Ancylostoma ceylanicum
Hookworm in Myanmar Refugees, Thailand, 2012–2015

Elise M. O’Connell, Tarissa Mitchell, Marina Papaiakovou, Nils Pilotte, Deborah Lee, Michelle Weinberg, Potsawin Sakulrak, Dilok Tongsukh, Georgiette Oduro-Boateng, Sarah Harrison, Steven A. Williams, William M. Stauffer,1 Thomas B. Nutman1

Learning Objectives
Upon completion of this activity, participants will be able to:

• Evaluate the epidemiology of hookworm infection among Myanmar refugees living in 3 camps along the Thailand-Myanmar border, based on a cohort study

• Analyze the response to treatment of hookworm infection assessed through molecular analyses among Myanmar refugees living in 3 camps along the Thailand-Myanmar border, based on a cohort study

• Identify risk factors for hookworm infection among Myanmar refugees living in 3 camps along the Thailand-Myanmar border, based on a cohort study

CME Editor
Kristina B. Clark, PhD, Copyeditor, Emerging Infectious Diseases. Disclosure: Kristina B. Clark, PhD, has disclosed no relevant financial relationships.

CME Author
Laurie Barclay, MD, freelance writer and reviewer, Medscape, LLC. Disclosure: Laurie Barclay, MD, has disclosed the following relevant financial relationships: owns stock, stock options, or bonds from Pfizer.

Authors
Disclosures: Elise M. O’Connell, MD; Tarissa Mitchell, MD; Marina Papaiakovou, MSc; Nils Pilotte, MS; Deborah Lee, MPH; Michelle Weinberg, MD, MPH; Potsawin Sakulrak, BS; Dilok Tongsukh, MS; Georgiette Oduro-Boateng, BS; Sarah Harrison, BS; Steven A. Williams, PhD; William M. Stauffer, MD; and Thomas B. Nutman, MD, have disclosed no relevant financial relationships. This article may include discussion of off-label uses of drugs, mechanical devices, biologics, or diagnostics approved by the FDA for use in the United States and investigational drugs, mechanical devices, biologics, or diagnostics not approved by the FDA for use in the United States.

Author affiliations: National Institutes of Health, Bethesda, Maryland, USA (E.M. O’Connell, G. Oduro-Boateng, S. Harrison, T.B. Nutman); Centers for Disease Control and Prevention, Atlanta, Georgia, USA (T. Mitchell, D. Lee, M. Weinberg, W.M. Stauffer); Smith College, Northampton, Massachusetts, USA (M. Papaiakovou, N. Pilotte, S.A. Williams); University of Massachusetts, Amherst, Massachusetts, USA (N. Pilotte, S.A. Williams); International Organization for Migration, Mae Sot, Thailand (P. Sakulrak, D. Tongsukh); University of Minnesota Medical School, Minneapolis, Minnesota, USA (W.M. Stauffer)

DOI: https://doi.org/10.3201/eid2408.180280

1These authors contributed equally to this article.
During 2012–2015, US-bound refugees living in Myanmar–Thailand border camps (n = 1,839) were surveyed for hookworm infection and treatment response by using quantitative PCR. Samples were collected at 3 time points: after each of 2 treatments with albendazole and after resettlement in the United States. Baseline prevalence of Necator americanus hookworm was 25.4%, Ancylostoma duodenale 0%, and Ancylostoma ceylanicum (a zoonosis) 5.4%. Compared with N. americanus prevalence, A. ceylanicum hookworm prevalence peaked in younger age groups, and blood eosinophil concentrations during A. ceylanicum infection were higher than those for N. americanus infection. Female sex was associated with a lower risk for either hookworm infection. Cure rates after 1 dose of albendazole were greater for A. ceylanicum (93.3%) than N. americanus (65.9%) hookworm (p<0.001). Lower N. americanus hookworm cure rates were unrelated to β-tubulin single-nucleotide polymorphisms at codons 200 or 167. A. ceylanicum hookworm infection might be more common in humans than previously recognized.

Hookworm infection affects >470 million persons worldwide (1). Childhood infection has been associated with growth stunting, severe anemia, and iron deficiency (2,3). Ancylostoma duodenale and Necator americanus hookworms are believed to be the most prevalent species that infect humans. Infections with these species are acquired by transdermal penetration of the hookworm larvae or by the fecal-oral route (A. duodenale hookworm only), and infection is limited to humans (4). Dogs and cats infected with Ancylostoma ceylanicum have been found in close association with human populations (5–9).

With the use of molecular techniques, an increased number of human A. ceylanicum hookworm infections have been documented in parts of Asia and the Solomon Islands (10–13).

Hookworms and other soil-transmitted helminths are neglected tropical pathogens targeted for worldwide control by the World Health Organization by 2030 (14). This goal is being pursued through the mass administration of benzimidazole compounds (i.e., albendazole, mebendazole). However, the ubiquitous use of a single class of drug in both human and veterinary medicine has raised concern for the emergence of drug resistance (15–20). We report hookworm infection and cure rates in a large cohort of US-bound refugees from Myanmar residing in camps in Thailand along the Myanmar–Thailand border and assess the presence of β-tubulin mutations that could confer drug resistance among persons with persistent infection.

Materials and Methods

Recruitment of Participants and Sample Collection
This investigation was part of a larger program involving refugees living in camps along the Myanmar–Thailand border that was conducted by the Centers for Disease Control and Prevention during 2012–2015 (21). In our analysis, we included 1,839 (92%) of the 2,004 refugees ≥6 months of age from this cohort who provided fecal samples. (Figure 1; online Technical Appendix, https://wwwnc.cdc.gov/EID/article/24/8/18-0280-Techapp1.pdf). Fecal samples were collected at time point 1 (T1, during the required medical examination for US resettlement), T2 (before departing the refugee camp), and T3 (after US resettlement). All refugees were offered albendazole after fecal specimens were collected to treat presumptive infection with helminths.

Molecular Detection of Hookworm Species
We performed stool extraction (online Technical Appendix) as previously described (22). For the initial 233 samples, we performed quantitative PCR (qPCR) with primer-probe sets Ad1 (for amplifying A. duodenale) and Na (for amplifying N. americanus) (Table 1) (23,24). Then, we switched to a more sensitive primer-probe set targeting a repetitive element in A. duodenale (Ad2) (24). When qPCR with the Ad2 primer-probe set failed to amplify the samples positive by qPCR with Ad1, we subjected 7 discordant samples to PCR restriction fragment length polymorphism, as previously described (26). We also sequenced these PCR products using standard (Sanger) sequencing technology.

Figure 1. Study design showing collection of fecal samples from and treatment of US-bound Myanmar refugees for hookworm infection, Thailand, 2012–2015. Myanmar refugees (n = 2,004) from 3 camps in Thailand (Mae La [camp 1], Mae Ra Ma Luang [camp 2], Mae La Oon [camp 3]) along the Myanmar–Thailand border were recruited to donate fecal samples and receive treatment (ivermectin and albendazole) for parasitic infections. T1 was the time of the resettlement medical exam, T2 occurred before camp departure, and T3 was a time after resettlement in the United States. Albendazole and ivermectin were given immediately after fecal collection at T1 and T2. T1, time point 1; T2, time point 2; T3, time point 3.
Definitions

Participants whose fecal samples were positive for hookworm DNA by qPCR and became negative at the immediate next time point were considered cured. Those whose fecal samples were negative for hookworm DNA by qPCR but then positive the immediate next time point were considered to have a newly acquired infection. We defined persistent infection as having detectable hookworm DNA at 2 successive time points.

Single-Nucleotide Polymorphism Detection in N. americanus–Positive Samples

For the participants who were positive for N. americanus hookworm at all 3 time points, we tested fecal samples from T1 and T3 for β-tubulin single-nucleotide polymorphisms (SNPs) at codon 200. We also tested refugee T3 fecal samples for SNP167 by using an allele-specific real-time PCR approach with common primers and SNP-specific probes (Table 1) and defined heterozygosity and homozygosity of SNPs on the basis of change in the cycle threshold, similar to previously described methods (27–29) (online Technical Appendix).

Statistical Analyses

Unless stated otherwise, we used the geometric mean to measure central tendency. We determined the odds ratios (ORs) of risk factors for infection with A. ceylanicum and N. americanus hookworms by using a generalized linear model that used overdispersion with binomial distribution and logit link. We performed a maximum likelihood analysis using JMP 12.0.1 (https://www.jmp.com/en_us/home.html). We used these models to test the following parameters: sex, age, and the interaction between sex and age. The odds ratios (ORs) and 95% confidence intervals (CIs) were calculated using the generalized linear model with overdispersion with binomial distribution and logit link. The p values were calculated using the Wald chi-square test.

Table 1. Primer-probe sets used to determine genotypes of hookworms present in US-bound Myanmar refugees in camps along Myanmar–Thailand border, Thailand, 2012–2015*

<table>
<thead>
<tr>
<th>Genome target/primer-probe set name, sequence type</th>
<th>Sequence</th>
<th>Final concentration, mmol/L</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITS2/Ad1 Forward primer</td>
<td>5'-GAATGACAGAAACTCGTTGTG-3'</td>
<td>900</td>
<td>(23)</td>
</tr>
<tr>
<td>Reverse primer</td>
<td>5'-ATACTAGCCATCCGCCAACGT-3'</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Probe</td>
<td>5'-ATCGTTTACGACCTT-3'</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Repetitive element/Ad2 Forward primer</td>
<td>5'-GTATTTCTACTCATATGATCAGTGTTCC-3'</td>
<td>900</td>
<td>(24)</td>
</tr>
<tr>
<td>Reverse primer</td>
<td>5'-GTTGGAATTGAGGTATTTCGACA-3'</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Probe</td>
<td>5'-TGACAGTGTCATACCTGGA-3'</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Repetitive element/Ac Forward primer</td>
<td>5'-CAATATTACTGTGCGCATTTAGC-3'</td>
<td>900</td>
<td>(25)</td>
</tr>
<tr>
<td>Reverse primer</td>
<td>5'-GCGAATTATTTAGGTTTACCTG-3'</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Probe</td>
<td>5'-CGGTGAAAGCTTTGCGTATT-3'</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Repetitive element/Na Forward primer</td>
<td>5'-CCAGAATCGCACAAATTATGAT-3'</td>
<td>900</td>
<td>(24)</td>
</tr>
<tr>
<td>Reverse primer</td>
<td>5'-GGGTGGAAGCTTTGCGTATT-3'</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Probe</td>
<td>5'-CCGTTAAGCTTTGCGTATT-3'</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>SNP200 Forward primer</td>
<td>5'-AATGCTACCTCTTCGGGCTTAGTT-3'</td>
<td>900</td>
<td>This paper</td>
</tr>
<tr>
<td>Reverse primer</td>
<td>5'-CGGAAAGCATATCATAAAGCTT-3'</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Probe</td>
<td>5'-AATACAGATGAGACCT(T/A)CT-3'</td>
<td>166; 231</td>
<td></td>
</tr>
<tr>
<td>SNIP167 Forward primer</td>
<td>5'-TCCGGAAGAATACCCCCATTAG-3'</td>
<td>900</td>
<td>This paper</td>
</tr>
<tr>
<td>Reverse primer</td>
<td>5'-CTTTTGCTCTTATTTCCATGAA-3'</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Probe</td>
<td>5'-TGCCTCTGCT(T/A)TTCC-3'</td>
<td>125; 350</td>
<td></td>
</tr>
</tbody>
</table>

*Ac, Ancylostoma ceylanicum set; Ad1, A. duodenale set 1; Ad2, A. duodenale set 2; ITS2, internal transcribed spacer 2; Na, Necator americanus set; FAM and VIC probes (Integrated DNA Technologies, Skokie, IL, USA).

Table 2. Baseline characteristics of 1,839 US-bound Myanmar refugees in camps along Myanmar–Thailand border, by camp, Thailand, 2012–2015

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mae La, camp 1</th>
<th>Mae La Oon, camp 2</th>
<th>Mae Ra Ma Luang, camp 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total participants, no.</td>
<td>549</td>
<td>667</td>
<td>623</td>
</tr>
<tr>
<td>Sex, no. (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>261 (47.5)</td>
<td>327 (49.0)</td>
<td>304 (48.8)</td>
</tr>
<tr>
<td>M</td>
<td>288 (52.5)</td>
<td>340 (51.0)</td>
<td>319 (51.2)</td>
</tr>
<tr>
<td>Age, y, mean (range)</td>
<td>20.8 (0.6–79.9)</td>
<td>19.3 (0.86–89.9)</td>
<td>18.9 (0.55–83.1)</td>
</tr>
<tr>
<td>Any hookworm infection, no. (%)</td>
<td>180 (32.8)</td>
<td>173 (25.9)</td>
<td>182 (29.2)</td>
</tr>
<tr>
<td>Hemoglobin, g/L, geometric mean (range)</td>
<td>130 (71–179)</td>
<td>127 (71–180)</td>
<td>126 (71–183)</td>
</tr>
<tr>
<td>Eosinophil concentration, × 10⁷ cells/L, geometric mean (range)*</td>
<td>3.56 (0.01–55.3)</td>
<td>4.27 (0.01–107)</td>
<td>5.21 (0.01–178)</td>
</tr>
</tbody>
</table>

*Eosinophil concentration reference range: 0–4.5 × 10⁷ cells/L.
Results

A total of 4,330 fecal samples from 1,839 refugees underwent DNA extraction and multiparallel qPCR. After excluding 4 participants positive for hookworm at T1 who did not receive albendazole, the number of participants with T1-T2 paired samples totaled 1,548; we had samples from all 3 time points for 517 participants. The geometric mean time between T1 and T2 sample collections was 188 (range 48–1,013) days and between T2 and T3 was 46.2 (range 14–413) days. Baseline hookworm infection (any type) in this population was high, ranging from 25.9%–32.8% depending on the camp of residence (Table 2).

Detection of A. ceylanicum

When a highly sensitive primer-probe set specific to the A. duodenale genome (Ad2) was used on samples positive for Ancylostoma DNA by qPCR with primer-probe set Ad1, none was positive. Because of concern that Ad1 might enable the cross-amplification of other hookworms and Strongyloides stercoralis, Ascaris lumbricoides, and Trichuris trichiura roundworms) by the Mann-Whitney test using Prism GraphPad 6.0e (https://www.graphpad.com/scientific-software/prism/).

Results from restriction fragment length polymorphism PCR indicated the presence of A. ceylanicum hookworm (online Technical Appendix Figure); these results were further confirmed by sequencing (98% identity to A. ceylanicum ribosomal sequence [GenBank accession no. LC036567]). The internal transcribed spacer 2 regions of the A. duodenale and A. ceylanicum genomes, which the Ad1 primer-probe set aligned with, are identical (Figure 2). Cross-species identification with this primer-probe set has been previously predicted (23), although not previously demonstrated in the literature.

We then determined the prevalence of A. ceylanicum hookworm among the refugee population using a primer-probe set specific to a repetitive DNA element in the A. ceylanicum genome (Ac; Table 1). When using Ac, the total number of A. ceylanicum–positive samples increased from 106 (using the Ad1 set) to 124 (using the Ac set). We tested or retested these samples (n = 124) by qPCR using the Ad2 primer-probe set, and 0% were positive. All samples positive by qPCR with Ad1 were positive by qPCR with Ac.

Response to Treatment

Baseline prevalence of N. americanus (26.3%) hookworm was higher than that of A. ceylanicum (5.3%) hookworm among all participants (n = 1,839); likewise, prevalence of N. americanus (25.4%) species was higher than that of A. ceylanicum (5.4%) species among all participants who gave paired T1-T2 fecal samples (n = 1,548) (Table 3). Refugees in their sixth (50–59 years) and seventh (60–69 years) decades of life had the highest N. americanus hookworm prevalence (>40% positive), and refugees in their third decade of life had the highest A. ceylanicum hookworm prevalence (9%) (Figure 3).

A. ceylanicum infection had a higher cure rate than did N. americanus infection (Table 3): 92.8% of A. ceylanicum hookworm–infected refugees were cured by T2, despite the

**Table 3. Hookworm prevalence and cure rate in US-bound Myanmar refugees in camps along Myanmar–Thailand border with paired samples, by time point, Thailand, 2012–2015**

<table>
<thead>
<tr>
<th>Species</th>
<th>T1, n = 1,548</th>
<th>T2, n = 1,548</th>
<th>T3, n = 517</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline prevalence, no. (%)</td>
<td>Cure, no. (%)</td>
<td>Persistent infection, no. (%)</td>
</tr>
<tr>
<td>Ancylostoma ceylanicum</td>
<td>833,548 (5.4)</td>
<td>77/83 (92.8)</td>
<td>6/83 (7.2)</td>
</tr>
<tr>
<td>Necator americanus</td>
<td>393,548 (25.4)</td>
<td>273/393 (69)</td>
<td>122/393 (31)</td>
</tr>
</tbody>
</table>

*The geometric mean time from T1 to T2 was 188.2 (range 48–1,013) d and from T2 to T3 was 46.2 (range 14–413) d. T1, time point 1; T2, time point 2; T3, time point 3.

In total, 151 refugees had persistent *N. americanus* infections, and 6 refugees had persistent *A. ceylanicum* infections. At T2, the hookworm genomic DNA relative quantity in fecal samples of those with persistent *N. americanus* infection (n = 122) decreased significantly (p<0.001) (Figure 4). Of the 6 persons with persistent *A. ceylanicum* infections at T2, 4 (67%) had a decrease and 2 (33%) an increase in hookworm genomic DNA in their fecal samples. Those infected with *N. americanus* hookworm at T2 and T3 (n = 29) had no significant decrease in parasite genomic DNA relative quantity.
DNA relative quantity at T3, and 26 refugees were positive for *N. americanus* hookworm at all 3 time points.

We detected a small number of newly acquired hookworm infections. Of the 1,548 participants with T1-T2 paired samples, we detected 15 (~1%) new *A. ceylanicum* infections and 36 (2.3%) new *N. americanus* infections (Table 4). Of the 517 participants with T2-T3 paired samples, we detected 3 (0.58%) new *A. ceylanicum* infections and 13 (2.5%) new *N. americanus* infections.

**Risk Factors Associated with *N. americanus* and *A. ceylanicum* Infection**

A generalized linear model was used to assess whether co-incident helminth or protozoa infection, age, sex, or camp affected the risk for infection with *N. americanus* or *A. ceylanicum* hookworm at T1 (Table 5). The y-intercept for the model of *N. americanus* hookworm was 2.4 (95% CI 2.14–2.69) and for *A. ceylanicum* hookworm 2.34 (95% CI 2.77–3.74). The strongest predictors (ORs >1.5 and p values <0.0001) of *N. americanus* infection were adult age (OR 3.83), *T. trichiura* infection (OR 1.90), and *A. lumbricoides* infection (OR 1.71). Female participants had a reduced odds of *N. americanus* infection (OR 0.68; p<0.0001). *N. americanus* infection was the only 1 of the 5 infections assessed that was associated with *A. ceylanicum* co-infection (OR 2.08; p = 0.0018); female sex (OR 0.57; p<0.0001) and residence in camp 1 (Mae La, OR 0.69; p = 0.03) were associated with reduced odds of *A. ceylanicum* infection.

We used a similar model that took age, sex, and camp into account to compare participants who cleared their infection with *N. americanus* hookworm after 1 treatment (n = 290) with those who did not clear infection after 2 treatments (n = 26). Female sex, but not age or camp, was associated with clearance after a single treatment (OR 2.14, 95% CI 1.23–4.44; p = 0.0045).

**N. americanus** Benzimidazole Resistance and β-Tubulin SNP Changes

Because 26 participants were positive for *N. americanus* hookworm at all 3 time points despite 2 courses of albendazole treatment, benzimidazole drug resistance was a concern. In total, 19 of 26 persistently infected participants had T1 fecal samples available for DNA reextraction and SNP200 testing; 3 samples showed no amplification, and 16 were wild type. We then performed DNA reextraction and SNP200 and SNP167 testing with the T3 fecal samples available (n = 24). Only 11 of 24 samples had sufficient quantities of *N. americanus* DNA (>150 pg/μL) to be amplified. All samples were positive for wild-type SNP200 and SNP167. None were homozygous or heterozygous for mutant alleles. Thus, no alterations in the β-tubulin gene could be detected at codons 167 or 200 to account for drug resistance.

An additional 213 samples (from multiple time points) had sufficient *N. americanus* DNA to test SNP200 variation further; 173 of 213 samples were evaluable by allelic discrimination qPCR. All were homozygous wild type for SNP200.

**Blood Cell Concentration Differences Between *N. americanus* and *A. ceylanicum* Infections**

We further evaluated refugees with either *N. americanus* (n = 143) or *A. ceylanicum* (n = 24) hookworm monoinfections; participants co-infected with both hookworms or other soil-transmitted helminths (i.e., *S. stercoralis*, *A. lumbricoides*, and *T. trichiura* roundworms) were excluded. Peripheral blood eosinophil concentrations were significantly higher (p<0.001) in those with *A. ceylanicum* monoinfections (geometric mean 8.49 × 10⁸ cells/L, 95% CI 5.98–12.04 × 10⁸ cells/L) than those with *N. americanus* monoinfections (geometric mean 3.44 × 10⁸ cells/L, 95% CI 2.92–4.05 × 10⁸ cells/L) (Figure 5, panel A). The hemoglobin levels did not differ between those with only *A. ceylanicum* and those with only *N. americanus* infections (Figure 5, panel B).

**Discussion**

*A. ceylanicum* hookworm is increasingly being recognized as a pathogen in humans, particularly in Southeast Asia (32). *A. ceylanicum* is the only hookworm species known to achieve patency in both humans and other animals (e.g., dogs and cats) (33). In this group of US-bound refugees from Myanmar, *N. americanus* infection was the most prevalent hookworm infection at all 3 time points tested (25.4% at baseline); *A. ceylanicum* was the only other hookworm species found, with a baseline prevalence of 5.4%. Because *A. ceylanicum* infection has been described in both Thailand (7,10) and Myanmar (11,34), whether these persons were infected in their home country or in the camps in Thailand is unknown. Camp allocation seemed to have an effect on infection status for both hookworms; camps 2 and 3 imparted a higher risk for *A. ceylanicum* hookworm acquisition, and camp 1 had a higher rate of *N. americanus* infection. Evidence of newly acquired infections for both hookworms at T2 and T3 (Table 4) indicates that active transmission of both species was ongoing at these 3 camps. However, whether the majority of hookworm infections at baseline were acquired prior to entry or while residing in the camps is unknown. Differential infection rates at the 3 camps might reflect environmental and hygiene conditions in the camps, the historical exposure of the persons at these camps, or other factors. Of note, a risk factor for infection with either *A. ceylanicum* or *N. americanus* hookworm was infection with the other hookworm (Table 5). This finding contrasts with previous surveys showing that *A. ceylanicum* and *N. americanus* co-infections are rare (26,32). Although
A. ceylanicum infection by the fecal-oral route is thought to be possible (33), walking barefoot has been shown to be a major risk factor for A. ceylanicum and N. americanus hookworm infections (35). Thus, the high propensity for co-infection in the population we evaluated suggests a similar mode of transmission, namely transdermal penetration, for both hookworms.

Despite possible co-transmission, those infected with A. ceylanicum hookworm had slightly different risk factors than those infected with N. americanus hookworm. A. ceylanicum hookworm prevalence peaked in the third decade of life, compared with N. americanus prevalence, which peaked in the sixth and seventh decades. However, N. americanus prevalence remained high for many decades of life (20–69 years of age).

T. trichiura roundworm, Entamoeba histolytica ameba, and A. lumbricoides roundworm infection as risk factors for N. americanus hookworm co-infection reflects the high prevalence of parasitic infections in this population (27), in a setting with inadequate sanitary infrastructure despite improvement efforts (36). Why infections with these pathogens but not S. stercoralis roundworm (acquired similarly to hookworm) or Giardia duodenalis protozoa (acquired similarly to E. histolytica ameba) put refugees at risk for N. americanus infection deserves further study.

Female participants were less likely to acquire both N. americanus and A. ceylanicum hookworms, a finding that might reflect differential exposures, differences in immunity (37,38), differences in albendazole metabolism (39), or a combination of these factors. Although eosinophilia has been previously reported in experimental human infections with A. ceylanicum hookworm (33) and in A. ceylanicum case reports (34,40), a more striking eosinophilia was seen among those with A. ceylanicum infections than those with N. americanus infections. This observation supports the idea that, unlike the hookworms that only infect humans, the zoonotic A. ceylanicum parasite might be less able to downregulate the host’s IgE-mediated response to infection (41). No difference in hemoglobin levels was found between those with either hookworm species. Anemia is typically seen in A. duodenale infection and is less commonly associated with N. americanus infection (3); for A. ceylanicum infection, data on anemia are scant.

The treatment for N. americanus infection was only modestly effective (cure rate 42%–69%). It has been suggested that deworming might have enabled the zoonotic A. ceylanicum hookworm to fill a niche left by a decrease in anthropophilic hookworms (32). That A. ceylanicum infection was largely cured after single courses of treatment with albendazole (cure rate 92.8%–100%) is reassuring, although follow-up time periods in this evaluation were more varied than in most controlled studies specifically assessing response to treatment. Still, reinfection and newly acquired infection rates (0.58%–0.97% for A. ceylanicum and 2.3%–2.5% for N. americanus) were modest after deworming, compared with previous projections suggesting reinfection rates as high as 30% (14) after 3 months. With the average time between T1 and T2 exceeding 6 months (and the wide time range of 1–33 months), this population experienced a lower reinfection rate than has been suggested for endemic areas.

Persons who were infected with N. americanus hookworm at all 3 time points represent a group that might have never cleared the infection or might have cleared infection but were subsequently reinfected. However, the time between sample collections was not statistically different between those who were persistently positive and those who cleared infection after a single treatment (E.M. O’Connell,

---

### Table 4. New hookworm infections acquired by US-bound Myanmar refugees in camps along Myanmar–Thailand border, by time point, Thailand, 2012–2015

<table>
<thead>
<tr>
<th>Species</th>
<th>T2, n = 1,548, no. (%)</th>
<th>T3, n = 517, no. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ancylostoma ceylanicum</td>
<td>15 (0.97)</td>
<td>3 (0.58)</td>
</tr>
<tr>
<td>Nectator americanus</td>
<td>36 (2.3)</td>
<td>13 (2.5)</td>
</tr>
</tbody>
</table>

*Time point 2; T3, time point 3.

---

### Table 5. Characteristics of US-bound Myanmar refugees in camps along Myanmar–Thailand border associated with increased risk for infection with Ancylostoma ceylanicum or Nectator americanus hookworm, Thailand, 2012–2015

<table>
<thead>
<tr>
<th>Category</th>
<th>N. americanus</th>
<th>A. ceylanicum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Odds ratio</td>
<td>p value</td>
</tr>
<tr>
<td>Children compared with infants and toddlers</td>
<td>8.17</td>
<td>0.0025</td>
</tr>
<tr>
<td>Adults compared with children</td>
<td>3.83</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Ancylostoma ceylanicum infection</td>
<td>2.08</td>
<td>0.0017</td>
</tr>
<tr>
<td>Trichuris trichiura infection</td>
<td>1.90</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Entamoeba histolytica infection</td>
<td>1.79</td>
<td>0.0173</td>
</tr>
<tr>
<td>Ascaris lumbricoides infection</td>
<td>1.71</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Residence at camp 1, Mae La</td>
<td>1.27</td>
<td>0.0039</td>
</tr>
<tr>
<td>Female sex</td>
<td>0.68</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Nectator americanus infection</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

*We built the following factors into the model: other infections (Strongyloides stercoralis, A. lumbricoides, E. histolytica, Cryptosporidium spp., T. trichiura, Giardia duodenalis); camp (1, 2, 3); age (infants and toddlers <2 years of age, children 2–18 years of age, adults >18 years of age); and sex. Associations with Cryptosporidium spp. and G. duodenalis were not significant. We used a generalized linear model that used overdispersion with binomial distribution and logit link, and we performed maximum-likelihood analysis using JMP 12.0.1 (https://www.jmp.com/en_us/home.html). NA, not applicable; NS, not significant.
unpub. data). Reports of benzimidazole resistance are increasing in the literature on veterinary medicine; resistance in canine *Ancylostoma caninum* hookworm (15) and phylogenetically similar bovine intestinal nematodes (17) was associated with SNPs in the β-tubulin gene, particularly in codon 200 but also in codon 167 and, rarely, in codon 198. Likewise, other studies have shown low cure rates after benzimidazole administration in the setting of *N. americanus* infection, and research suggests that resistance is emerging (42). One group found that albendazole administration exerts selective pressure on *T. trichiura* codon 200 in Kenya and Haiti (20). The same group found that, in pooled *N. americanus* eggs from Haiti, the allele containing the resistant codon 200 had a mean allelic frequency of 36% (43). A frequency of 0% was found for the homozygous resistant genotype in hookworm eggs (species not identified) from Haiti and Panama (20), and although the authors reported a 2.3% frequency of the homozygous resistant genotype in hookworm eggs from Kenya, the frequency of the resistant genotype after treatment did not increase (20), raising questions about the significance of this allele. Our examination of codons 167 and 200 in samples persistently positive for *N. americanus* hookworm across all 3 time points, and of codon 200 in those with high levels of *N. americanus* DNA in fecal samples at any time point, revealed only homozygous wild type β-tubulin genes.

Several possibilities might explain why β-tubulin mutations were not found to account for persistent *N. americanus* infections. First, the lesser-known codon 198 or another codon within the β-tubulin gene might be responsible for resistance in the hookworms infecting these refugees. Second, whereas amplification rates for our qPCR assay were as high as or higher than those in most other reports, up to 54% of samples positive for *N. americanus* DNA at T3 did not amplify adequately to determine genotype. Therefore, mutations in SNPs at either codon 167 or 200 could have been missed. Last, β-tubulin might not be the only gene involved in drug resistance and responsible for low cure rates in *N. americanus*. In this population, 88.5% (23 of 26) of those persistently positive for *N. americanus* at all 3 time points were male. The peak concentration in serum and area under the serum concentration time curve for albendazole sulfoxide and albendazole sulfone (the main active metabolites of albendazole) have been found to be higher in female than in male volunteers (39). Also, male refugees were possibly more likely than female refugees to quickly reacquire infection due to differences in environmental exposures.

One lesson from this evaluation was that unbiased surveys are necessary before pursuing highly specific molecular techniques when profiling organisms that infect a population, particularly when considering emerging infectious diseases. Although the use of the highly repetitive genomic sequence for *A. duodenale* hookworm is superior in sensitivity and specificity than the internal transcribed spacer 2 region (44), targeting the more conserved genomic region ultimately enabled detection of an unexpected organism, *A. ceylanicum* hookworm, which otherwise would have been missed in this population.

---

**Figure 5.** Eosinophil and hemoglobin concentrations in US-bound Myanmar refugees at 3 camps along the Myanmar–Thailand border who were mono-infected with *A. ceylanicum* (n = 24) or *N. americanus* (n = 143) hookworm at baseline, Thailand, 2012–2015. Those co-infected with both hookworms or *Strongyloides stercoralis*, *Ascaris lumbricoides*, or *Trichuris trichiura* roundworms were excluded from analysis. Horizontal line indicates geometric mean. Significance was calculated by Mann-Whitney test. A) The geometric mean eosinophil cell concentration was significantly higher in those with *A. ceylanicum* mono-infection (8.49 × 10⁸ cells/L, 95% CI 5.98–12.0 × 10⁸ cells/L) than those with *N. americanus* mono-infection (3.44 × 10⁸ cells/L, 95% CI 2.92–4.05 × 10⁸ cells/L) (**p<0.01**). B) The geometric mean hemoglobin level of the 2 groups was not significantly different.
This project had several limitations. Control and non-treatment groups were absent. Participation was completely voluntary. The number of fecal sample collections for the third time point dropped off substantially because of logistical issues relating to collecting and shipping samples from the various US states after resettlement. Unlike other studies focused on *A. ceylanicum* hookworm, this evaluation did not include surveying the local cat and dog populations to establish potential reservoirs, which might be a worthwhile future research direction.

In summary, this cohort of US-bound refugees living in 3 camps in Thailand on the Myanmar–Thailand border was found to have a high prevalence of *N. americanus* hookworm with suboptimal cure rates after albendazole administration that do not seem to be attributable to mutations in the β-tubulin gene at codons 200 or 167. In addition, *A. ceylanicum* hookworm was the only other hookworm species identified in this population. *A. ceylanicum* infection had a much higher cure rate after a single course of albendazole, and those with *A. ceylanicum* monoinfection had a similar hemoglobin level as those with *N. americanus* monoinfection. Future mapping efforts of soil-transmitted helminths should take into account the emergence of *A. ceylanicum* hookworm infection in humans to further understand its distribution across the world. The recognition of the increased importance of zoonotic *A. ceylanicum* hookworm over that of *A. duodenale* hookworm in some populations raises epidemiologic questions about transmission dynamics and the differential effect on local health of these 2 species.

**Acknowledgments**

We thank Diana Martin and Chaohua Li for help in processing samples. We thank Marla Petway for assistance in specimen management.

This project was funded in part through the Division of Intramural Research, National Institute of Allergy and Infectious Diseases, Bethesda, Maryland, USA, and the Centers for Disease Control and Prevention, Atlanta, Georgia, USA.

**About the Author**

Dr. O’Connell is an assistant clinical investigator in the Laboratory of Parasitic Diseases, National Institute of Allergy and Infectious Diseases, National Institutes of Health, Bethesda, Maryland, USA. Her primary research interests are in helminthic infections; she works on the development of biomarkers and deciphering the host-parasite interactions in neurocysticercosis.

**References**


Address for correspondence: Elise M. O’Connell, National Institute of Allergy and Infectious Diseases, 4 Center Dr, B105, Bethesda, MD 20892-6612, USA; email: oconnellem@niaid.nih.gov