Pharmacokinetic behavior of doxycycline after intramuscular injection in sheep

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Objective—To determine the pharmacokinetics of a commercial formulation of doxycycline hyclate after IM administration of a single dose to sheep.

Animals—11 healthy domestic sheep.

Procedures—For each sheep, doxycycline was administered as a single dose of 20 mg/kg, IM. Blood samples were obtained prior to and for 84 hours after doxycycline administration. Plasma concentrations of doxycycline were determined via high-performance liquid chromatography with UV detection. Pharmacokinetic data were analyzed with noncompartmental methods.

Results—Mean ± SD values for pharmacokinetic parameters included maximum plasma concentration (2.792 ± 0.791 µg/mL), time to reach maximum plasma concentration (0.856 ± 0.472 hours), mean residence time (91.1 ± 40.78 hours), elimination half-life (77.88 ± 28.45 hours), and area under the curve (65.67 ± 9.877 µg•h/mL).

Conclusions and Clinical Relevance—Results indicated that doxycycline had prolonged absorption and elimination in sheep after IM administration. A daily dose of 20 mg/kg would be sufficient to reach effective plasma concentrations against *Chlamydia* spp (minimum inhibitory concentration, 0.008 to 0.031 µg/mL) and *Staphylococcus aureus* (minimum inhibitory concentration, 0.12 µg/mL). Doxycycline administered IM could be an option for therapeutic use in sheep, although further studies are needed. (Am J Vet Res 2012;73:714–718)
of the dose was excreted in urine and the remainder in feces (excreted mostly by the gastrointestinal mucosa). Modification of the dose was not required in humans with impaired renal function.26,27

Although pharmacological characteristics of doxycycline may make it a treatment option for several infections in sheep, data on its pharmacokinetics in that species are scarce; only 2 studies on the pharmacokinetics of doxycycline after IV24,28 and PO24 administration have been conducted in sheep. To our knowledge, information about pharmacokinetics following IM administration in sheep is lacking, even though the IM route is commonly used for drug administration in livestock. The purposes of the study reported here were to investigate the pharmacokinetics of doxycycline in sheep after IM administration of a commercial formulation of doxycycline hyclate at a dose of 20 mg/kg and to evaluate whether the IM route is appropriate for administering doxycycline to sheep. In the study reported here, IM administration of doxycycline in sheep was considered extralabel use because, in Spain, the commercial formulation used is only approved for pigs and poultry via PO administration.

Materials and Methods

Animals—Eleven 4-year-old Spanish Churra ewes that ranged in weight from 33 to 37 kg were used in the study. The sheep were determined to be healthy on the basis of results of physical examination. They were dewormed with netobimin® (10 mg/kg, PO) 45 days before the study. Sheep were housed in a ventilated building and allowed to acclimatize to their environment for 2 weeks before the study was initiated. They were provided an antimicrobial-free diet of alfalfa hay and pelleted feed, with unlimited access to water and a salt lick. The Institutional Animal Care and Use Committee of the University of León approved all procedures.

Doxycycline administration and sample collection—A commercial formulation of doxycycline® was administered to animals at a single dose of 20 mg/kg, IM. The dose was selected because it had already been used in sheep for IV24,28 and PO23 administration. Also, the same dose of doxycycline had been administered IM to goats.16,17

Doxycycline was administered into the deep gluteal muscle of the right hind limb. Serial blood samples (5 mL) were collected into EDTA (K3) evacuated tubes from a jugular vein immediately before (time 0) and at 10, 20, 30, 45, 60, 75, 90, 120, 150, and 180 minutes and 4, 6, 10, 16, 24, 32, 40, 48, 60, 72, and 84 hours after doxycycline administration. Samples were immediately centrifuged at 500 × g, and plasma was harvested and stored at −80°C until analyzed. For each sheep, a physical examination was performed daily by the same veterinarian (LJCR), and sheep were visually evaluated at the time of doxycycline administration and when each blood sample was obtained until 3 days after the end of the study.

Analytic procedures—Plasma concentrations of doxycycline were determined via high-performance liquid chromatography with UV detection in accordance with a method previously described,29 with minor modifications. Solid-phase extraction was performed with solid-phase extraction cartridges. Cartridges were conditioned with 1 mL of methanol and 1 mL of water. Then, 1 mL of plasma was added, and the cartridges were washed 3 times with 1 mL of 5% methanol in water. Doxycycline was eluted with 1 mL of a 50:50 (vol/vol) mixture of acetonitrile and water.

The high-performance liquid chromatography system was equipped with an autosampler and UV detector at a wavelength of 350 nm. A reversed-phase column (4 µm; 3.9 × 150 mm) was used. The mobile phase consisted of a 50:50 (vol/vol) mixture of acetonitrile and water (pH, 2.5; adjusted with trifluoroacetic acid) at a flow rate of 1.25 mL/min. Oxytetracycline was used as the internal standard. The minimum limits of detection were 0.007 and 0.02 µg/mL for doxycycline and oxytetracycline, respectively. Interday and intraday coefficients of variation were between 1.95% and 11.2%, and the mean ± SD recovery of doxycycline was 96.5 ± 26.3% for plasma samples fortified with doxycycline to final concentrations ranging from 0.05 to 20 µg/mL.

Pharmacokinetic analysis—Pharmacokinetic analyses were performed for each sheep by use of non-compartmental methods via a computer program. Expressions based on statistical moments theory30 and standard equations were used to calculate the model-independent pharmacokinetic parameters.31,32 Slope of the terminal phase was determined by least squares regression of the logarithm of the plasma concentration-time curve divided by the terminal elimination phase.
and efficacy,8–21 in sheep, the pharmacokinetics of doxycycline has been extensively conducted to evaluate the pharmacokinetics of doxycycline after IM administration in domestic sheep. Although the pharmacokinetic parameters calculated for doxycycline on the basis of noncompartmental analysis were determined (Table 1). Doxycycline was detected in plasma 10 minutes after administration, and a mean ± SD Cmax of 2.79 ± 0.79 µg/mL was achieved at a tmax of 0.86 ± 0.47 hours after administration. Mean ± SD half-life associated with the slope of the terminal phase (77.88 ± 28.45 hours), AUC (65.67 ± 9.88 µg•h/mL), and mean residence time (91.1 ± 40.78 hours) was also determined.

**Table 1—Mean ± SD and range values for pharmacokinetic parameters obtained via noncompartmental analysis after IM administration of a single dose of doxycycline (20 mg/kg) to 11 healthy sheep.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cmax (µg/mL)</td>
<td>2.79 ± 0.79</td>
<td>1.62–3.82</td>
</tr>
<tr>
<td>tmax (h)</td>
<td>0.86 ± 0.47</td>
<td>0.33–2.00</td>
</tr>
<tr>
<td>AUC (µg•h/mL)</td>
<td>65.67 ± 9.88</td>
<td>48.67–81.48</td>
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<tr>
<td>λ1 (h)</td>
<td>0.010 ± 0.003</td>
<td>0.005–0.014</td>
</tr>
<tr>
<td>t1/2 (h)</td>
<td>23.33–31.58</td>
<td>9.61–38.30</td>
</tr>
<tr>
<td>MRT (∞)</td>
<td>8.24 ± 0.003</td>
<td>6.75–8.24</td>
</tr>
<tr>
<td>AUMC0–t (h2•µg/mL)</td>
<td>11.19 ± 2.38</td>
<td>9.40–16.75</td>
</tr>
<tr>
<td>AUMCt–∞ (h2•µg/mL)</td>
<td>9.21 ± 8.97</td>
<td>65.68–92.95</td>
</tr>
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The Cmax and tmax were obtained directly from examination of data points, and the AUC was calculated on the basis of the trapezoidal rule, with extrapolation to infinity.

**Results**

No adverse effects were observed in any of the sheep during or after the IM injection of doxycycline. Mean plasma concentration of doxycycline as a function of time was plotted (Figure 1). Mean pharmacokinetic parameters calculated for doxycycline on the basis of noncompartmental analysis were determined (Table 1). Doxycycline was detected in plasma 10 minutes after administration, and a mean ± SD Cmax of 2.79 ± 0.79 µg/mL was achieved at a tmax of 0.86 ± 0.47 hours after administration. Mean ± SD half-life associated with the slope of the terminal phase (77.88 ± 28.45 hours), AUC (65.67 ± 9.88 µg•h/mL), and mean residence time (91.1 ± 40.78 hours) was also determined.

**Discussion**

To our knowledge, the present study is the first conducted to evaluate the pharmacokinetics of doxycycline after IM administration in domestic sheep. Although the pharmacokinetics of doxycycline has been extensively studied in several animal species because of its wide use and efficacy,8–21 in sheep, the pharmacokinetics of doxycycline has only been determined for IV and PO administration.24,25 Prior to the study reported here, the pharmacokinetics of doxycycline after IM administration had only been reported in goats,9,15,17,20,22,23 calves,21 ostriches,21 and houbara bustards.24

Compared with results in other species, the mean half-life associated with the slope of the terminal phase obtained for sheep in the present study (77.88 ± 28.45 hours) was higher, which suggested doxycycline was slowly eliminated from sheep. The elimination half-life associated with IM administration of doxycycline ranged from 3.7 to 38.3 hours in goats15,20 and was 9.6 hours in calves.21

Slope of the terminal phase represents the absorption process, rather than the elimination process. Thus, the overall disposition of the drug is determined primarily by its absorption rate from the injection site. It is not uncommon for the absorption process to be the rate-limiting step in the overall disposition and elimination of tetracyclines following IM administration as evidenced by results of studies that involved the use of long-acting formulations of doxycycline in goats15,22 and calves23 and a commercial formulation of oxytetracycline in sheep.25

Mean ± SD residence time from time 0 to infinity was 91.10 ± 40.78 hours for IM administration of doxycycline in sheep, which exceeded that for goats15,17,20 (16.4 and 12.9 hours) and calves23 (12 hours). Even if mean residence time from time 0 to the last measured concentration (27.80 ± 2.38 hours) in the present study was considered, it was twice those previously reported.

The IM administration of doxycycline resulted in a mean ± SD Cmax of 2.79 ± 0.79 µg/mL, which was within the Cmax range15,17,19 (1.9 to 5.6 µg/mL) determined for goats following IM administration of doxycycline at the same dose used in the present study. When 10 mg of doxycycline/kg was administered IM, the Cmax was 3.2 µg/mL in goats22 and 2.9 µg/mL in calves,23 whereas 5 mg of doxycycline/kg IM in goats20 resulted in a Cmax of 1.6 µg/mL.

The mean ± SD tmax (0.856 ± 0.472 hours) in the present study was similar to those (0.83 to 1.17 hours) determined in studies15,17,20 involving goats. Higher tmax values have been determined in goats21 (3.15 hours) and in calves23 (4.5 hours).

The mean ± SD AUC from time 0 to infinity (65.67 ± 9.877 µg•h/mL) in the present study was higher than that (39.72 µg•h/mL) determined after IM administration of a long-acting formulation of doxycycline to goats15 at the same dose used in the study reported here. When 10 mg of doxycycline/kg was administered as an aqueous solution to goats22 and calves,23 AUC values were 22.19 and 21.16 µg•h/mL, respectively. The AUC from time 0 to the last measured concentration represented approximately 62% of the AUC from time 0 to infinity; therefore, in the present study, blood samples should have been obtained for a period longer than 84 hours after administration of doxycycline to determine complete elimination from the sheep’s bodies.

The reason the pharmacokinetic parameters in the present study varied from those reported in other studies15,17,20,22,23 was probably the differences in species, age, breed, and health status of the animals studied. Additional factors that may have contributed to the variation in pharmacokinetic parameters are dose, formulation of doxycycline administered, assay method used to determine pharmacokinetic parameters (some investigators used a microbiological method), and interval after doxycycline administration at which blood samples were obtained and assayed. The variation in the pharma-
kinetic parameters observed among sheep in the present study may have been caused by differences in local blood perfusion at the injection site. It is important to consider all these variables when pharmacokinetic studies are used to determine an appropriate treatment regimen for a drug in a particular species.

Compared with the pharmacokinetics and pharmacodynamics of β-lactams, fluoroquinolones, and aminoglycosides, those of tetracyclines have been under-studied. Thus, information obtained by the use of animals to determine the pharmacokinetics and pharmacodynamics as well as the antimicrobial effects of tetracyclines in species of veterinary interest is limited.

Tetracyclines are regarded as time-dependent antimicrobial drugs, and the best pharmacokinetic and pharmacodynamic indices are achieved when plasma concentrations are maintained above the MIC during treatment or for prophylaxis.36–38 Nevertheless, several investigators37,39–41 have recommended that the ratio for AUC0–24:MIC should be used to determine the susceptibility of pathogens to tetracyclines. The efficacy of tetracyclines is related to the time that the plasma concentration exceeds the MIC by 1- to 5-fold for 40% to 100% of the dosing interval, respectively, and a ratio of AUC0–24:MIC ≥ 125 hours42; however, these values have not been validated for doxycycline specifically.

Minimum inhibitory concentrations for doxycycline against bacterial pathogens in sheep are lacking because tetracycline and oxytetracycline are the drugs commonly used to represent the tetracycline class during susceptibility testing. To our knowledge, the only MIC determined specifically for doxycycline in sheep is that for Listeria monocytogenes (4 µg/mL).43 Therefore, in the present study, the MIC values used for comparative purposes were obtained from other animal species or humans.

Mean plasma concentrations of doxycycline detected in sheep after IM administration of a single dose exceeded > 40% of the dosing interval MIC reported for Chlamydia pecorum (0.008 to 0.031 µg/mL),44 Chlamydia psittaci (0.06 µg/mL),45 and S aureus (0.12 to 0.25 µg/mL)46,47 but did not exceed > 40% of the dosing interval MIC for Pasteurella haemolytica (< 0.5 µg/mL).48 Given these MIC values and an AUC0–24 of 21.80 h·µg/mL, the ratio of AUC0–24:MIC after IM administration of 20 mg of doxycycline/kg, IM, once daily to sheep infected with susceptible bacteria would be a viable treatment option. Moreover, the in vivo effectiveness of doxycycline against these pathogens may be improved because it is a highly liposoluble drug that readily penetrates tissues and cells.

A dosing schedule for a specific drug in a particular species should be made on the basis of pharmacokinetic and pharmacodynamic indices obtained from the species that is to be treated. To our knowledge, the present study is the first conducted to evaluate the pharmacokinetics and IM administration of doxycycline in domestic sheep, and the results were characterized by a slow absorption and elimination of doxycycline. Effective plasma concentrations of doxycycline against susceptible pathogens such as Chlamydia spp and S aureus could be achieved with daily administration of doxycycline at 20 mg/kg, IM. These results suggested that IM administration of doxycycline could be an alternative for the treatment of susceptible infections in domestic sheep, although further studies are needed to support the present findings and to optimize the clinical efficacy of doxycycline in sheep.

References
15. Ole-Mapenay IM, Miteuma ES. Some pharmacokinetic param-


