vasopressin concentration in naive rats, which could be prevented by coinfusion of l-NAME. In the current study, l-NAME blocked the antidiuretic action of chloroquine and inhibited the increase in plasma vasopressin concentration in paracetamol-treated rats. Figure 6 depicts a model that could explain the apparently contradictory actions of chloroquine on urine flow rate and the role of nitric oxide in mediating its actions.

In the nonparacetamol-treated rat (Fig. 6A), chloroquine stimulates an increase in vasopressin secretion via a nitric oxide-dependent pathway, leading to an increase in cAMP generation in collecting duct cells via V₂ receptors. However, nitric oxide also increases cGMP generation and prostaglandin synthesis, both of which inhibit CAMP generation. If this inhibitory influence on cAMP is large enough, water permeability will not increase and a diuresis will ensue. In the paracetamol-treated rat (Fig. 6B) the inhibitory effect of prostaglandins is lost as paracetamol inhibits prostaglandin synthesis, thus sufficient CAMP is generated to cause an increase in aquaporin 2 insertion into the apical membrane and water permeability increases, resulting in an antidiuresis. l-NAME prevents these actions of chloroquine by lowering the plasma vasopressin concentration and blocking nitric oxide-mediated cGMP generation and prostaglandin synthesis.

Chloroquine administration in paracetamol-treated rats also induced a profound increase in sodium excretion by comparison with vehicle-infused controls. This was reversible by l-NAME in the 3rd h postequilibration, but not in the 2nd h during chloroquine administration. Nitric oxide has been shown to inhibit proximal tubular fluid reabsorption by inhibiting sodium reabsorption (Eitle et al., 1998), suggesting that this may be one site of action for chloroquine. However, this does not explain why the chloroquine-induced natriuresis in the 3rd h was not blocked by l-NAME nor why l-NAME administration alone in paracetamol-treated rats also resulted in a natriuresis.

A paracetamol-induced shift in the arachidonic acid cascade toward the cytochrome P450 monooxygenase pathway could offer an explanation. The P450 pathway leads to the production of hydroxyeicosatetraenoic acids (HETEs) and epoxyeicosatrienoic acids (Murray and Brater, 1993). 20-HETE is the primary product of P450 and has been reported to be an essential component of tubuloglomerular feedback and renal autoregulation, modulating sodium transport in the medullary thick ascending limb and proximal tubules (Oyekan et al., 1999). Increased production of 20-HETE by the proximal tubules and medullary thick ascending limb reduced sodium reabsorption in these regions (Nowicki et al., 1997). Nitric oxide inhibits renal P450 activity, thus l-NAME administration could lead to an increase in the synthesis of 20-HETE, which in turn results in an increase in sodium excretion (McGiff and Quilley, 1999). Clearly, further work is required to establish the complex relationship between prostaglandins and nitric oxide in rats treated with paracetamol.

In summary, we have developed a subclinical model of analgesic nephropathy based on the administration of a high dose of paracetamol over a short period. This approach does not lead to gross changes in renal morphology, but clearly results in perturbations in renal function. Using this model, we have also shown that long-term paracetamol ingestion alters the renal response to chloroquine compared with naive rats in our previous study (Ahmed et al., 2003). Most notably, the chloroquine-induced increase in vasopressin was associated with an antidiuresis in paracetamol-treated rats compared with a diuresis in nontreated rats, despite a similar increase in plasma vasopressin concentration. These effects were reversed by l-NAME, suggesting a role for nitric oxide. The reason for these differing effects may lie in the inhibitory effect of paracetamol on renal prostaglandin synthesis and their role in moderating AVP-induced CAMP generation.

**References**


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