Cryptosporidium Species and Subtypes and Clinical Manifestations in Children, Peru

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Cryptosporidiosis is often observed as a pediatric disease in areas where Cryptosporidium spp. are endemic. Children <2 years of age are frequently infected in these areas in community (1–4) and hospital (5) settings. The spectrum of symptoms is diverse, ranging from acute diarrhea, severe chronic diarrhea (6), or vomiting to asymptomatic infections (2,3). In community-based studies in Peru, ≈30% of immunocompetent children with cryptosporidiosis reported diarrhea (2,7). In AIDS patients, the diversity of symptoms has been linked to immune status; severe chronic diarrhea affects patients whose CD4+ counts are <200 cells/mm³ (8). A recent study in HIV-infected patients in Peru showed that only 38% with Cryptosporidium infections had diarrhea (9), although 64% of participants had CD4+ counts <200 cells/mm³. However, the cause for these variations is not clearly understood.

The use of molecular tools in epidemiologic investigations has provided new insights into the diversity of Cryptosporidium spp. infecting humans and animals (10). There are at least 16 established Cryptosporidium spp. and >40 unnamed genotypes that are potentially different species. At least 8 of them have been reported in humans: C. hominis, C. parvum, C. meleagris, C. felis, C. canis, C. muris, and C. suis, and the Cryptosporidium cervine genotype. Molecular characterization of the 60-kDa glycoprotein (GP60) gene of C. hominis and C. parvum has enabled further division into subtype families and subtypes (11).

Humans are most frequently infected with C. hominis and C. parvum (7,11,12); recent reports indicate possible associations between these 2 organisms and different clinical manifestations. In Brazil, children infected with C. hominis had increased parasite shedding, more frequent presence of fecal lactoferrin, and delayed growth when compared with those infected with C. parvum (13). In a study of sporadic cryptosporidiosis in the United Kingdom, illness was more severe in persons infected with C. hominis than in those infected with C. parvum (14,15). A recent study reported different clinical manifestations among Cryptosporidium spp. in HIV-positive persons, and C. hominis was linked to more severe symptoms. The high virulence of C. hominis was evident within its subtype family Ia, while absent in subtype families Ia and Ie (16).

In this study, we analyzed the diversity of Cryptosporidium at the species, subtype family, and subtype levels in
children living in an area with endemic cryptosporidiosis. We also analyzed the association between clinical manifestations and infections with specific Cryptosporidium spp. and C. hominis subtype families.

Methods

Study Design
Specimens and data were obtained from a longitudinal birth cohort study of diarrheal diseases conducted during 1995–1998 in Pampas de San Juan de Miraflores, Lima, Peru. This community was initially settled in the 1980s by immigrants from rural areas. It is located in the outskirts of Lima and had at the time of the study ≈40,000 inhabitants. In this community, the prevalence of HIV infection was <1% (2,7). The study protocol was reviewed and approved by the institutional review boards of Johns Hopkins University and the Centers for Disease Control and Prevention. All participants provided informed consent before participation in the study.

Microscopy
The study participants were asked to provide weekly fecal specimens for microscopic detection of ova and parasites, including Cryptosporidium spp. Stool specimens were washed and concentrated by using the modified Ritchie formalin-ether method and examined for Cryptosporidium spp. oocysts by microscopy of smears stained with a modified acid-fast stain. Intensity of Cryptosporidium spp. oocyst shedding in stools was determined by counting the number of oocysts per 50 μL of concentrated sample. We used a 0 to 3+ scoring system in which 0, negative; 1+, 1–50 oocysts; 2+, 51–150 oocysts; and 3+, >150 oocysts.

Genotyping and Subtyping
Cryptosporidium spp. were identified by using a small subunit rRNA-based PCR–restriction fragment length polymorphism genotyping tool (7,12,17). Subtyping of C. hominis and C. parvum was based on sequence analysis of GP60 genes (18). Each specimen was analyzed by either method at least twice. Subtype families within C. hominis and C. parvum were determined on the basis of sequence differences in the nonrepeat region of the gene. Within each subtype family, subtypes differed from each other, mostly in the number of serine-coding trinucleotide repeats (TCA, TCG, or TCT microsatellite) located in the 5′ region of the gene. The previously established nomenclature system was used to differentiate subtypes within each subtype family (11,16,17). For C. parvum subtype family IIC, the original GP60 sequence for C. parvum subtype family IIC (GenBank accession no. AF164491) was assigned as IIC5G3a. Subtypes that diverged from this sequence were assigned subsequent alphabetical extensions.

Associated Clinical Manifestations and Risk Factors
Daily information on clinical manifestations was gathered by using structured questionnaires. These data were collected by study personnel during interviews of adult caregivers of the participants. Data included relevant gastrointestinal symptoms such as abdominal pain, fever, general malaise, nausea, vomiting, number and consistency of bowel movements, and blood in stools.

Study of potential risk factors for infections was based on sanitation and socioeconomic data obtained at study enrollment. These factors included hygiene parameters (water piped inside the house and presence of flush toilets), presence of animals (dogs, chicken, ducks, guinea pigs, rabbits, parrots, and sheep), house infrastructure (sturdy walls and roof), and indirect economic indicators (house infrastructure and possession of electronic appliances).

Definitions
For the epidemiologic and statistical analyses, we included data from eligible children who had ≥6 months of participation in the study and <20% noncompliance of study procedures. For the epidemiologic analyses we used the following definitions.

Duration of an infection episode was defined as an episode that started on the first date that Cryptosporidium spp. oocysts were microscopically detected in stools and ended on the date of the last positive stool that was followed by at least 3 weekly specimens that were microscopically negative. The length of the infection episode was the number of days between the start and end dates.

An episode of diarrhea was defined as a child having ≥3 liquid or semiliquid bowel movements on any day and the mother’s assessment that the child had diarrhea. Diarrhea was considered associated with an episode if it occurred within 7 days of a positive result for Cryptosporidium spp.

Statistical Analysis
Statistical analyses included data from participants infected with 1 species of Cryptosporidium and compared children with a specific Cryptosporidium sp. or C. hominis subtype family with all other participants not infected with that species or subtype family. Subtype families were compared because of the extensive sequence polymorphism in the nonrepeat regions of GP60, and subtypes within families primarily differed from each other in the length of the serine stretch at the beginning of the protein. Data from the few children infected with >1 species or subtype determinations that were conflicting with genotype categorizations were excluded from that particular comparison. Because all C. parvum in this population belonged to 1 subtype family, results were presented at the species level. Few participants were infected with C. canis and C. felis and these species
are genetically divergent from *C. hominis*, *C. parvum*, and *C. meleagridis*. Therefore, the data for these persons were pooled.

Poisson regression was used to compare incidence rates of gastrointestinal symptoms (dependent variables) and infections with *Cryptosporidium* spp. or subtype families (independent variables) detected in each infection episode. This model was used to incorporate individual incidence rates of infections and the duration that each person participated in the study. These regression analyses were conducted by using SAS Proc Genmod (SAS Institute, Cary, NC, USA) for linear models. The generalized estimating equations procedure was implemented to adjust for correlation among multiple infections for the same child. Statistical significance for a priori tests was set at $\alpha = 0.05$. Whenever multiple subtypes were compared, a separate Bonferroni adjustment was used to maintain an overall experiment-wide $\alpha$ of 0.05.

The $\chi^2$ or Fisher exact tests were used to analyze any association between *Cryptosporidium* spp. or subtypes and animal contacts or socioeconomic risk factors. Pooled $t$ test was used to investigate the differences in age at first infection episode among *Cryptosporidium* spp. and subtype families. All statistical analyses were performed by using SAS version 9.1 (SAS Institute).

**Results**

A total of 533 children were enrolled, and their median age at enrollment was 14 days. They contributed 44,042 stool specimens for detection of enteric parasites and 324,067 child-days of clinical manifestation surveillance.

**Prevalence of Cryptosporidiosis**

Data from 368 participants who met the evaluable criteria were included in the epidemiologic analyses. Cryptosporidiosis was detected by microscopy for 109 participants, for a total of 156 infection episodes. Among them, 71 children had 1 infection, 30 had 2 infections, 7 had 3 infections, and 1 had 4 infections.

**Cryptosporidium** spp. Genotypes and Subtypes

Genotype data for *Cryptosporidium* spp. were obtained from 127 (81%) of 156 infection episodes. Among those genotyped, *C. hominis* (70%) was the species most frequently detected, followed by *C. parvum* (13%) and *C. meleagridis* (8%). In contrast, *C. canis* and *C. felis* were detected in 2% and 5% of cases, respectively (Table 1). Among 106 infection episodes with either *C. hominis* (89) or *C. parvum* (17), subtype analysis was successfully accomplished for 78 of 89 infections with *C. hominis* and 14 of 17 infections with *C. parvum*. Four subtype families were identified within *C. hominis*: Ia, Ib, Id, and Ie, the least frequent was Id. All infections with *C. parvum* belonged to subtype family IIc. Novel subtype sequences were deposited in GenBank under accession nos. EU095258–EU095267 (Table 2).

Several subtypes were found within subtype families Ia and Id of *C. hominis* and Ic of *C. parvum*. Subtype family Ia was the most diverse with 6 subtypes, followed by subtype families Id and Ic, each with 3 subtypes. In contrast, subtype families Ib and Ie each had only 1 subtype: IbA10G2 was the only subtype in subtype family Ib and IeA11G3T3 was the only subtype in subtype family Ie (Table 2).

**Cryptosporidium** spp. and Oocyst Shedding

The mean age for first infections was 1.6 years of age (median 1.4 years, range 0.2–4.7 years). Infections with *C. parvum* occurred at a younger age than those with other genotypes, and infections with *C. canis* or *C. felis* occurred in older children. However, these differences were not statistically significant after the Bonferroni correction (Table 3).

The mean duration of the first infection episode was 8.1 days (median 5.5 days, range 1–40 days). Infections with *C. hominis* (mean 10.3 days) lasted longer than infections with other species of *Cryptosporidium* (mean 5.8 days; $p = 0.001$). The length of the infection episodes among children infected with different subtype families of *C. hominis* was not significantly different (9.3, 13.1, 7.7, and 12.8 days for Ia, Ib, Id, and Ie, respectively).

Similar patterns were observed for intensity of parasite excretion. Children infected with *C. hominis* had higher parasite excretion scores (mean 1.93) than those infected with other species of *Cryptosporidium* (mean 1.42; $p = 0.021$). Among children infected with different subtype families of *C. hominis*, the intensity of parasite shedding was similar.

**Sequential Cryptosporidium** spp. Infections

Among children with complete genotyping data, sequential infections were detected in 17 children: 15 had 2 episodes of *Cryptosporidium* spp. infection and 2 had 3 episodes (total of 19 reinfection events). The median in-
terval between infections was 10 months (range 2.1–26 months). The same Cryptosporidium sp. was detected in 6 of 15 children with 2 episodes and 1 of 2 children with 3 infections, all involving *C. hominis* (Table 4). When analysis of reinfections included *C. hominis* subtype family data, only 2 sequential infections occurred with the same subtype family: child 5395 had *C. hominis* subtype family Id in the first and second infections, and child 5076 had *C. hominis* subtype family Ie in the second and third episodes of cryptosporidiosis.

**Cryptosporidium spp. and Subtypes and Associated Clinical Manifestations**

Distribution of species and subtype families at first infection among 109 *Cryptosporidium* spp.–infected children was similar to the distribution in all infection episodes. A second model analyzed the data from all infection episodes (Table 5).

On the basis of microscopy results, 36% of infected children had diarrhea, 28.4% had general malaise, 16.5% had abdominal pain, 15.7% had vomiting, and 7.9% had nausea. None of the study participants reported fever or blood in stools. Overall, 44.1% reported ≥1 of the manifestations assessed in the study.

Associated clinical manifestations at first infection varied among different *Cryptosporidium* spp. First infections with *C. hominis* were associated with nausea, vomiting, general malaise, and diarrhea (Table 5). In contrast, infections with other species were associated with diarrhea only.

Patterns of clinical manifestations also varied among *C. hominis* subtype families. Infections with subtype family Ib were associated with nausea, vomiting, general malaise, and diarrhea. Infections with other subtype families (Ia, Id, and Ie) were generally associated with diarrhea only. A similar trend was also seen in the cumulative analysis of all infection episodes at the species and subtype family levels. A possible exception was *C. hominis* subtype family Ia, which showed an association with nausea and vomiting at first infections but did not show such associations with subsequent infections.

### Table 2. Distribution of subtype families and subtypes of *Cryptosporidium hominis* and *C. parvum* in 533 children, Peru

| Species          | Subtype families | No. episodes (%) | Subtype: no. (%) | GenBank accession no. |
|------------------|------------------|------------------|------------------|------------------------|
| *C. hominis*     | Ia               | 15 (24.6)        | 21 (26.9)        | laA11R4: 3 (14)        | EU095258*               |
|                  |                  |                  |                  | laA12R4: 7 (33)        | EU095259*               |
|                  |                  |                  |                  | laA13R4: 1 (5)         | EU095260*               |
|                  |                  |                  |                  | laA13R7: 1 (5)         | EU095261*               |
|                  |                  |                  |                  | laA14R6: 5 (24)        | EU095262*               |
|                  |                  |                  |                  | laA15R3: 3 (14)        | EU095263*               |
|                  | Ib               | 16 (26.2)        | 23 (29.5)        | lbA10G2: 23 (100)      | AY262031                |
|                  | Id               | 7 (11.5)         | 12 (15.4)        | IdA10: 9 (75)          | EU095264*               |
|                  | le               | 15 (24.6)        | 19 (24.4)        | leA11G3T3:19 (100)    | DQ665689                |
|                  | lb + le         | 1 (1.6)          | 1 (1.3)          |                         |                         |
|                  | lb + id         | 1 (1.6)          | 1 (1.3)          |                         |                         |
|                  | Id + le         | 1 (1.6)          | 1 (1.3)          |                         |                         |
|                  | Id + Ib         | 1 (1.6)          | 1 (1.3)          |                         |                         |
|                  | Id + Id         | 1 (1.6)          | 1 (1.3)          |                         |                         |
|                  | Id + le         | 1 (1.6)          | 1 (1.3)          |                         |                         |
|                  | Ia + Ib         | 1 (1.6)          | 1 (1.3)          |                         |                         |
|                  | Ia + Id         | 1 (1.6)          | 1 (1.3)          |                         |                         |
|                  | Ia + le         | 1 (1.6)          | 1 (1.3)          |                         |                         |
|                  | Ia + Id + le    | 1 (1.6)          | 1 (1.3)          |                         |                         |
| *C. hominis*     | Ib + Id + le    | 1                | 1                |                         |                         |
| *C. parvum*      | Id               | 14 (100)         | 14 (100)         | IicA5G3a: 12 (86)      | AY738195                |
|                  | Iic              | 14 (100)         | 14 (100)         | IicA5G3b: 1 (7)        | EU095266*               |
|                  | IicA5G3c: 1 (7) |                  |                  | EU095267*               |

*From this study.*

### Table 3. Age at first infection by *Cryptosporidium* spp. and subtype family in 533 children, Peru

| Species or subtype family | No. episodes | Age, y, mean (range) | p value |
|---------------------------|--------------|----------------------|---------|
| *C. hominis*              | 61*          | 1.93 (0.19–9.51)     | 0.026†  |
| Subtype family Ia         | 15           | 2.13 (0.67–8.05)     | 0.113   |
| Subtype family Ib         | 16           | 1.38 (0.60–2.82)     | 0.176   |
| Subtype family Id         | 7            | 1.41 (0.19–3.34)     | 0.645   |
| Subtype family le         | 13           | 1.81 (0.25–9.51)     | 0.723   |
| *C. parvum*               | 15           | 1.22 (0.44–2.49)     | 0.034†  |
| *C. meleagridis*          | 9            | 1.43 (0.78–2.75)     | 0.615   |
| *C. canis* or *C. felis*‡ | 6            | 2.26 (0.68–3.74)     | 0.039†  |
| Mixed infections          | 2            | 1.62 (1.44–1.79)     | Not done|

*Eight *C. hominis* infections did not have subtype family data.
†Not significant after Bonferroni adjusted α = 0.05/5 = 0.01.
‡Includes 1 mixed infection with *C. meleagridis* and *C. canis.*
of 42 participants infected with than rates reported for a birth cohort in Brazil, where 81% of clinical identiﬁcations (Table 5).

Discussion

Rates of clinical manifestations in our study were lower than rates reported for a birth cohort in Brazil, where 81% of 42 participants infected with C. hominis or C. parvum had diarrhea (13). This difference can be attributed to differences in study designs. Our study analyzed weekly stool samples for the presence of Cryptosporidium spp. and other parasites in a cohort of healthy children. In contrast, the cohort study in Brazil was designed to identify causes of diarrhea, and the specimens were collected within 2 weeks of clinical identiﬁcation of diarrhea.

C. hominis was the predominant species in this community-based longitudinal study, followed by C. parvum (7). This predominance of C. hominis has been observed in persons in other developing countries, such as pediatric populations from Malawi (19), Kenya (20), India (21), Haiti (22), and Brazil (13), children and elderly persons from South Africa (23), and hospitalized HIV-infected children from South Africa and Uganda (24,25). As reported in previous studies (21,24,26,27), we also detected few concurrent infections with multiple Cryptosporidium spp. or C. hominis subtype families.

We observed a comparatively large proportion of participants infected with C. meleagris, a ﬁnding that was also reported at a high frequency in HIV-infected adults in Lima, Peru (12,16). This species has been rarely reported for studies from other locations such as Portugal (28), India (21,26,29), Taiwan (30), or Iran (31) that included either children or adults with or without HIV infections. It should be noted that the diversity of Cryptosporidium spp. is also affected by the methods used. We used a genotyping tool proven to distinguish several dozen species and genotypes. However, methods based on genes coding for a 70-kDa heat-shock protein (32), Cryptosporidium spp. oocyst wall protein (33), or a smaller fragment of the small subunit rRNA gene (34) discriminate fewer Cryptosporidium spp. and genotypes.

Overall, distribution of species and C. hominis subtype families in our study was similar to that found in an HIV study in Lima, Peru (12,16). These 2 studies were conducted in the same area but in different study populations. In both studies, all C. parvum specimens belonged to subtype family Ic, which is considered anthropoetic in origin (17). The normally zoonotic subtype family Ia was not seen in our study population. This ﬁnding is also supported by our risk factor data, which showed the lack of bovines in the study households and the absence of cattle farms in or near the community of Pampas de San Juan. The similarity of the species and subtype distribution in both studies is highly suggestive that the prevalence of Cryptosporidium spp. and subtypes in a speciﬁc location is independent of the immune status of the study population.

The role of parasite genetics in clinical manifestations of cryptosporidiosis is not clear. Studies of human volunteers showed that exposure provided some degree of protection against infection and illness; the infection rates and frequencies of infection-associated clinical manifestations were lower for subsequent infections (35). Thus, clinical manifestations caused by parasite differences would be better observed in primary infections. Our longitudinal birth cohort study enrolled children at an early age (median 14 days), which enabled us to study genotypes and subtypes present at ﬁrst infections and their associations with different clinical manifestations.

First infections with all species and C. hominis subtype families were associated with diarrhea. However, only C. hominis subtype family Ib was also associated with nausea, vomiting, and general malaise, but C. hominis subtype families Ia, Id, and le and other Cryptosporidium spp. were not. Previously, other studies had suggested that C. hominis might be more pathogenic than other species or might induce different clinical manifestations (13,15,21). Our results indicate that within C. hominis, subtype family Ib may be more pathogenic than Ia, Id, and le. Subtype family Ib of C. hominis is the most frequently detected Cryptosporidium spp. in waterborne outbreaks of cryptosporidiosis in industrialized nations (36).

A previous study of cryptosporidiosis in HIV-infected persons in Peru showed that infections with different species or subtype families were associated with different clin-

| Event | First Infection | Second Infection | Third Infection |
|-------|-----------------|------------------|-----------------|
| 5444  | C. parvum (Ib)  | C. hominis (Id and Ie) | C. hominis (Ia) |
| 5076  | C. hominis (Id) | C. hominis (Ie) | C. hominis (Ia)* |
| E392  | C. hominis (lb) | C. hominis (Ie) | C. hominis (Ia) |
| K283  | C. hominis (Id) | C. hominis (Ib) | C. hominis (Ia) |
| 5395  | C. hominis (Id) | C. hominis (Id)* | C. hominis (Ia) |
| 5125  | C. hominis (Id) | C. hominis (Ia) | C. hominis (Ia) |
| D037  | C. hominis (Id) | C. hominis (Id) | C. hominis (Id) |
| 5492  | C. hominis (Id) | C. hominis (Id) | C. hominis (Id) |
| 5471  | C. hominis (lb) | C. parvum | C. felis |
| 5399  | C. hominis (Ie) | C. felis |
| 5370  | C. parvum | C. hominis (Id) |
| 5266  | C. meleagris | C. hominis (Ib) |
| H131  | C. meleagris | C. hominis (Ia) |
| 5082  | C. meleagris | C. hominis |
| 5300  | C. felis | C. hominis |
| 5085  | C. canis | C. hominis |
| 5049  | C. hominis and C. parvum | C. felis |

*Reinfections with the same subtype family.
We did not identify statistically significant risk factors of infection, including age at infection, between any Cryptosporidium patterns of clinical manifestations associated with different Cryptosporidium spp. and subtype families. Nevertheless, our study corroborated the previous observation of de
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| Clinical manifestation | First infection | All infections |
|------------------------|-----------------|----------------|
| Diarrhea               | IRR 3.690       | p value <0.001† |
| Vomiting               | IRR 2.523       | p value <0.001† |
| General malaise        | IRR 2.347       | p value 0.007† |
| Nausea                 | IRR 2.161       | p value 0.001† |
| Headache               | IRR 2.071       | p value 0.035‡ |
| Postural instability   | IRR 3.206       | p value <0.001† |

We also conducted a risk factor analysis for predictors of infection, including age at first infection, in which we did not identify statistically significant associations between any Cryptosporidium spp. or subtype families and any of the variables analyzed, although they covered basic aspects of sanitation and zoonotic, foodborne, and waterborne transmission. One possible explanation is that our questionnaires did not obtain data on factors that were relevant. However, the same questionnaire successfully identified infection risk factors for other organisms in the same community. A more likely explanation is that because most Cryptosporidium spp. in this study were anthropogenic in origin, children may be constantly exposed to these ubiquitous parasites through different transmission routes. Therefore, single exposure variables were not identified as risk factors. This constant exposure may also fit the age distribution pattern of cryptosporidiosis in the community, in which most cases are found in children <2 years of age, occasionally found in older children, and almost never found in immunocompetent adults. This finding is in contrast to transmission of Cryptosporidium spp. in industrialized nations, where infections have been frequently associated with waterborne transmission from either drinking water or recreational water. In conclusion, clinical manifestations of cryptosporidiosis in healthy populations in disease-endemic areas are likely diverse, and the spectrum of these clinical manifestations can be attributed in part to the different species of Cryptosporidium and subtype families of C. hominis.

**Table 5. Associations between infections with Cryptosporidium spp. or C. hominis subtype families and clinical manifestations expressed as incidence rate ratios in 533 children, Peru**

| Clinical manifestation | First infection | All infections |
|------------------------|-----------------|----------------|
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In conclusion, clinical manifestations of cryptosporidiosis in healthy populations in disease-endemic areas are likely diverse, and the spectrum of these clinical manifestations can be attributed in part to the different species of Cryptosporidium and subtype families of C. hominis.
Although further laboratory and longitudinal cohort studies in other disease-endemic areas are needed to validate our observations, these results demonstrate that parasite genetics may play an important role in the clinical manifestations of human cryptosporidiosis. Future studies should be conducted in different geographic settings; they should overcome some potential limitations of this study, such as lack of data on other gastrointestinal pathogens, which might have confounded the clinical findings, and small sample sizes, which had limited the power of the statistical analyses.

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