Cryptosporidium parvum causes acute infectious diarrhea in humans and animals worldwide. Molecular studies have identified at least 2 major genotypes within human-pathogenic C. parvum: human genotype 1 (HuG1) and bovine genotype 2 (BoG2). These genotypes have biological differences in terms of host range; BoG2 isolates appear to be infectious for a wide variety of mammalian species, whereas HuG1 isolates appear to be highly selective, infecting principally humans [1]. This difference is important, because most human cases of cryptosporidiosis (>75%) are caused by HuG1; <25% are caused by BoG2 [1, 2].

The biological behavior of BoG2 C. parvum has been studied in several animal models, including the gnotobiotic pig [3–7], and can be defined by time to onset of oocyst shedding, or prepatent period; duration of shedding, or patent period; and severity of disease and pathologic lesions. The prepatent periods of BoG2 isolates in calves [5], mice [6], pigs [3], and humans [7] vary considerably. BoG2-infected calves and gnotobiotic pigs typically show symptoms of moderate-to-severe diarrhea with weight loss and sometimes death due to dehydration and wasting. The biological behavior of HuG1 C. parvum in animals has not been studied until now because of the parasite’s inability to infect nonhuman hosts. However, longitudinal studies in humans suggest that the human and bovine genotypes behave differently in the human host [8, 9].

High doses (thousands to millions of oocysts) of BoG2 C. parvum are traditionally used in animal pathogenesis studies, although most naturally acquired Cryptosporidium infections result from ingestion of relatively few oocysts. In fact, the risk of C. parvum infection is heightened as a result of the parasite’s low infective dose. The recent finding that HuG1 isolates can infect neonatal gnotobiotic pigs [3, 4] has made possible comparative studies on the biological behavior of HuG1 and BoG2 C. parvum in a single host species. We believe that the present study is the first to compare the clinical and pathologic outcome of HuG1 and BoG2 C. parvum infections by using small numbers of oocysts (1–10 oocysts) to better emulate naturally acquired infections.

Methods

BoG2 C. parvum GCH1 was supplied to our laboratory by S. Tzipori (Tufts University, School of Veterinary Medicine, Grafton, MA). GCH1 was first isolated from a patient with AIDS and was subsequently maintained by passage in neonatal calves. HuG1 C. parvum H2132 and H2265 were obtained from persons infected in waterborne disease outbreaks in South Carolina and Nebraska, respectively. Each C. parvum isolate was serially passaged in gnotobiotic pigs and confirmed to be BoG2 or HuG1 before and after
selected pig passages by nested polymerase chain reaction restriction fragment–length polymorphism (RFLP) targeting the small subunit rRNA gene [10].

For the first pig passage, day-old gnotobiotic pigs were fed 10⁷ and 10⁹ oocysts extracted from infected calf or human feces by immunomagnetic beads (IMB) (Dynabeads Anti-Cryptosporidium [no. 730.01]; Dynal). Pigs were euthanized 24–48 h after the detection of oocyst shedding by acid-fast stain and UV light microscopy [11], and their intestinal contents were collected and stored at 4°C. For subsequent passages, oocysts were extracted from pig intestinal contents by IMB and counted by hemocytometer. Sterile water was added to create a suspension of 10⁷ oocysts/mL, and a 5-µL droplet of each oocyst suspension was then placed on a drop slide and examined microscopically (×400 magnification). Droplets with 1–10 oocysts were covered with 50 µL of 1% low-melting-point agarose (Life Technologies) and fed to pigs within 1 h. In the present study, 1–10 oocysts from the intestinal contents of the third (for strain H2132) and fifth (for strains GCH1 and H2265) pig passages were isolated as described and fed to pigs.

Forty gnotobiotic pigs were derived and maintained as described elsewhere [12]. At age 1 day, 15 pigs were fed 1–10 HuG1 oocysts, 15 pigs were fed 1–10 BoG2 oocysts, and 10 pigs were fed agarose. Pigs were monitored daily for clinical disease and oocyst shedding by acid-fast stain and UV light microscopy [11]. Feces were examined and scored as follows: 0, normal; 1, pasty; 2, opaque liquid; and 3, watery. Diarrhea was considered to be present at scores ≥2. Dehydration was described as mild (visible vertebrae), moderate (prominent vertebrae and eyes retracted in orbit <1 mm), and severe (prominent protruding vertebral and pelvic bones and eyes retracted in orbit >1 mm).

Three pigs from each infected group and 2 uninfect ed control pigs were killed 3 days after inoculation (DAI) and 0, 7, 21, and 42 days after onset (DAO) of oocyst shedding. Intestinal contents from each pig were collected and stored at 4°C. Sections of duodenum, jejunum, ileum, and colon were collected as described elsewhere [13], placed in fixative (Prefil; Anatech) for 24–48 h, processed through graded alcohols, embedded in paraffin, sectioned at 4 µm, and stained with hematoxylin-eosin (HE).

Slides were coded and examined by an examiner who had no knowledge of infecting genotype or strain. The average intestinal infection rate per 100 linear micrometers in 10 random fields per intestinal section was evaluated at ×400 magnification and scored as follows: 0, no parasites detected; 1, 1–10 parasites/100 µm; 2, 11–30 parasites/100 µm; and 3, >30 parasites/100 µm. Villus height and width, crypt height and width, and epithelial cytoplasmic vacuolation at villus tips were used to determine the extent of mucosal attenuation and were scored as follows: 0, same as in control pigs; 1, mild; 2, moderate; and 3, severe. The extent to which lymphoid cells had infiltrated the submucosa and the lamina propria and the size of organized submucosal lymphoid follicles (i.e., Peyer patches) determined the extent of lymphoid hyperplasia and was scored as follows: 0, same as in control pigs; 1, mild; 2, moderate; and 3, marked.

Between-group differences in mean diarrhea scores, dehydration, and prepatent and patent periods were identified by the general linear model (SAS Institute). We used χ² analysis to compare data

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**Figure 1.** Photomicrographs show peak oocyst infection rates in ileum (A and B) villus attenuation in small intestine (C and D), and lymphoid hyperplasia in cecum (E and F) tissues from gnotobiotic pigs infected with bovine (A, C, and E) or human (B, D, and F) *Cryptosporidium parvum* (hematoxylin-eosin stain; original magnifications, ×400 [A and B] and ×25 [C–F]).
Lymphoid hyperplasia
Villus attenuation

revealed BoG2 parasites in the duodenum, jejunum, ileum, and no dehydration or weight loss in comparison with control pigs. BoG2-infected pigs developed moderate-to-severe dehydration ( ) at 0 DAO (figure 1 asites than BoG2 parasites were observed per villus in the ileum time during the study (table 1). Significantly more HuG1 parasites were detected in the duodenum and jejunum at any period. However, HuG1 parasites were only seen tissues of pigs killed during the prepatent (3 DAI) and patent period. Mild lymphocytic infiltrates and rare inflam-
sia and infiltration of scattered neutrophils. Lymphoid hyper-
plasia in the HuG1-infected pigs was noted only during the patent period. Mild lymphocytic infiltrates and rare inflam-

Table 1. Mean scores for pathologic lesions in the duodenum (D), jejunum (J), ileum (I), and colon (C) of gnotobiotic pigs infected with human and bovine Cryptosporidium parvum.

<table>
<thead>
<tr>
<th>Genotype, time point</th>
<th>Parasite burdena</th>
<th>Lymphoid hyperplasiab</th>
<th>Villus attenuationc</th>
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<tbody>
<tr>
<td>Human</td>
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<td>3 Days after inoculation</td>
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<td>Days after onset</td>
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<td>0</td>
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<td>7</td>
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<td>42</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Bovine</td>
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<td>3 Days after infection</td>
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<td>Days after onset</td>
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<td>7</td>
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<td>1.3</td>
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<td>42</td>
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</table>

NOTE. For each C. parvum genotype, 3 pigs were infected. 

a Score: 0, no parasites detected; 1, 1–10 parasites/100 μm; 2, 11–30 parasites/100 μm; 3, >30 parasites/100 μm.
b Score: 0, same as control pigs; 1, mild; 2, moderate; 3, marked.
c Score: 0, same as control pigs; 1, mild; 2, moderate; 3, severe.

Results

The prepatent period for HuG1-infected pigs was signifi-
cantly longer (mean ± SE, 8.6 ± 0.5 days) than for BoG2-in-
fected pigs (5.6 ± 0.6 days) (P = .001). HuG1-infected pigs shed oocysts for 16.6 ± 1.8 days, whereas BoG2-infected pigs shed oocysts for 10.3 ± 1.7 days (P = .03). In the first week after the onset of shedding, HuG1-infected pigs had daily fecal scores of 1.8 ± 0.16, and BoG2-infected pigs had significantly higher daily fecal scores of 2.6 ± 0.14 (P = .009). Daily fecal scores of control pigs were 0.48 ± 0.8. During the patent period, BoG2-infected pigs developed moderate-to-severe dehydration and weight loss, whereas HuG1-infected pigs showed mild-to-

Microscopic examination of HE-stained tissue sections re-
vealed BoG2 parasites in the duodenum, jejunum, ileum, and colon (figure 1A). BoG2 parasites were detected in the intestinal tissues of pigs killed during the prepatent (3 DAI) and patent (0–21 DAO) periods. However, HuG1 parasites were only seen during the patent period in the ileum and colon. No HuG1 parasites were detected in the duodenum and jejunum at any time during the study (table 1). Significantly more HuG1 par-
asites than BoG2 parasites were observed per villus in the ileum (P = .05) at 0 DAO (figure 1A and 1B).

Moderate lymphoid hyperplasia was seen at 0 DAO in the duodenum, at 7 DAO in the jejunum and ileum, and at 7 and 21 DAO in the colon of BoG2-infected pigs (table 1 and figure 1E). Other intestinal sections showed mild lymphoid hyperplasia and infiltration of scattered neutrophils. Lymphoid hyper-
plasia in the HuG1-infected pigs was noted only during the patent period. Mild lymphocytic infiltrates and rare inflam-
matory cells were seen at this time in the ileum and colon only (table 1 and figure 1F). The difference between the mean lymphoid hyperplasia scores for the 2 genotypes in the duodenum (P = .002), jejunum (P = .02), ileum (P = .02), and colon (P = .008) during the patent period was statistically significant.

Mild and moderate villus attenuation with epithelial slough-
ing was seen at 0 DAO and 7 DAO in the duodenum and at 21 DAO in the colon of BoG2-infected pigs (table 1). All other intestinal sections showed only mild villus attenuation between 3 DAI and 21 DAO. Comparatively few HuG1-infected pigs showed mild villus/mucosal attenuation during the patent pe-

Discussion

Infection of day-old gnotobiotic pigs with ≤10 HuG1 or BoG2 oocysts resulted in extensive parasite colonization and disease. It has been suggested that serial passages in a host may increase virulence, with ingestion of lower doses achieving higher infection rates and more-severe disease in young gno-
tobiotic pigs [3]. Our findings suggest otherwise: the minimum infective dose of each isolate for gnotobiotic pigs was a single oocyst, after the first pig passage. In addition, the 8–9- and 5–6-day prepatent periods of HuG1 and BoG2 isolates in gno-
tobiotic pigs were evident after the first passage and remained so after several additional passages. The HuG1 isolates also elicited minimal disease in all subsequent passages, whereas the BoG2 isolate elicited moderate-to-severe disease accompanied by loss of weight that often was not regained. Examination of intestines from pigs in these early and subsequent serial pas-
sages revealed parasite infection rates, parasite tissue distribution, and pathologic lesions similar to those described in the present study (L.A.W., unpublished data).

Preliminary studies of 2 other BoG2 and 3 other HuG1 isolates in gnotobiotic pigs similarly have shown that all BoG2 strains have shorter prepatent periods (3–6 vs. 8–12 days) and have elicited more disease than HuG1 strains (L.A.W., unpublished data). Thus, the clinical outcome of a *C. parvum* infection in gnotobiotic pigs appears to be determined in part by the genotype of the parasite, and serial low-dose passage of the *C. parvum* used in this study did not significantly alter the strain virulence for gnotobiotic pigs.

HuG1-infected pigs had significantly more parasites in the ileum than did the BoG2-infected pigs, yet HuG1-associated intestinal lesions were only mild to moderate, compared with BoG2-associated lesions. This apparent discrepancy between infection intensity and lesion severity may be the result of unique parasite virulence factors yet to be identified. Differences in the host’s immune response to each genotype may also contribute to the observed discrepancy.

We have demonstrated elsewhere that a strong time-dependent correlation exists between intestinal mucosal cytokine responses, disease onset, intestinal pathology, disease resolution, and parasite clearance in BoG2-infected pigs [3]. The immune response to BoG2 parasites may limit parasite load and eliminate infection sooner but simultaneously contribute to pathology and disease, whereas the absence of such a response would permit greater parasite replication for a longer period of time, with minimal pathology, as was observed in HuG1-infected pigs in the present study. Comparative studies of the gnotobiotic pig’s cytokine and antibody responses to BoG2 and HuG1 *C. parvum* isolates are under way.

The observed differences between tissue colonization sites for HuG1 and BoG2 *C. parvum* also may help to explain the differences seen in the clinical outcome of infection in the same host species. BoG2 *C. parvum* colonized the entire small intestine (duodenum, jejunum, and ileum) and colon, whereas HuG1 *C. parvum* colonized only the ileum and colon. Because the upper small intestine is important in regulating absorption of nutrients and electrolytes, hindrance of its function often leads to a malabsorptive diarrhea. We noted a loss in epithelial integrity and villus attenuation of the small intestine, which was associated with the presence of parasites within the epithelial brush border and moderate-to-severe clinical disease in BoG2-infected pigs. Thus, we propose that the colonization site of the parasite within the host is a determinant of disease expression by that host. A clinical case study in patients with AIDS who had a history of cryptosporidiosis showed that different anatomic locations of the parasite produced different disease outcomes [14].

In conclusion, HuG1 and BoG2 *C. parvum* were identified by RFLP and used to infect gnotobiotic pigs. During sequential low-dose passages, these isolates showed distinctly different biological behaviors in the pig host, in terms of prepatent and patent periods, disease severity, pathology, and tissue colonization sites, that correlated with the strain’s genotype. Given the increasingly significant molecular and biological differences between these genotypes that are being identified, reexamination and redefinition of the *Cryptosporidium* taxa may be in order.

Acknowledgments

We thank Christine Nielsen, Chris McCloskey, Arden Agnes, and Scott Glaberman, for technical support; Elzi Volk, for help preparing the manuscript; and Rich McCormick and Don Westfall, for assistance with gnotobiotic pigs.

References