Shiga Toxin–Producing *Escherichia coli* Infection: Temporal and Quantitative Relationships among Colonization, Toxin Production, and Systemic Disease

Nancy A. Cornick, Ilze Matise, James E. Samuel, Brad T. Bosworth, and Harley W. Moon

Edema disease, a naturally occurring disease of swine caused by Shiga toxin–producing *Escherichia coli* (STEC), was used as a model for the sequence of events that occur in the pathogenesis of STEC infection. The mean time from production of levels of Shiga toxin 2e (Stx2e) detectable in the feces (day 1) to the onset of clinical disease (neurologic disturbances or death) was 5 days (range, 3–9). Bacterial colonization and titers of Stx2e in the ileum peaked at 4 days after inoculation in pigs without signs of clinical disease and at 6 days after inoculation in clinically affected pigs. Animals with the greatest risk of progressing to clinical disease tended to have the highest fecal toxin titers (>1:4096). Stx2e was detected in the red cell fraction from blood of some pigs showing clinical signs of edema disease but was not detected in the serum or cerebrospinal fluid.

Shiga toxin–producing *Escherichia coli* (STEC) cause diarrhea, hemorrhagic colitis, and hemolytic-uremic syndrome (HUS) in humans. These strains of *E. coli* are often referred to as enterohemorrhagic *E. coli* (EHEC) because of their propensity to cause hemorrhage in the human intestinal tract. Infection is usually transmitted by the consumption of contaminated food or water or, secondarily, by person-to-person contact [1]. STEC produce several distinct Shiga toxins: Stx1, which is nearly identical to the toxin produced by *Shigella dysenteriae*, and Stx2 and its variants, Stx2c, Stx2d, and Stx2e. EHEC strains produce some combination of Stx1, Stx2, and/or Stx2c or Stx2d [2]. Strains of *E. coli* that cause edema disease of swine produce Stx2e [3, 4]. Shiga toxins are composed of an enzymatically active A subunit surrounded by a pentamer of B subunits that recognize specific glycolipid receptors [5, 6]. The A subunit enters the host cell and mediates cell death by the inhibition of protein synthesis at the ribosomal level [7]. Shiga toxins induce vascular damage [8–10], which can lead to the systemic complications of STEC infection: acute renal failure, hemolytic anemia, and thrombocytopenia in HUS and edema and vascular necrosis in edema disease of swine.

Different aspects of EHEC disease can be reproduced experimentally in rabbits, mice, neonatal calves, and gnotobiotic pigs [11–15]. STEC also cause naturally occurring dysentery in calves [16–19]. However, there is no evidence that the disease in calves involves toxemia or systemic vascular damage [15]. Idiopathic cutaneous and renal glomerular vasculopathy of greyhound dogs is thought to be caused by STEC infection [20, 21].

Edema disease is a naturally occurring disease of young pigs that involves systemic vascular damage as a result of intestinal infection with STEC that are host adapted to swine [22]. The hallmark of clinical edema disease is neurologic impairment and death. Gross lesions include edema of the eyelids, mesentery, and gastrointestinal tract [23, 24]. Necrosis of the arterioles in the intestinal tract and brain is a characteristic microscopic lesion [25, 26]. Like HUS, edema disease often has a prodromal phase of diarrhea. However, in edema disease, the diarrhea is due to heat-stable enterotoxin (STa and/or STb) and is only rarely associated with intestinal hemorrhage [24, 27]. Stx2e is not enterotoxigenic in pigs [28]. The *E. coli* strains that cause edema disease colonize the small intestines of pigs by an attaching and effacing mechanism similar to that used by enteropathogenic *E. coli* [34–36]. However, EHEC strains that lack the attaching and effacing gene, *eae*, also cause hemorrhagic colitis and HUS in humans and presumably colonize by another mechanism(s) [37–39].

Although much is known about the pathogenesis of STEC...
infections, the temporal and quantitative relationships between intestinal colonization, toxin production, toxemia, and the clinical manifestations of toxemia due to Shiga toxin have not been adequately defined. In this study, we used edema disease to define stages in the pathogenesis of STEC disease. We determined the times from inoculation to the peak of intestinal colonization with STEC and to the peak of Stx2e titers in the intestinal content and feces. We also sought to determine whether Stx2e titers in the feces and blood were predictive of systemic disease and the temporal and quantitative relationships between toxin production and systemic disease.

Materials and Methods

Bacterial strains. E. coli S1191 (serogroup O139) was first isolated from a clinical case of edema disease [3]. This strain is hemolytic on sheep blood agar (SBA) and produces Stx2e, heat-stable enterotoxin STb, and F18 fimbriae, which mediate attachment to the porcine small intestine [29–32]. S1191 is resistant to chloramphenicol. E. coli 123 (serogroup O43) was isolated from a healthy pig and is not pathogenic. Inocula were prepared as described elsewhere [40].

Experimental design. Three-week-old pigs (weaned at 14 days of age, all from the same commercial herd) were randomly assigned to groups of controls or principals. Pigs were acclimated to the diet of 21% protein for 4 days before challenge [41]. Rooms were kept at 21°C, and heat lamps were available. Pigs were weighed at -1, 7, and 14 days after inoculation. Rectal swabs were collected before inoculation and at days 2 and 4 after inoculation. The principals (a total of 50 from 3 replicates of the experiment) were orally inoculated with 10⁹ cfu of strain S1191 in a gelatin capsule, and controls (n = 34) were inoculated with 10⁸ cfu of strain 123.

Individual fecal samples were collected daily from all principals and 3 controls on days 1–10 after inoculation and assayed for free fecal Stx2e. Pigs were observed at least twice daily for signs of clinical edema disease and were killed and necropsied when advanced neurologic signs were detected. Randomly selected principal pigs without signs of clinical edema disease were killed and necropsied on days 2, 4, 6, 8, 10, 12, and 14 after inoculation (3/day on days 2–10 and 2/day on days 12–14). Randomly selected control pigs were killed and necropsied on days 1, 5, and 13 after inoculation (3/day on days 1 and 5 and 8/day on day 13). Blood samples (serum or whole blood with EDTA) were collected from some pigs before death. At necropsy, 5-cm sections of ileum and colon were collected for bacteriologic counts. Contents from ileum, colon, and rectum (feces) were collected for toxin assay. Tissue samples from ileum, brain stem, colon, and kidney were collected for histologic examination. Attempts to collect cerebrospinal fluid from clinically affected principals and from controls at necropsy yielded acceptable (blood-free) samples for toxin assay from 5 principals and 2 controls.

Pigs that died were also necropsied, and (except for 1 pig) tissue samples were collected for histologic examination. However, because of the potential for postmortem bacterial proliferation and toxin production, samples for bacteriology and toxin assay were not collected from pigs found dead. At the end of the experiment, 14–15 days after inoculation, the remaining principals were killed and necropsied, and their tissues were examined histologically.

Bacteriology. Intestinal samples were immediately placed on ice and processed within 2 h of collection. Samples for quantitative bacteriology were diluted in 20 mL of PBS and processed in a
inoculation were inoculated onto SBA without antibiotics. He-
Stomacher laboratory blender (Seward Medical, London, UK) for
1 min. Samples were serially diluted 10-fold in PBS, inoculated
encoding Stx2, by use of a multiplex polymerase chain reaction
assay [42]. Rectal swabs from principals after challenge were in-
cerebrospinal fluid were also assayed for Stx2e. All positive blood
samples and at least 1 positive intestinal sample from each pig were
neutralized with bovine polyclonal antibody that neutralizes Stx2
of Vero cells as previously described [43, 44]. All samples were
and Stx2e [46]. The intestinal samples were diluted to titers of
4
7
samples (unpublished data). Fecal and intestinal samples were pro-
cessed by a modification of the method of Karmali et al. [45].
Samples were centrifuged at 7600 g for 10 min, and the supernatant
was added after the first centrifugation step if the sample did not
contain 2 mL of supernatant. The sample was mixed well and
then sterilized through a 0.22-µm filter. PBS (1 vol/1 vol feces)
was added after the first centrifugation step if the sample did not
contain 2 mL of supernatant. The sample was mixed well and
recentrifuged twice. Intestinal and fecal samples were initially di-
luted 1 : 32, because preliminary studies indicated that there was
nonspecific toxicity to Vero cells at lower dilutions in normal pig
feces. Blood samples were centrifuged at 1500 g for 10 min. The
plasma and buffy coat were removed, and the whole red blood
cells were used in the assay. Preliminary in vitro studies, in which
purified Stx2e was added to whole blood, indicated that the ma-
jority of the Stx2e was detected in the red blood cell fraction (un-
published data). Twofold dilutions of red blood cells were made in
Hanks’ balanced salt solution without Ca or Mg rather than in
tissue culture medium. Blood samples were considered positive if
the titer was >1 : 8, because there was nonspecific Vero cell toxicity
at lower dilutions in the blood of a few normal pigs. Serum and
cerebrospinal fluid were also assayed for Stx2e. All positive blood
samples and at least 1 positive intestinal sample from each pig were
neutralized with bovine polyclonal antibody that neutralizes Stx2
and Stx2e [46]. The intestinal samples were diluted to titers of
~1 : 100 before neutralization. Fetal calf serum was used as an
antibody-negative neutralization control. Samples were considered
neutralized and their Vero toxic activity to be due to Stx2e if the
polyclonal antibody reduced the toxin titer by ≥4-fold [47].

<table>
<thead>
<tr>
<th>Pig</th>
<th>Status</th>
<th>Vascular necrosis</th>
<th>Titer at day after inoculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>727</td>
<td>Asymptomatic</td>
<td>+</td>
<td>NT 128 131,072 8192 65,536 131,072 131,072 32,768 8192 128</td>
</tr>
<tr>
<td>635</td>
<td>Asymptomatic</td>
<td>–</td>
<td>128 64 128 512 256 128 NT 512 64 64</td>
</tr>
<tr>
<td>730</td>
<td>Asymptomatic</td>
<td>+</td>
<td>128 512 4096 2048 16,384 NT 1024 1024 128 128</td>
</tr>
<tr>
<td>631</td>
<td>Clinical</td>
<td>–</td>
<td>128 2048 4096 4096 128</td>
</tr>
<tr>
<td>621</td>
<td>Clinical</td>
<td>–</td>
<td>256 8192 16,384 1024 4096b</td>
</tr>
<tr>
<td>616</td>
<td>Clinical</td>
<td>+</td>
<td>64 512 2048 512 256 131,072 131,072b</td>
</tr>
</tbody>
</table>

NOTE. Asymptomatic, pigs that did not develop clinical edema disease; clinical, pigs that developed clinical edema disease; NT, not
tested.

Table 1. Titers of Shiga toxin 2e in feces of selected pigs after inoculation with Shiga toxin–producing Escherichia coli S1191.

Histopathology. Samples were fixed in 10% formalin, processed
by standard procedures, and stained with hematoxylin-eosin [25].
The slides were numerically coded and examined with a light mi-
roscope by 2 investigators who were not aware of the challenge
strain or toxin levels for the pigs under examination.

Statistics. The weight gain of principal and control pigs was
compared by use of a one-way analysis of variance. Pigs that died
or were killed before day 7 were not included in the weight analysis.
Average toxin titers were calculated as the geometric means of the
reciprocal value. Differences in intestinal toxin titers among dif-
f erent tissue sites were compared by one-way analysis of variance
(mixed model). Fecal toxin titers were analyzed with repeated-meas-
ures analysis of variance for days 1–5 after inoculation. Statistical
analysis was not done on fecal toxin titers from days 6–10 after
inoculation because of the small number of clinical pigs still sur-
viving. Average colony-forming units of bacteria were calculated as
the geometric means.

Results

Clinical signs. Nine of the 50 principal pigs exhibited ataxia
and circling or became moribund and were killed. An additional
7 principal pigs did not exhibit neurologic signs during obser-
vation but were found dead. Edema disease (characterized by
the presence of gross edema, fibrinous exudates, or microscopic
vascular lesions) was determined to be the cause of neurologic
signs or death in all 16 of these animals. Clinical edema disease
(signs or death) occurred 4–10 days (mean, 6) after inoculation.
Average toxin titers were calculated as the geometric means of the
reciprocal value. Differences in intestinal toxin titers among dif-
f erent tissue sites were compared by one-way analysis of variance
(mixed model). Fecal toxin titers were analyzed with repeated-meas-
ures analysis of variance for days 1–5 after inoculation. Statistical
analysis was not done on fecal toxin titers from days 6–10 after
inoculation because of the small number of clinical pigs still sur-
viving. Average colony-forming units of bacteria were calculated as
the geometric means.

Microscopic vascular lesions. Vascular lesions were detected
Figure 2. Geometric mean Stx2e titers (log$_{10}$) in feces of pigs inoculated with Shiga toxin-producing Escherichia coli strain S1191. Clinical, pigs ($n = 16$) that developed clinical edema disease; asymptomatic, pigs ($n = 34$) that did not develop clinical edema disease. Bars indicate SEs. Slope of mean fecal toxin titer for clinical pigs 1–5 days after inoculation was greater than that for asymptomatic pigs ($P < .05$). Data were analyzed by repeated-measures analysis of variance for days 1–5 after inoculation. Data from days 6–10 were not analyzed for statistical significance, because too few pigs remained in the clinical group.

in 8 of the 15 principals with clinical disease that were examined and in 12 of 34 asymptomatic principals. The lesions were detected in the brain, ileum, and colon but not in the kidney. The earliest detection of vascular necrosis was in clinical pigs at 5 days after inoculation and in randomly selected asymptomatic principals at 12 days after inoculation (figure 1). None of 14 control pigs necropsied had vascular lesions.

**Fecal toxin titers.** Stx2e was not detected in the feces of control pigs. Stx2e was detected in the feces of all principals on day 1 after inoculation. Thus, the mean time from production of Stx2e in intestine to the onset of clinical edema disease was 5 days (range, 3–9; figure 1). The range of fecal toxin titers varied widely both in pigs that developed and in those that did not develop clinical signs (table 1). For example, pig 727 attained fecal toxin titer of 1 : 131,072 for several days but did not exhibit any clinical signs of edema disease. In contrast, the peak fecal toxin titer of pig 631 was 1 : 4096 on day 3 after inoculation, and the pig was found dead from edema disease the following day (table 1). None of the 16 principals that attained maximal fecal toxin titers < 1 : 4096 progressed to clinical disease. However, of 34 animals that attained fecal toxin titers $\geq 1 : 4096$, 16 (47%) progressed to clinical disease and 18 did not. The slope of the mean fecal toxin titer for principals with clinical disease was significantly greater than that for asymptomatic principals on days 1–5 after inoculation ($P < .05$; figure 2). The mean fecal toxin titer of asymptomatic principal pigs that developed vascular necrosis was not significantly higher than that of the asymptomatic pigs without lesions.

**Bacterial colonization and toxin titers in the intestine.** Stx2e$^+$ E. coli were not detected in any of the pigs before inoculation. All the principals shed the inoculum strain in their feces 2–4 days after inoculation. Control pigs did not have detectable levels of Stx2e$^+$ E. coli in their intestinal tracts after inoculation. In randomly selected asymptomatic principals, the peak of both bacterial colonization and titer of Stx2e in the ileum occurred at 4 days after inoculation and fell sharply thereafter (figure 3). On this day, the geometric mean bacterial count of strain S1191 in the ileum was $1.6 \times 10^8$ cfu/cm, and the geometric mean toxin titer was 1 : 16,384. In the 9 pigs that were killed with clinical signs of edema disease, the greatest intensity of bacterial colonization and highest titer of Stx2e occurred at 6 days after inoculation. The geometric mean density of bacteria in these 3 pigs was $2.4 \times 10^8$ cfu/cm, and the geometric mean titer of Stx2e was 1 : 32,768. The toxin titers of the colon and rectal content from randomly selected asymptomatic pigs followed a course similar to that seen in the ileum (figure 4). During the early stage of the disease (days 2–4), the titer of Stx2e in the ileal content was significantly higher than that in the colon or rectal content ($P < .01$).

**Titer of Stx2e in relation to the density of colonization by strain S1191.** Although the titer of Stx2e in the ileum tended to increase with the number of STEC, there was not an absolute correlation between toxin titer and bacterial density (figure 5). The majority of animals (14/15) that had Stx2e titers $\geq 1 : 4096$ in their intestinal contents also had densities $>10^8$ cfu/cm of ileum. However, the individual animals that had the highest...
titers of Stx2e did not have the greatest density of bacterial colonization. A high ileal toxin titer (>1:8192) and a high density of bacterial colonization (>10^6 cfu/cm) of the ileum occurred in most (8/9) of the clinically affected animals examined. The only clinical pig that had a relatively low ileal toxin titer and bacterial density at the time of necropsy (figure 5) attained a peak fecal toxin titer of 1:8192 at 4 days before necropsy.

Bacterial layers, characterized by aggregates of basophilic rod-shaped bacteria in immediate apposition to the epithelial brush border, were detected in the ileal sections of 8 of 34 asymptomatic principals and 6 of 15 clinical pigs. The mean bacterial count of strain S1191 in the ileum of these pigs with bacterial layers was 2.3 × 10^6 cfu/cm (range, <500 to 1 × 10^6). The bacterial layers were detected as early as 2 days and as late as 12 days (mean, 6) after inoculation in asymptomatic principals and 5–7 days (mean, 6) after inoculation in clinical pigs. Six of the 8 asymptomatic principals with adherent bacterial layers attained peak fecal toxin titers >1:8192. One of those 6 attained fecal toxin titers 1:131,072 on day 3 and remained clinically normal (pig 727; table 1). The mean bacterial count of strain S1191 in the ilea of pigs without adherent layers was 2.9 × 10^3 cfu/cm (range, <50 to 7.7 × 10^3). Bacterial layers were not detected in sections of colon. None of the 14 control pigs necropsied had detectable adherent bacteria in their intestinal sections.

**Stx2e in blood and cerebrospinal fluid.** Blood samples were obtained from 25 principal pigs, 7 of which were exhibiting clinical signs of edema disease at the time the blood was collected (before death). Stx2e was detected in the red cell fraction of blood from 5 of 7 animals with clinical edema disease (table 2). The mean titer of Stx2e in the blood of these 5 animals was 1:64 (range, 1:16–1:512). The ileal and peak fecal toxin titers of these 5 animals ranged from 1:8192 to 1:65,536 and from 1:16,384 to 1:131,072, respectively. The ileal and peak fecal toxin titers of the 2 clinical pigs that did not have detectable Stx2e in blood ranged from 1:64 to 1:32,768 and from 1:8192 to 1:16,384, respectively. The blood from the 18 asymptomatic pigs and 8 controls examined did not have detectable toxin. The cerebrospinal fluid samples from the 5 clinical and 2 control pigs examined were also negative. All the serum samples from the 7 clinical, 18 asymptomatic principal, and 8 control pigs examined were negative for Stx2e. Serum from 1 control animal was toxic to Vero cells, but that activity was not neutralized by bovine antibody to Stx2.

Serum samples collected at the end of the experiment were also assayed for Stx2e-neutralizing antibodies [44]. The geometric mean neutralizing titers for control pigs and asymptomatic principal pigs were 1:4 and 1:5, respectively.

In an experiment similar to that reported here but conducted as part of a different study, we detected Stx2e in the red cell...
fraction from the blood of 5 of 8 clinical and 2 of 12 asymptomatic pigs infected with strain S1191 (unpublished data).

Discussion

The reason(s) for the variable latent period of several days between the production of Stx2e in the intestine and the onset of systemic disease manifested as clinical signs or vascular necrosis (figure 1) is not known. Because the delay between intravenous administration of purified Stx2e and the onset of systemic disease in pigs is only 7–28 h [22], it seems likely that much of the latent period reflects the time required to attain critical levels of toxin in blood and/or vascular endothelium. Presumably, the time required to attain critical systemic levels of toxin is a function of the amount produced and the rate of transport across intestinal epithelium into blood [48, 49]. The onset of vascular necrosis in asymptomatic principals at 12 days after inoculation, well after the peak of toxin production (figures 1 and 3), leads us to speculate that Stx2e may act accumulatively during STEC infections. Whatever the mechanism(s) involved in the delay between the onset of toxin production and clinical disease, the occurrence of the delay suggests use of the edema disease model to determine if systemic disease can be prevented by intervention with antibody [50] or other anti-Shiga toxin therapy during the latent period.

The data indicate that fecal toxin titers were reflective of intestinal toxin titers (figure 4). Fecal toxin titers of clinical pigs as a group were significantly greater than those of asymptomatic principals (figure 2). Furthermore, none of the pigs that attained fecal toxin titers <1 : 4096 progressed to clinical disease, but nearly 50% of those that did attain titers ≥1 : 4096 developed clinical disease. However, the range of toxin titers

<table>
<thead>
<tr>
<th>Status</th>
<th>Range</th>
<th>Mean</th>
<th>No. positive/no. tested</th>
<th>Titera in ileum</th>
<th>Range</th>
<th>Mean</th>
<th>No. positive/no. tested</th>
<th>Titera in blood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinical</td>
<td>64–65,536</td>
<td>16,384</td>
<td>7/7</td>
<td></td>
<td>16–512</td>
<td>64</td>
<td>5/7</td>
<td></td>
</tr>
<tr>
<td>Asymptomatic</td>
<td>64–16,384</td>
<td>709</td>
<td>17/17</td>
<td></td>
<td>ND</td>
<td>ND</td>
<td>0/8</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td></td>
<td>ND</td>
<td>ND</td>
<td>0/8</td>
<td></td>
</tr>
</tbody>
</table>

NOTE. Clinical, pigs that developed clinical edema disease; asymptomatic, pigs that did not develop clinical edema disease; ND, none detected.

* Reciprocal of toxin titer.
in individual pigs varied widely both in clinical and in asymptomatic principals (figure 2, table 1). Thus, fecal toxin titers tended to correlate with the relative risk of clinical disease for a group of pigs but (because of variable susceptibility of individual pigs to intestinal toxin) were not predictive for individual pigs. These data are consistent with the notion that the risk of clinical disease during human STEC infections increases with the level of intestinal toxin [51] but that intestinal toxin levels are not predictive of clinical outcome for individual patients [45, 52].

In general, the density of STEC colonization in the intestine was reflected by the titer of Stx2e in the gut contents. However, the individual animals with the highest titers of Stx2e did not have the greatest density of STEC colonization. One possible explanation for these results is that toxin production by strain S1191 is inducible in vivo and is stimulated by attachment to the intestinal wall or by interaction with metabolites in the intestinal lumens of some animals. We do not have any additional evidence for this hypothesis. In vitro–grown cultures of S1191 routinely produce an Stx2e titer of 1 : 1000 in culture supernatant, but sonic lysates of these same cultures have titers that are 100-fold higher [3]. Some of the pigs in this study had intestinal Stx2e titers similar to the titers of sonic lysates of S1191. Some EHEC strains produce a variant of Stx2 (Stx2d) that is activated by mouse or human intestinal mucus [53]. In the presence of this activator, toxin titers are increased 100-fold per cfu of bacteria. Stx2e produced by strain S1191 was not activated in vitro by mouse or human mucus, but porcine mucus was not tested [53]. However, the cytotoxicity of purified Stx2e [28] and the culture supernatant of strain S1191 (unpublished data) was not altered by incubation with intestinal fluid from pigs. The fact that Stx2e titers were higher in ileum than in colon or rectum suggests that small intestine may be the major site of Shiga toxin production in this model of STEC infection. The small intestine is the site of adhesion to intestinal epithelium (mediated by F18 fimbriae) during colonization by edema disease–causing strains of STEC [23, 27, 29–32]. We speculate further that STEC adherent to intestinal epithelium may be in a niche that enhances production, release, or activation of Shiga toxin. In contrast to the fimbria-mediated ileal colonization by STEC in edema disease, many (but not all) EHEC apparently colonize human colon, at least in part, via the attaching/effacing mechanism. Such differences in site and attachment mechanism among bacterial species may cause species differences in production, release, activation, or absorption of Shiga toxin. Therefore, results from edema disease may not be directly applicable to hemorrhagic colitis and HUS.

Early fecal samples greatly increase the recovery of E. coli O157:H7, a serotype of STEC frequently associated with human EHEC infections [54–57]. The data from the study reported here also emphasize the importance of fecal samples collected early in the disease. By 6 days after inoculation, the density of STEC in the ilea of randomly selected asymptomatic pigs had dropped to $10^6$ cfu/cm, and toxin titers in the intestinal content were $<1 : 500$ (figure 3). Even in pigs with clinical signs, the mean bacterial count in the ileum dropped by 2 orders of magnitude, and the mean toxin titer dropped from $1 : 32,768$ to $1 : 9506$ between days 6 and 7. The delay in obtaining fecal samples may be one explanation for the comparatively low fecal

Figure 5. Titer of Shiga toxin 2e (log$_{10}$) relative to density of bacterial colonization (log$_{10}$) in ilea and occurrence of clinical edema disease in pigs inoculated with Shiga toxin–producing Escherichia coli strain S1191.
toxin titers reported from patients with EHEC infections [45, 52].

Some asymptomatic pigs had fecal toxin titers >10-fold higher (1 : 131,072) than the apparent minimum threshold level (1 : 4096) required for clinical disease (table 1). It may be that not all pigs transport an equal percentage of free toxin from the intestine into the blood. Previous studies indicate that purified Stx2e given intraintestinally does not cause clinical edema disease. However, when sodium deoxycholate is given to increase intestinal permeability, intraintestinal Stx2e causes clinical edema disease [49]. Alternatively, differences in the availability of receptors on erythrocytes and/or blood vessels may explain the variability among pigs in response to intestinal toxin loads [5]. We cannot exclude the possibility that variation in preexisting Stx2e antibody levels contributed to the variable susceptibility of pigs to clinical disease. However, we think that this is unlikely, because, in our experience [25, 41, 44], weanling pigs do not have detectable levels of serum Stx2e antitoxin before vaccination or challenge with STEC. Furthermore, assays of serum from the pigs used in the work reported here indicate little or no preexisting Stx2e antitoxin. Adherent layers of bacteria were demonstrated in the ilea of some but not all principals. It seems unlikely that this contributed to the variable susceptibility of pigs to toxin, for several reasons: first, adherent bacteria probably occurred segmentally and at varying times during the disease [23]. Adherent layers of STEC probably occurred at some site and time in most principals; otherwise, the STEC could not have colonized intensively enough to attain high toxin titers. Next, 6 of the 8 asymptomatic principals in which adherent layers of bacteria were found attained fecal toxin titers >1 : 8192, and 1 of those 6 attained a fecal toxin titer of 1 : 131,072 on 3 separate days. Finally, in a pilot experiment, we found that all 4 asymptomatic principals tested 17 days after inoculation with strain S1191 had ileal epithelial cell brush borders receptive to adhesion by F18* E. coli in vitro (unpublished data).

To our knowledge, this is the first report of Stx2e being detected in the red cell fraction of blood from individual STEC-infected animals. This provides further evidence that Stx2e contributes to the systemic damage seen in clinical edema disease [22]. It also supports the concept that Stx2e is transported from the gut, by the blood, to the site of tissue damage [5, 22, 49]. Previous work has demonstrated that Stx2e binds to pig erythrocytes and that the tissue distribution of intravenously administered toxin is dependent on the blood flow to particular sites [5, 58]. The fact that we detected Stx2e in the red blood cell fraction but not in the serum is consistent with the evidence that Stx2e binds to erythrocytes. Presumably, the Stx2e detected was a portion of that in equilibrium with the receptors on erythrocytes. In contrast to our results with edema disease, cytotoxic activity (presumed to be Shiga toxin) was detected in the serum of gnotobiotic pigs infected with EHEC strains [59, 60]. Concentrated serum samples from mice infected with EHEC also contained detectable Shiga toxin [61]. Our inability to detect Stx2e in the blood of most asymptomatic infected pigs that had high titers of Stx2e in their intestines may indicate that the toxin had not yet entered into the blood of these animals. Alternatively, erythrocyte receptors in most asymptomatic infected pigs may not have been sufficiently saturated to release detectable levels of toxin. In vitro studies with fluorescent-labeled Shiga toxin demonstrate that human erythrocytes also bind Shiga toxin, although the degree of binding varies considerably among donors of different blood group antigen types [62]. This suggests that variations in the toxin binding capacity of erythrocytes may cause variations in clinical outcome in edema disease, as has been suggested by some but not all studies of human STEC infections [62–66].

In conclusion, this study demonstrated a delay of several days from the production of Stx2e to the onset of clinical disease. It also demonstrated that fecal toxin titers could be used to identify a population of pigs that were at greatest risk for developing clinical disease after STEC infection. However, such titers were not predictive for individual animals. Stx2e was detected in the peripheral blood of pigs with clinical disease. This provides further evidence that Stx2e is transported, by blood, from the gut to sites of systemic tissue damage.

Acknowledgments

We thank Sheridan Booher, Sophi Franck, and Matt Mettenberg for technical assistance; Claire Andreasen and Michael Wannemuehler for helpful discussions; and William Christensen for statistical analysis.

References


8. Obrig TG, Louise CB, Lingwood CA, et al. Shiga toxin-endothelial cell interactions. In: Karmali MA, Goglio AG, eds. Recent advances in vero-


Note added in proof. Subsequent review of the histologic slides revealed vascular lesions in an additional asymptomatic principal at 8 days postinoculation.