Theophylline Toxicokinetics in Premature Newborns

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**Background:** While cytochrome P4501A2 is the primary pathway for theophylline (aminophylline ethylenediamine) metabolism in adults, it is developmentally immature in the newborn.

**Objective:** To report the developmental differences in theophylline toxicokinetics of neonates.

**Design:** Case series. Three premature neonates received inadvertent intravenous overdoses of theophylline for apnea of prematurity while in newborn intensive care. Maximum serum concentrations ranged from 55 to 123 mg/L. Theophylline-derived caffeine levels plateaued at 8.4 to 13 mg/L and did not decline during the sampling period. All newborns experienced sinus tachycardia and agitation. Sequential theophylline and caffeine serum levels were obtained periodically for 62 to 100 hours. In contrast to older children and adults, in whom theophylline disposition follows zero-order kinetics at high concentrations, a monoexponential function best described theophylline elimination in the premature newborn, with half-lives ranging from 24.7 to 36.5 hours and estimated clearance from 0.02 to 0.05 L/kg per hour. These values are consistent with those previously reported in neonates. All patients were treated with supportive care without invasive procedures. No seizures or apparent sequelae occurred.

**Conclusion:** Developmental differences in the balance between nonrenal (ie, metabolic) and renal elimination pathways produce the unique toxicokinetics of theophylline in the neonate.

METHODS

Each newborn was monitored clinically for signs and symptoms of theophylline intoxication, including hyperthermia, dehydration, seizures, agitation, tachycardia, blood pressure changes, emesis, and diuresis. Serum chemistry was repeatedly monitored to assess electrolyte and glucose balance. One newborn (case 3) received propranolol for control of sinus tachycardia and phenobarbital for seizure prophylaxis. No invasive techniques, such as gastrointestinal decontamination or extracorporeal methods, were used to accelerate theophylline elimination in any of the cases.

Theophylline and caffeine serum concentrations were measured at least every 24 hours by high-performance liquid chromatography until theophylline levels were less than 10 mg/L. Visual inspection of a semilog plot of progressive postoverdose serum theophylline concentrations demonstrated an apparent linear pattern of decline in each patient. Accordingly, the apparent terminal elimination rate constant (ke), the extrapolated serum concentration at time zero (C0), and the area under the concentration-time curve (AUC) for each patient were estimated from a nonlinear least squares fit of the progressive theophylline concentrations. Best statistical fit of the data (Akaike criterion17) was achieved using a simple 1-compartment open model (PkAnalyst software; MicroMath Scientific Software, Salt Lake City, Utah). Total body clearance (CI) was calculated from

\[ CI = V_d \times ke, \]

where \( V_d \), is the average population volume of distribution (0.7 L/kg) for theophylline at steady state. The administered overdose was estimated from

\[ D = V_d \times (C_0 - C_{ss}), \]

where \( C_{ss} \) was the predicted average steady state serum concentration modeled from the patient-specific estimates of theophylline pharmacokinetic parameters and the prescribed dose prior to the overdose. A corrected dose was calculated to account for steady-state theophylline concentrations since the patients had received theophylline for at least 3 days prior to the overdose.

CASE REPORTS

CASE 1

A 670-g male newborn was delivered by vaginal breech extraction at an estimated gestational age of 24 weeks. Apgar scores were 2 and 4 at 1 and 5 minutes, respectively. His hospital course was complicated by respiratory distress syndrome, pulmonary interstitial emphysema, intraventricular hemorrhage, necrotizing enterocolitis, and bronchopulmonary dysplasia. By age 8 weeks, the infant weighed 880 g and was being gradually transitioned from receiving intermittent mandatory ventilation to continuous positive airway pressure. Intravenous aminophylline ethylenediamine (79% theophylline base) was administered at a prescribed dose of 1.7 mg (2 mg/kg) every 12 hours to facilitate discontinuation of mechanical ventilation and reduce recurrent central apnea.

On the 59th hospital day (32 weeks postconceptional age), the patient suddenly developed sinus tachycardia (>200 beats per minute), restlessness, and agitation associated with a serum theophylline concentration of 55.2 mg/L. Urine output increased from 2.1 to 4.3 mL/kg per hour without significant changes in fluid administration, accompanied by a reduction in serum potassium from 4.0 to 3.0 mEq/L. There were no significant changes in ventilatory requirements, arterial blood gases, or blood pressure, and no evidence of seizure activity was observed.

Following discontinuation of theophylline and treatment with supportive care, the patient had an uneventful recovery. His clinical symptoms dissipated during a 12- to 48-hour period, although serum theophylline concentrations did not fall below 10 mg/L for more than 60 hours. He was discharged from the hospital at 159 days of age with no sequelae attributable to the theophylline overdose.

CASE 2

A 1220-g male newborn was delivered by emergency cesarean delivery for abruptio placenta at an estimated gestational age of 28 weeks. Apgar scores were 1 and 2 at 1 and 5 minutes, respectively. His hospital course included severe respiratory distress syndrome and persistent patent ductus arteriosus. By age 3 weeks, the patient weighed 1060 g and continued to require supplemental oxygen by hood. Intravenous aminophylline ethylenediamine (79% theophylline base), 2.7 mg (2.5 mg/kg), every 12 hours was prescribed for recurrent apneic episodes.

On the 28th hospital day (32 weeks postconceptional age), the patient suddenly developed sinus tachycardia to 220 beats per minute. The theophylline serum concentration at that time was 66.5 mg/L. Urine output increased from 2.1 to 3.2 mL/kg per hour and was associated with a reduction in serum potassium from 4.0 to 2.8 mEq/L. Serum glucose increased from 69 mg/dL prior to the previous aminophylline dose to 195 mg/dL at 6 hours and 179 mg/dL at 11 hours postoverdose with no significant increases in fluid or dextrose infusion rates. Arterial blood gases, blood pressure, respiratory rate, and oxygen requirement remained unchanged. No seizure activity was observed. Abdominal distention and bilious emesis were noted within an hour of the apparent aminophylline overdose. Plain abdominal films revealed multiple loops of dilated bowel but no evidence of pneumatosis intestinalis, obstruction, or free intraperitoneal air. The emesis and distention responded to open nasogastric drainage and temporary discontinuation of oral feedings.

The patient had an uneventful recovery following discontinuation of treatment with aminophylline and the pro-
vision of supportive care. Symptoms of toxic overdose disappeared during a period of 24 to 36 hours although serum theophylline concentrations remained at greater than 10 mg/L for 96 hours. At the time of transfer to an intermediate-care nursery at 5 weeks of age, no sequelae attributable to theophylline intoxication were identified.

**CASE 3**

This 1801-g male newborn was delivered by spontaneous vaginal delivery at an estimated gestational age of 31 weeks. The pregnancy was complicated by twin pregnancy, premature rupture of membranes, and preterm labor. Apgar scores were 6 and 8 at 1 and 5 minutes, respectively. The patient initially had apnea and bradycardia that were treated with intravenously administered amphotericin ethylenediamine (79% theophylline base) at the prescribed dose of 2 mg/kg every 12 hours. At 10 days of age, the newborn developed heme-positive stools and a positive rectal swab, consistent with presumed necrotizing enterocolitis. Symptoms of toxicity appeared shortly after the theophylline overdose in each patient, presented in Table 1. All patients exhibited sinus tachycardia, agitation, glucose and electrolyte abnormalities, and significant diuresis. One patient developed bilious emesis; the other 2 underwent gastric suction for suspected necrotizing enterocolitis. Symptoms of toxicity appeared shortly after the theophylline overdose in each patient but resolved well before theophylline concentrations returned to levels less than 20 mg/L. Sinus tachycardia was controlled in case 3 with short-term propranolol therapy. No patient developed seizures and all recovered without apparent permanent sequelae consequent to theophylline overdose.

Serum theophylline levels of 55.2 mg/L (case 1), 66.5 mg/L (case 2), and 123 mg/L (case 3), were measured in the initial blood samples obtained shortly after the onset of clinical symptoms. Monoexponential curve fits of progressive serum theophylline concentrations in each case provided support for elimination via first-order kinetics. Coefficients of determination for the curve fits were 0.997, 0.998, and 0.998 for cases 1, 2, and 3, respectively. Values for the pharmacokinetic parameters for each patient, presented in Table 2, were similar to those previously reported in premature newborns receiving therapeutic doses of theophylline.13,18

Although caffeine had not been administered to the patients, caffeine was identified in their serum samples at concentrations in the desired therapeutic range for the treatment of apnea and bradycardia of prematurity.19 Caffeine concentrations increased during the first 24 hours of intoxication before seeming to plateau in 2 of the pa-

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**Table 1. Demographics and Clinical Signs and Symptoms**

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gestational age, wk</td>
<td>25</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td>Birth weight, kg</td>
<td>0.67</td>
<td>1.22</td>
<td>1.8</td>
</tr>
<tr>
<td>Age when dose received, d</td>
<td>59</td>
<td>27</td>
<td>16</td>
</tr>
<tr>
<td>Tachycardia</td>
<td>Present</td>
<td>Present</td>
<td>Present</td>
</tr>
<tr>
<td>Peak HR, bpm</td>
<td>224</td>
<td>220</td>
<td>194</td>
</tr>
<tr>
<td>Duration of HR &gt;180 bpm, h</td>
<td>2</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>Agitation</td>
<td>Present</td>
<td>Present</td>
<td>Present</td>
</tr>
<tr>
<td>Emesis</td>
<td>None</td>
<td>Bilious</td>
<td>None</td>
</tr>
<tr>
<td>Glucose, mg/dL</td>
<td>41</td>
<td>195</td>
<td>162</td>
</tr>
<tr>
<td>(hypoglycemic)</td>
<td></td>
<td>(hyperglycemic)</td>
<td></td>
</tr>
<tr>
<td>Δ Urine output from baseline, mL/kg per hour</td>
<td>−0.9</td>
<td>−1.9</td>
<td>−1.5</td>
</tr>
<tr>
<td>Δ K+ from baseline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concurrent medications</td>
<td>Ampicillin sodium</td>
<td>Ampicillin</td>
<td>Gentamicin sulfate</td>
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<tr>
<td></td>
<td>Gentamicin</td>
<td>Gentamicin</td>
<td>Vancomycin hydrochloride</td>
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<td>Vancomycin</td>
<td>Calcium gluconate</td>
</tr>
<tr>
<td></td>
<td>Calcium gluconate</td>
<td>Calcium gluconate</td>
<td>Phytanodionone</td>
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</table>

*HR indicates heart rate; bpm, beats per minute; and K+, potassium.

**Table 2. Pharmacokinetic Results**

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated theophylline dose received, mg</td>
<td>33.4</td>
<td>46.3</td>
<td>178</td>
</tr>
<tr>
<td>Dose in mg/kg</td>
<td>38.0</td>
<td>43.7</td>
<td>96.8</td>
</tr>
<tr>
<td>Peak theophylline level, mg/L</td>
<td>55.2</td>
<td>66.5</td>
<td>123</td>
</tr>
<tr>
<td>Mean caffeine level, mg/L</td>
<td>8.4</td>
<td>11.5</td>
<td>13</td>
</tr>
<tr>
<td>Half-life, h</td>
<td>25.1</td>
<td>36.5</td>
<td>24.7</td>
</tr>
<tr>
<td>Assumed volume of distribution, L/kg</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Clearance, L/hr per kilogram</td>
<td>0.02</td>
<td>0.01</td>
<td>0.06</td>
</tr>
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</table>
tients (Figure 1A and B) at levels ranging from 8 to 13 mg/L, suggesting attainment of a steady state.

COMMENT

The elimination of most drugs following therapeutic or nontoxic doses seems to proceed by a first-order process (i.e., the rate of drug elimination is proportional to the amount of drug in the body). However, at high concentrations, drug elimination mechanisms (e.g., routes of clearance or metabolism) may become saturated, resulting in concentration-dependent elimination; thus, the apparent decline of plasma drug concentration can be described by either the Michaelis-Menton equation (i.e., mixed order) or zero-order kinetics.

In older children and adults, theophylline elimination usually exhibits saturation kinetics at concentrations greater than 20 mg/L.20,21 Zero-order elimination kinetics have been reported in older children with toxic concentrations of theophylline.21 In contrast, theophylline elimination in our patients, with serum concentrations 5 to 12 times greater than the recommended therapeutic serum levels, seemed to be best described by a first-order process. Wells and Ferlauto22 previously described a premature newborn who had received an intravenous theophylline overdose from an improperly prepared parenteral nutrition solution resulting in a theophylline level of 330 mg/L—the highest theophylline level in a neonate documented in the literature. Although the authors did not describe the elimination kinetics in this case, independent modeling of the data revealed an apparent first-order elimination process. The persistence of first-order theophylline kinetics in premature newborns with overdose seems to be a consistent phenomenon in cases reported to date.13-16 We propose that this is because of immaturity of the rate-limiting metabolic pathway for theophylline.

Cytochrome P4501A2 (CYP1A2) is responsible for demethylation of theophylline to 1-methylxanthine and 3-methylxanthine3,4 (Figure 2). This pathway accounts for more than 80% of theophylline elimination at therapeutic doses. It also is partly responsible for the conversion to 1,3-dimethyluric acid, whereas CYP2E1 and CYP3A4 are responsible for C8 oxidation.23 In the neonate, these cytochrome P450 isoforms are not fully expressed and, as a consequence, their activity (i.e., ability to biotransform a substrate) is markedly reduced.3-6,24-26

Cytochrome P4501A2 is not fully expressed until approximately 5 to 6 months of age.5,18,24 It is a high-affinity, low-capacity enzyme responsible for theophylline demethylation, and is saturable at supratherapeutic concentrations.9 In the absence of CYP1A2 activity, theophylline elimination is primarily dependent on renal elimination, which does not seem to be saturable. Accordingly, theophylline overdose in the neonate would...
be expected to easily saturate the available CYP1A2, leaving renal excretion of the unchanged drug as the predominant pathway for drug clearance.

In contrast to CYP1A2, methyltransferase pathways are well developed in the newborn as reflected by the detection of caffeine (the 7N-methylated product of theophylline) in the serum of all 3 patients. Saturation of the theophylline 7N-methylation pathway would explain the relatively low apparent steady-state caffeine levels observed in the patients in this study despite very high concentrations of theophylline. The apparent plateauing of caffeine serum levels in the 2 patients in whom caffeine concentrations were repeatedly measured (Figure 1A and B) most likely represents a steady state between the ongoing formation from theophylline and the slow elimination of caffeine by renal clearance, previously documented by reports of long half-lives for caffeine in the neonate.

It is speculated that this “therapeutic misadventure” occurred from dilutional errors, which are not uncommon in the administration of medication to newborns. The 3 newborns reported herein displayed clinical symptoms typically associated with methylxanthine toxicity. Tachycardia and hyperirritability are the most commonly reported symptoms while abdominal distention, emesis, diuresis, and hyperglycemia occur more sporadically. Hyperglycemia, hypoglycemia, diuresis, and reductions in serum potassium concentrations were transient and resolved within 24 hours of intoxication. Pharmacokinetic-based estimation revealed that the newborns actually received 10 to 25 times the prescribed dose. The acute theophylline overdoses were successfully treated with supportive care without the use of invasive procedures or methods to enhance drug clearance.

Limitations to this study exist. First, urine was not obtained from the 3 patients. Documentation of theophylline and its metabolites in the urine would have been particularly helpful in confirming the absence of CYP2A1 metabolites and excretion of unmetabolized theophylline. However, there is substantial support in the literature for our explanation of persistent first-order elimination at high concentrations in the newborns. Furthermore, this limitation does not detract from using the experience described in our study in the future treatment of neonatal theophylline intoxication. Second, lower serum theophylline concentrations were obtained for the third patient compared with the other 2. Although having more data points would optimize the pharmacokinetic calculations, the coefficient of determination (0.998) for this patient is such that a reasonable reliability of the estimate can be made.

In contrast to older children and adults, theophylline elimination remains a first-order process during acute intoxication in premature newborns, even at plasma concentrations 10 times those achieved with therapeutic doses. This can be attributed to normal developmental differences in the activity of rate-limiting pathways required for theophylline clearance.

The cases reported here document that large acute overdoses of theophylline in newborns, while inducing symptoms and signs of toxicity along with pharmacokinetic calculations, the coefficient of determination (0.998) for this patient is such that a reasonable reliability of the estimate can be made.

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REFERENCES