Pharmacokinetics and tissue distribution of amoxicillin in healthy and Salmonella Typhimurium-inoculated pigs

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Objective—To determine pharmacokinetics and tissue distribution of amoxicillin in healthy and Salmonella Typhimurium-inoculated pigs.

Animals—12 healthy pigs and 12 S Typhimurium-inoculated pigs.

Procedure—Concentration of amoxicillin in tissue was measured by use of high-performance liquid chromatography 4, 8, 12, and 24 hours after IM administration. Pharmacokinetic values of amoxicillin in plasma were assessed by use of a 1-compartment model with first-order absorption.

Results—Inoculation caused diarrhea and increased rectal temperature and WBC count. Absorption half-life was shorter in inoculated pigs (0.26 hours) than in healthy pigs (0.71 hours), and inoculated pigs had longer elimination half-life. Distribution ratios in healthy pigs ranged from 0.31 to 0.56 and in inoculated pigs ranged from 0.14 to 0.48. Ratios for distribution to intestinal mucosa ranged from 0.34 to 1.16 in healthy pigs and from 0.22 to 0.36 in inoculated pigs.

Conclusions and Clinical Relevance—Salmonella Typhimurium inoculation altered absorption of amoxicillin from the injection site and prolonged elimination half-life. However, distribution of amoxicillin to intestinal tract tissue was only affected to a minor degree. (Am J Vet Res 2000;61:992–996)

Infection with Salmonella Typhimurium is a concern to veterinarians and swine producers as a cause of septicaemia and diarrhea in pigs and as a source of foodborne salmonellosis in humans. The mechanisms by which Salmonella spp induce diarrhea are not fully understood, but enterotoxins are important factors. Another important factor is invasiveness of the bacteria; only invasive Salmonella strains induce an intestinal fluid response. Following penetration of the intestinal mucosa, Salmonella organisms may spread to the mesenteric lymph nodes and other tissues. High concentrations of amoxicillin have been detected throughout the small intestine following oral administration to calves, indicating that oral administration is an effective method of achieving high concentrations in the gastrointestinal tract. However, elimination of Salmonella organisms in the intestinal lumen alone may not be satisfactory when treating salmonellosis. Generally, limited information is available for the distribution of drugs during pathologic conditions, although it is known that pathophysiologic changes induced by inflammation may influence drug disposition. The objective of the study reported here was to determine pharmacokinetics and tissue distribution of amoxicillin following IM administration to healthy and S Typhimurium-inoculated pigs.

Materials and Methods

Pigs—Twenty-four healthy female pigs (Landrace X Yorkshire) weighing 25 to 41 kg and obtained from a herd known to be free from salmonellosis were included in the study. Pigs were randomly allocated into 2 groups of 12 pigs. Pigs were fed pelleted commercial feed twice daily and had free access to drinking water. Pigs were housed in individual pens. Experiments were performed in 2 different locations and periods to separate infected pigs from healthy pigs.

Drug administration and blood sampling—Amoxicillin sodium was supplied by the manufacturer. Concentration of amoxicillin in the preparation was determined by use of high-performance liquid chromatography (HPLC), using an amoxicillin standard containing 97.6% amoxicillin. All other chemicals were obtained from commercial sources and were of analytic grade.

For all pigs, amoxicillin (15 mg/kg of body weight) was administered IM in the cervical region, 10 cm caudal to the ear. Blood samples were collected into tubes containing heparin before and 0.25, 0.5, 0.75, 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, and 24 hours after drug administration.

For Salmonella-inoculated pigs, rectal temperatures were recorded, and supplementary blood samples for differential cell counts were collected into tubes containing EDTA before and 6, 12, and 24 hours after inoculation and just before pigs were euthanatized. Serum and plasma was separated and stored at −20°C until assayed.

Experimental design—For healthy pigs, tissue samples and intestinal contents were collected serially from groups of 3 pigs 4, 8, 12, and 24 hours after drug administration. At sampling time, pigs were killed by use of a bolt-pistol and bled by cutting the vena jugularis externa. The intestine was removed intact, and specimens of intestinal wall tissue and mucosa as well as contents were collected at dilated jejunal loops, cecum, and the flexura centralis of colon. Specimens were also collected from the mesenteric lymph nodes.

For Salmonella Typhimurium-inoculated pigs, an inoculation model was used, as described. Briefly, Salmonella strain NVL810 was prepared from a stock culture kept at −80°C and subcultured on call blood agar for 24 hours at 37°C. One colony was inoculated in a 10-ml aliquot of veal infusion broth (VB) and incubated at 37°C for 16 hours, without shaking. From this broth culture, 100-µl aliquots were inoculated into twelve 100-ml vials of...
pooled and centrifuged at 2,000 g for 10 minutes at 4 C. The pellet was resuspended in saline (0.9% NaCl) solution. Viable count in the suspension was determined, using a standard dilution technique. Each pig received 20 ml of this suspension intragastrically by use of a stomach tube. Amoxicillin was administered 24 hours after inoculation. Arrow indicates time of administration of amoxicillin (15 mg/kg of body weight, IM).

Dry matter content—Samples of intestinal contents (jejunum, cecum, and colon) of approximately 1 to 5 g wet weight were obtained for determination of dry matter content. Dry weight of samples was recorded after dehydration for 24 hours at 100 C. Percentage dry matter was calculated as: dry weight × 100/wet weight.

Amoxicillin analysis—Concentration of amoxicillin in plasma, tissue, and mucosa was determined by a HPLC method adopted from Miyazaki et al.\textsuperscript{14,15} and described in detail elsewhere.\textsuperscript{16} Limit of quantification (LOQ) was 0.05 µg/ml in plasma and 0.1 µg/ml in tissue and mucosa. All values lower than LOQ were excluded from the calculations.

Pharmacokinetic analysis of data—Pharmacokinetic analysis of amoxicillin concentration versus time in plasma was performed individually for 6 pigs in each group, by use of a least-squares nonlinear regression program.\textsuperscript{17} Data were fit to 2 models: a 1-compartment model with equal first-order input and first-order output and a 1-compartment model with first-order input and first-order output. Best fit was determined by application of Akaike and Swartz criteria.

Pathologic changes were characterized by catarrhal enterocolitis, hyperemia of the intestinal mucosa, and in 2 of 12 pigs, fibrinonecrotic typhlitis and colitis. The associated mesenteric lymph nodes were greatly enlarged and moist.

Figure 1—Mean (± SD) rectal temperature and WBC count after inoculation of 12 pigs with Salmonella Typhimurium at time 0. Data for hours 28 to 48 represent values for 3 pigs. *Significant (P < 0.05) increase in rectal temperature, compared with temperature at time 0. #Significant decrease in rectal temperature, compared with temperature 24 hours after inoculation. €Significant increase in WBC count, compared with WBC counts 6 hours after inoculation. Arrow indicates time of administration of amoxicillin (15 mg/kg of body weight, IM).

Figure 2—Mean (± SD) dry matter content in jejunum, cecum, and colon in healthy (n = 12) and Salmonella Typhimurium-inoculated pigs (6). *Significantly (P < 0.05) different from value in healthy pigs.
Primerized by significantly faster absorption from the injection site and an increase in the elimination half-life (Fig 3), compared with healthy pigs. Peak concentration (Cmax) was not altered in inoculated pigs, whereas time to reach peak concentration (tmax) was shorter in inoculated pigs, although not significantly (P = 0.09; Table 1).

Volume of distribution (V) and clearance cannot be calculated directly from the estimated parameters. Assuming bioavailability (F) was the same in the 2 groups, alteration in the V/F value (Table 1) indicated a significant increase in volume of distribution in the inoculated pigs.

Disposition to tissue and mucosa—The distribution of amoxicillin to the intestinal wall tissue was lower in inoculated than in healthy pigs, although not significantly (Fig 4–6). At certain sampling points, tissue concentrations were lower than LOQ and were included in the calculations as 0. Likewise, the tissue to plasma ratio of amoxicillin for cecum, colon, and lymph nodes was lower in infected pigs, compared

Table 1—Pharmacokinetic values (mean ± SD; n = 6 for each group) for amoxicillin after IM administration to healthy and Salmonella Typhimurium-inoculated pigs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Healthy pigs</th>
<th>S Typhimurium-inoculated pigs</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>V/F (mg/L)</td>
<td>2.3 ± 0.6</td>
<td>3.9 ± 1.5</td>
<td>0.04</td>
</tr>
<tr>
<td>kabs (h⁻¹)</td>
<td>1.04 ± 0.24</td>
<td>3.1 ± 1.0</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>k (h⁻¹)</td>
<td>0.21 ± 0.07</td>
<td>0.12 ± 0.09</td>
<td>0.06</td>
</tr>
<tr>
<td>t½ (abs) (h)</td>
<td>0.21 ± 0.07</td>
<td>0.12 ± 0.09</td>
<td>0.06</td>
</tr>
<tr>
<td>t½ (el) (h)</td>
<td>3.6 ± 1.1</td>
<td>11.2 ± 11.3</td>
<td>0.06</td>
</tr>
<tr>
<td>k (h⁻¹)</td>
<td>0.20 ± 0.08</td>
<td>0.08 ± 0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>t½ (h)</td>
<td>3.9 ± 1.8</td>
<td>12 ± 10</td>
<td>0.02</td>
</tr>
<tr>
<td>AUC (mg·h/L)</td>
<td>35 ± 4</td>
<td>54 ± 32</td>
<td>0.18</td>
</tr>
<tr>
<td>AUC0–t (mg·h/L)</td>
<td>33 ± 5</td>
<td>31 ± 6</td>
<td>0.39</td>
</tr>
<tr>
<td>MRT (h)</td>
<td>6.3 ± 1.7</td>
<td>17 ± 13</td>
<td>0.03</td>
</tr>
<tr>
<td>MRT0–t (h)</td>
<td>5.3 ± 1.3</td>
<td>6.3 ± 1.9</td>
<td>0.24</td>
</tr>
<tr>
<td>Cmax (µg/mL)</td>
<td>4.7 ± 1.2</td>
<td>3.7 ± 1.0</td>
<td>0.24</td>
</tr>
<tr>
<td>tmax (h)</td>
<td>2.1 ± 0.5</td>
<td>1.3 ± 0.5</td>
<td>0.09</td>
</tr>
</tbody>
</table>

V/F = Volume divided by bioavailability. kabs = Absorption rate constant. k = Elimination rate constant. t½(abs) = Half-life. t½(el) = Half-life calculated by use of k. t½ = Slope for the last phase of the curve. t½ = Half-life calculated by use of k. AUC = Area under the curve. AUC0–t = Area under the curve from zero to the last sampling point. MRT = Mean residence time. MRT0–t = Mean residence time from zero to the last sampling point. Cmax = Peak plasma concentration of amoxicillin. tmax = Time to reach Cmax.
healthy pigs (Table 1); this variation may have been
monly had greater variation (ie, SD) than those of
the cecum and colon, although not significantly .
were not significant, whereas this value was lower in
haps caused by a rebound effect), although differences
was higher in inoculated pigs than in healthy pigs (per-
inoculation, dry matter concentration in the jejunum
was delayed. At the last sampling point, 24 hours after
inoculation, dry matter concentration in the jejunum
was higher in inoculated pigs than in healthy pigs (per-
haps caused by a rebound effect), although differences
were not significant, whereas this value was lower in
the cecum and colon, although not significantly .
Pharmacokinetic values in inoculated pigs com-
monly had greater variation (ie, SD) than those of
healthy pigs (Table 1); this variation may have been
caused by differences in response to inoculation.
However, although variation was high, the absorption
rate constant and the elimination half-life were influ-
enced by the inoculation. The significant increase in
absorption rate constant in the infected pigs may be
ascribed to the increase in body temperature and the
accompanying muscle shivering, which caused
increased blood flow at the site of injection.11 This find-
ing is in contrast to previous observations in calves, in
which experimental Escherichia coli endotoxemia
caused reduced absorption of amoxicillin.16 The dis-
crepancy may be explained by a different response to
inoculation between studies; the febrile response in the
calves was not as distinct as in the pigs reported here.
Intramuscular administration of penicillin G to
Streptococcus suis-infected pigs resulted in a significant
decrease in the plasma C max and a prolonged elimina-
tion half-life,19 which is in agreement with our results.
The observed significant increase in the elimina-
tion half-life (Table 1) may be explained by a con-
comitant increase in V (assuming F was the same in
the 2 groups). The change in V may reflect a shift in
blood flow away from heat loss tissues (eg, skin) to
heat production tissues (eg, shivering muscle).20 A sim-
ilar shift in V of amoxicillin has been described in
Actinobacillus pleuropneumoniae-infected pigs.21
Distribution of amoxicillin to the intestinal tis-
sues and mucosa decreased in inoculated pigs, com-
pared with healthy pigs, although not significantly.
The limited number of pigs evaluated at each time
point may explain the failure to detect statistical dif-
fences between groups. In theory, infection is
expected to cause dilation of capillaries and increased
vascular supply to the infected region, which should
facilitate entry of antimicrobials to the inflamed
area.22 However, several factors may influence the
concentration of amoxicillin in the intestinal tissues
and mucosa. First, the AUC for amoxicillin in plasma
were not equal for healthy and inoculated pigs, con-

### Table 2—Pharmacokinetic values describing the disposition of amoxicillin in the intestinal wall of the jejunum, cecum, colon, and in lymph nodes after IM administration to healthy and S Typhimurium-inoculated pigs

<table>
<thead>
<tr>
<th>Tissue</th>
<th>AUC(0–t) [mg·h/L]</th>
<th>AUC(0–t)/AUC plasma(0–t)</th>
<th>MRT(0–t) [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jejunum</td>
<td>15.56</td>
<td>14.95</td>
<td>0.47</td>
</tr>
<tr>
<td>Cecum</td>
<td>18.49</td>
<td>4.36</td>
<td>0.56</td>
</tr>
<tr>
<td>Colon</td>
<td>15.63</td>
<td>9.89</td>
<td>0.48</td>
</tr>
<tr>
<td>Lymph node</td>
<td>10.50</td>
<td>7.00</td>
<td>0.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tissue</th>
<th>AUC(0–t) [mg·h/L]</th>
<th>AUC(0–t)/AUC plasma(0–t)</th>
<th>MRT(0–t) [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jejunum</td>
<td>11.12</td>
<td>9.73</td>
<td>0.34</td>
</tr>
<tr>
<td>Cecum</td>
<td>25.74</td>
<td>11.08</td>
<td>0.78</td>
</tr>
<tr>
<td>Colon</td>
<td>37.99</td>
<td>11.14</td>
<td>1.16</td>
</tr>
</tbody>
</table>

### Table 3—Pharmacokinetic values describing the disposition of amoxicillin in the intestinal mucosa of the jejunum, cecum, and colon after IM administration to healthy and S Typhimurium-inoculated pigs

<table>
<thead>
<tr>
<th>Mucosa</th>
<th>AUC(0–t) [mg·h/L]</th>
<th>AUC(0–t)/AUC plasma(0–t)</th>
<th>MRT(0–t) [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jejunum</td>
<td>11.12</td>
<td>9.73</td>
<td>0.34</td>
</tr>
<tr>
<td>Cecum</td>
<td>25.74</td>
<td>11.08</td>
<td>0.78</td>
</tr>
<tr>
<td>Colon</td>
<td>37.99</td>
<td>11.14</td>
<td>1.16</td>
</tr>
</tbody>
</table>
centrations in tissues will indirectly reflect the concentration in plasma. Second, healthy pigs retained a normal appetite, whereas inoculated pigs became anorectic, which may have affected blood flow to the intestinal tissues. Third, fever reduces blood flow to the gastrointestinal tract; endotoxin-induced fever causes a 20 to 40% decrease in blood flow to the stomach and the small and large intestines. Decreased blood flow may also explain the prolonged MRT we observed in intestinal wall tissue and mucosa. It seems that distribution of drugs to infected tissues may depend on a number factors: the type of infection, the infection site, and the drugs used for treatment of the infection. Results of previous experiments in our laboratory indicated an improved distribution of amoxicillin to the lung mucosa in *Actinobacillus pleuropneumoniae*-infected pigs. Results of the study reported here indicated lower tissue and intestinal mucosa concentrations in infected pigs, although statistical differences from healthy pigs were not detected. Inflammation per se does not seem to be decisive for the distribution kinetics. Other factors such as changes in blood flow in the inflamed areas may be of greater importance.

References