Update on Human Granulocytic Anaplasmosis

Janet Foley
School of Veterinary Medicine, University of California, Davis, California

ABSTRACT: Granulocytic anaplasmosis (GA) is a disease of humans, domestic animals, and wildlife caused by Anaplasma phagocytophilum, formerly Ehrlichia phagocytophila, E. equi, and the unnamed agents of “human granulocytic ehrlichiosis” (HGE). This pathogen is inoculated into host skin by the bite of Ixodes spp. ticks, including I. pacificus in California and I. scapularis in the eastern U.S. After inoculation, A. phagocytophilum disseminates to the blood and is phagocytosed into host neutrophils. The clinical characteristics of GA in people vary from no symptoms to fever, headache, neurological symptoms, and occasionally death. Horses with GA may experience high fever, depression, reduced ability to eat, limb edema, jaundice, and ataxia. GA is an emerging disease in the eastern U.S. but only a handful of human cases have been reported in the western U.S., despite relatively common reports of disease in horses and dogs. Wildlife and dog-sentinel studies have clarified that infection is common in the coast range mountains and Sierra Nevada foothills, with ongoing research focusing on ecological determinants that can modify the prevalence of infection in any particular area. One known reservoir is the dusky-footed woodrat. However, important, poorly understood ecological determinants serve to modify the probability of rodent as well as human infections, including climate, vegetation, and possibly the presence of other reservoir-competent rodents and nidicolous woodrat-specialist ticks such as I. spinipalpis.

KEY WORDS: Anaplasma phagocytophilum, disease, dusky-footed woodrat, Ixodes pacificus, Ixodes spinipalpis, Neotoma fuscipes, tick-borne disease

THE ORGANISM AND DISEASE
Phylogeny and Biological Characteristics
Granulocytic anaplasmosis (GA) is a disease of humans, domestic animals, and wildlife caused by the newly renamed pathogen, Anaplasma phagocytophilum (Dumler et al. 2001). This new species combines Ehrlichia phagocytophila, E. equi, and the unnamed agents of “human granulocytic ehrlichiosis” (HGE), which cross-react serologically (Walker and Dumler 1995) and are indistinguishable morphologically (Popov et al. 1998). There is microvariability in the 16S rRNA gene of strains from the upper midwestern, eastern, and western U.S. among different host species (Chen et al. 1994, Reubel et al. 1998), but analysis of the 16S, 444 ep-Ank, and groESL heat shock protein genetic regions from equine and human-origin isolates from northern California suggested that the HGE agent and E. equi in the U.S. are synonymous, with multiple strains that may vary geographically but do not appear to be host-differentiated (Chae et al. 2000).

A. phagocytophilum shares common biological characteristics and immunopathological mechanisms in hosts with other chelidial and rickettsial bacteria. This organism is inoculated into host skin by tick bite, in context with tick saliva, which contains an array of anti-inflammatory and immunomodulatory chemicals during feeding to prevent host blood clotting, platelet aggregation, NK cell activity, and TNF-α cytokine responses (Wikel 1999). After tick inoculation and local host immune responses, A. phagocytophilum disseminates to the blood, where this obligate intra-cellular pathogen must persist within host neutrophils. The bacterium enters the neutrophil after attaching via an outer surface protein to a host cell receptor and being phagocytosed into a small host membrane-bound site called a phagosome. A. phagocytophilum-infected neutrophils secrete chemokines that recruit macrophages, which then secrete IFN-γ and IL-10 and amplify local and systemic inflammation (Dumler et al. 2000, Klein et al. 2000). Within the phagosome, A. phagocytophilum can inhibit fusion of this protected environment with the lysosome, overcoming initial host immune attacks against the bacteria. Ultimately, however, when host cells are primed with IFN-γ, they are able to kill the intracellular A. phagocytophilum (Webster et al. 1998, Mott et al. 1999).

Clinical Outcomes of Infection
The clinical characteristics of GA in people are variable including pyrexia, headache, myalgia, nausea, and ataxia (Goodman et al. 1996). More severe cases may result in organ failure, susceptibility to opportunistic infections, neuritis, or respiratory complications, with a case fatality rate up to 5% (Walker and Dumler 1995, Foley 2000). GA in horses is characterized by high fever, depression, reduced ability to eat, limb edema, petchiation, icterus, and ataxia (Madigan 1993). Counts of blood cells may document anemia, low platelet counts, and low white blood cell counts. Because much of the pathogenesis of GA is immune-mediated, there may be downstream immune-mediated sequelae, including possible polyarthritis and vasculitis.

Laboratory Findings in GA and Diagnosis
Although most cases of GA occur in areas where tick biting is common, not all human patients report a tick bite and not all dog or horse owners recognize that their animal has been infected. The symptoms and laboratory diagnostic results of GA are non-specific and may include elevated liver enzymes, thrombocytopenia, and neutro-
...enemia. In some cases, the symptoms (e.g., headache and fever) are severe, and yet there are only mild or no laboratory abnormalities.

Probably the most rapid method for diagnosis of GA is to find the characteristic membrane-bound inclusions (morulae) in neutrophils on blood smears, but the proportion of neutrophils with visible morulae may be as low as 1-2%. The Centers for Disease Control (CDC) criteria for a confirmed diagnosis require that visualization of morulae be accompanied by positive titer (≥64), probably because some cellular inclusions may appear similar to morulae. Although a single titer ≥64 may be part of a presumptive diagnosis, this does not document active infection. However, a 4-fold rise in specific titer over 4 weeks is considered confirmatory for GA. Titers become positive approximately 2 weeks after exposure for months to years, so there is a brief window early in the infection when the patient may be ill but seronegative.

Culture of *A. phagocytophilum* is time-consuming, specialized, and somewhat expensive. Polymerase chain reaction (PCR) for specific DNA is extremely valuable for confirming a suspected diagnoses but generally not available rapidly enough in practice for use in primary diagnosis and to guide treatment. There are multiple protocols for PCR of *A. phagocytophilum*. PCR may be most useful early in acute infection before the patient seroconverts, late in infection to rule-out chronic infection, or when serological titer to several agents are similar.

**ECOLOGY**

**Emergence**

Human granulocytic anaplasmosis (HGA) has emerged dramatically in the eastern and midwestern U.S. over the past 25 years. Since first reported in Wisconsin in 1994, over 400 cases of HGA have been diagnosed in the upper midwestern and northeastern United States (CDC 2000). In contrast, only 8 human cases have been documented in California as of April 2002, despite being reportable to the California Department of Health Services (CDHS), availability of diagnostic laboratory support, and dissemination of information to physicians by CDHS personnel and others. Yet, GA is common in dogs and horses (Madigan and Gribble 1987, Foley et al. 2001). However, following targeting of the north coast of California by state and local health officials, 4 cases of HGE were documented in one county within 12 months where no case had previously been confirmed (Foley et al. 1999a). Thus, cases within the state are no doubt somewhat under-reported.

**Tick Vectors**

Worldwide, *Anaplasma phagocytophilum* is vectored by at least 4 tick species and hosted by dozens or hundreds of mammals, reptiles, and birds. *Ixodes scapularis* is the vector in the eastern U.S., *I. pacificus* in California, *I. ricinus* in Europe, and *I. persulcatus* in Asia (MacLeod and Gordon 1933, Pancholi et al. 1995, Richter et al. 1996, Telford et al. 1996, Des Vignes and Fish 1997, Petrovec et al. 1997). Locally important or enzootic vectors may include *I. hexagonus* in England and *I. spinipalpis* in the western U.S.

The spatial distribution of human and equine cases of GA in the western U.S. corresponds with the range of *Ixodes pacificus*, the western black-legged tick, a common tick throughout much of low mountain California (Furman and Loomis 1984, Madigan and Gribble 1987, Richter et al. 1996). *I. pacificus* has been recorded from 55 of 58 counties in California, and adult *I. pacificus* containing *A. phagocytophilum* DNA have been detected in Alameda, El Dorado, Humboldt, Napa, Orange, Sacramento, Santa Cruz, Sonoma, and Yolo Counties (Barlough et al. 1997, Kramer et al. 1999; Nicholson et al. 1999; Lane et al. 2001), although tick surveillance has been limited. The vector competence of *I. pacificus* for *A. phagocytophilum* has been evaluated. Infected *I. pacificus* individuals can be found in nature (Richter et al. 1996; Barlough et al. 1997, Kramer et al. 1999, Lane et al. 2001); horses can be experimentally infected using field-caught, naturally-infected ticks (Reubel et al. 1998); and the agent can be transmitted from experimentally-infected horses to naïve horses by feeding of *I. pacificus* (Richter et al. 1996).

The prevalence of *A. phagocytophilum* in ticks ranges from 0-51% in the eastern U.S. (Magnarelli et al. 1995, Pancholi et al. 1995, Daniels et al. 1997, Varde et al. 1998), but typically is much lower in the western U.S., from 0.8-11% (Barlough et al. 1997, Kramer et al. 1999, Nicholson et al. 1999, Lane et al. 2001). The prevalence in *I. pacificus* nymphs is also low, with 0/465 nymphs positive even where the adult prevalence was 11% (Lane et al. 2001) and only 1/47 pools positive from Sonoma County (Barlough et al. 1997). Yet, nymphs may cause most human, deer, and mountain lion cases, because these peak typically in June and July, corresponding to nymphal tick abundance (Lane 1990; Foley et al. 1998, 1999b, 2001; CDC 2000). In contrast, cases in horses and dogs seem to peak in the winter, corresponding to peak activity of *I. pacificus* adults (Madigan and Gribble 1987, Vredevoe et al. 1999, Foley et al. 2001), although dog cases also occur in late spring, at the time of the emergence of nymphs (Foley et al. 2001). *A. phagocytophilum* is not transovarially transmitted among ticks (Lewis 1979, Munderloh and Kurtti 1995).

**Mammalian Hosts and Reservoirs**

Knowledge of natural reservoirs of *A. phagocytophilum* in California is limited. Immature *I. pacificus* commonly feed on lizards, birds, and small mammals, and occasionally on deer and carnivores (Furman and Loomis 1984). Adult *I. pacificus* occur frequently on dogs, coyotes, bears, bobcats, horses, deer, cattle, humans, and other large animals (Furman and Loomis 1984, Westrom et al. 1985, Lane 1994). The PCR-prevalence of *A. phagocytophilum* in cervids ranges from 9-64% across Connecticut, Wisconsin, and Maryland (Bakken et al. 1996, Belongia et al. 1997, Massung et al. 1998, Magnarelli et al. 1999a). In California, the *A. phagocytophilum* PCR-prevalence was 5% in Columbia black-tailed deer (*Odocoileus hemionus columbianus*) and 31% in tule elk (*Cervus elaphus nannodes*) (Foley et al. 1998). DNA sequencing from the blood of deer and elk confirmed that California cervid isolates were
homologous with horse isolates from northern California (Foley et al. 1998). Infected cervids have been observed from Sonoma, Marin, and Mendocino Counties. Because experimental studies have not been performed in deer, it is not known how they contribute to the maintenance of infection in nature, although their role as reservoirs would be limited to the number of nymphs they support.

Infections with *A. phagocytophilum* are common in several rodent species. Only a few incidents of infection with *A. phagocytophilum* have been reported in house mice (*Mus musculus*), chipmunks (*Tamias spp.*), and voles (*Microtus pennsylvanicus*), all in the eastern U.S. (Tyggyr et al. 1996, Walls et al. 1997). The primary reservoir for *A. phagocytophilum* in the eastern U.S. is the white-footed mouse (*Peromyscus leucopus*), with a seroprevalence from 1-50% (Telford et al. 1996, Walls et al. 1997, Nicholson et al. 1998, Stafford et al. 1999). However, even though the PCR-prevalence ranged from 10.5-36%, infections in these rodents were transient (Walls et al. 1997, Nicholson et al. 1998). Reservoir competence was documented by experimental transmission of *A. phagocytophilum* by feeding larval *I. scapularis* on infected *P. leucopus*, allowing these larvae to molt, and transmitting the infection to naive *P. leucopus* individuals via nymphs (Telford et al. 1996). There is not much evidence of anaplasmosis in other *Peromyscus* spp., with 11% seropositive in *P. boylei*, 6% in *P. maniculatus*, and 8% in *P. gossypinus* (Nicholson et al. 1998, 1999). PCR-positivity in *P. maniculatus* ranged from 0-21% (Nicholson et al. 1998, 1999; Zeidner et al. 2000).

Woodrats are likely reservoirs for *A. phagocytophilum* in California. Serologic evidence of exposure was found in *Neotoma fuscipes* (17.4-26.0%), *N. lepida* (25%), *N. albipigula* (1%), and *N. mexicana* (4.7%) (Nicholson et al. 1998, 1999), and *A. phagocytophilum* DNA was recovered from seropositive woodrats (Nicholson et al. 1999). Titors in woodrats averaged 194 (geometric mean titer) compared with 410 in all seropositive *Peromyscus* (Nicholson 1998). Persistent infection (1-8 months) with *A. phagocytophilum* was documented in wild-caught *N. fuscipes* with no clinical signs (Nicholson et al. 1999, Foley et al. 2002). The agent in woodrat blood was detectable by PCR and was transmissible via needle inoculation to susceptible woodrats. *Neotoma fuscipes* is particularly common in oak woodlands, which is also optimal habitat for *I. pacificus*.

Infection with *A. phagocytophilum* has been described also in carnivores, including coyotes (Pusterla et al. 2000), mountain lions (Foley et al. 1999b), black bears (Walls et al., unpubl. data), dogs (Madewell and Gribble 1982, Greig et al. 1996, Foley et al. 2001), and raccoons, cats, skunks, and bobcats (J. Foley, unpubl. data). The seroprevalence in coyotes, 46%, is surprisingly high, and a PCR-positive coyote has been described (Pusterla et al. 2000). The titors in coyotes were relatively high as well, with two coyotes having titors ≥1,280. Seropositive coyotes were reported from Los Angeles, Santa Clara, and Tehama Counties, and a PCR-positive coyote was detected in Santa Clara County (Pusterla et al. 2000). Mountain lions had relatively high serologic (17%) and PCR-prevalence (16%) of *A. phagocytophilum*, although with low titors (Foley et al. 1999b). If infections in mountain lions are clinically similar to infections in cats, the disease may be mild (Lewis et al. 1975). The prevalence of *A. phagocytophilum* in mountain lions varied from 19% in north coastal California to 25% in the Sierra Nevada and 0% from Monterey. Both coyotes and mountain lions have extensive home ranges or migration patterns and are likely to encounter hundreds of individual ticks from several independent foci, from which they might acquire *A. phagocytophilum*.

Dogs in California develop relatively mild clinical signs of anaplasmosis and have been used as sentinels of human risk, because of the frequency with which they are bitten by *I. pacificus* and their close association with people (Foley et al. 2001). The California statewide seroprevalence of *A. phagocytophilum* in dogs was 8.7% (Foley et al. 2001). Dogs in the eastern U.S. also have been reported to experience infection with *A. phagocytophilum*. Clinical, serological, and molecular descriptions were provided for 17 dogs with anaplasmosis from Minnesota and Wisconsin (Greig et al. 1996) and 3 dogs from North Carolina and Virginia (Goldman et al. 1998). A serosurvey of tick-borne disease in Oklahoma documented 33% prevalence of antibodies to *A. phagocytophilum* in dogs, but 0/100 in horses (Rodgers et al. 1989). In Connecticut and New York, 9.4% of ill dogs had antibodies to *A. phagocytophilum* (Magnarelli et al. 1997). In California, canine GA has been reported from Marin County (northern coast range) and the Sierra Nevada foothills (Madewell and Gribble 1982). A large serosurveillance study of 1,082 healthy dogs across California using Geographic Information Systems technology indicated a Bayes’ adjusted prevalence (BAP) 0.01 to 0.47 (Humboldt County) (Foley et al. 2001). Other north coast counties with moderately high seroprevalence were Mendocino, Sonoma, Lake, and Marin (from 0.15-0.20). Counties in the Sierra Nevada foothills had lower seroprevalence, ranging from 0.09-0.13. Santa Cruz County had a BAP of 0.10.

In contrast to dogs, horses (particularly older animals) experience relatively severe clinical disease (Madigan and Gribble 1987). Equine granulocytic anaplasmosis is common in California, with early reports from horses in northern coastal ranges (Sonoma and Mendocino Counties) and the foothills of the Sierra Nevada (Gribble 1969, Madigan and Gribble 1987, Madigan et al. 1990). Case reports were described for 5 clinically affected horses from the northeastern U.S. (Madigan et al. 1996). In horses from Connecticut and New York with clinical signs of anaplasmosis, the seroprevalence was 29% (Magnarelli et al. 1999b), and in well horses from Minnesota and Wisconsin, the seroprevalence was 17.6% from tick-endemic vs. 3.8% from non tick-endemic areas (Bullock et al. 2000). Infection with human origin *A. phagocytophilum* protected horses from challenge with *E. equi* (Barlough et al. 1995). Equine cases in California are reported regularly from counties in the northern coast ranges and Sierra Nevada foothills, with seroprevalence in horses from coast range and Sierra foothills of 10% (Madigan et al. 1990). A questionnaire-based study evaluated the spatial distribution of equine anaplasmosis (Vredeve et al. 1999). Of 62 practices in northern...
California, cases were diagnosed in the foothills of the Sierra Nevada and coast range mountains with spatial clustering based on nearest neighbor statistical analysis.

In summary, GA is a threat to humans, domestic animals, and wildlife in a range of habitats typical of *I. pacificus* ticks, although the spatial ecology is characterized by distinct patchiness. There appears to be a low disease incidence in humans but not other animals, suggesting key features of the ecology remain unidentified.

**ACKNOWLEDGMENTS**

Grateful thanks is due to colleagues and collaborators including the team that ran the 2006 Vertebrate Pest Conference and Nate Nieto, Niki Drazenovich, Mike Teglas, David Weber, Erica Queen, Patrick Foley, Bob Lane, Steve Dumler, Rick Brown, and Mourad Gabriel.

**LITERATURE CITED**

Bakken, J., J. Krueth, T. Lund, D. Malkovitch, K. Asanovich, and S. Dumler. 1996. Exposure to deer blood may be a cause of human granulocytic ehrlichiosis. Clin. Infect. Dis. 23:198.

Barlough, J., J. Madigan, and E. DeRock. 1995. Protection against *Ehrlichia equi* is conferred by prior infection with the human granulocytic ehrlichia (HGE agent). J. Clin. Microbiol. 33:3333-3334.

Barlough, J., J. Madigan, V. Kramer, C. Clover, L. Hui, J. Webb, and L. Vredevoe. 1997. *Ehrlichia phagocytophila*-genogroup rickettsiae in ixodid ticks from California collected in 1995 and 1996. J. Clin. Microbiol. 35:2018-2021.

Belongia, E., K. Reed, P. Mitchell, C. Kolbert, D. Persing, J. Gill, and J. Kazmierczak. 1997. Prevalence of granulocytic *Ehrlichia* infection among white-tailed deer in Wisconsin. J. Clin. Microbiol. 35:1465-1468.

Bullock, P. M., T. R. Ames, R. A. Robinson, B. Greig, M. A. Mellencamp, and J. S. Dumler. 2000. *Ehrlichia equi* infection of horses from Minnesota and Wisconsin: detection of seroconversion and acute disease investigation. J. Vet. Intern. Med. 14:252-257.

CDC. 2000. Human ehrlichiosis in the United States: Epidemiology. http://www.cdc.gov/ncidod/dvrd/ehrlihia/Epidemiology/Epidemiology.htm.

Chae, J. S., J. E. Foley, J. S. Dumler, and J. E. Madigan. 2000. Comparison of the nucleotide sequences of 16S rRNA, 444 Ep-ank, and groESL heat shock operon genes in naturally occurring *Ehrlichia equi* and human granulocytic ehrlichiosis agent isolates from Northern California. J. Clin. Microbiol. 38:1364-1369.

Chen, S.-M., J. Dumler, J. Bakken, and D. Walker. 1994. Identification of a granulocytotropic *Ehrlichia* species as the etiologic agent of human disease. J. Clin. Microbiol. 32:589-595.

Daniels, T. J., R. C. Falco, I. Schwartz, S. Varde, and R. G. Robbins. 1997. Deer ticks (*Ixodes scapularis*) and the agents of Lyme disease and human granulocytic ehrlichiosis in a New York City park. Emerg. Infect. Dis. 3:353-355.

Des Vignes, F., and D. Fish. 1997. Transmission of the agent of human granulocytic ehrlichiosis by host-seeking *Ixodes scapularis* (Acarina:Ixodidae) in southern New York state. J. Med. Entomol. 34:379-382.

Dumler, J. S., A. F. Barbet, C. P. J. Bekker, G. A. Dasch, G. H. Palmer, S. C. Ray, Y. Rikhis, and F. R. Rurangirwa. 2001. Reorganization of genera in the families Rickettsiaceae and Anaplasmataceae in the order Rickettsiales: unification of some species of *Ehrlichia* with *Anaplasma*, *Cowdria* with *Ehrlichia* and *Ehrlichia* with *Neorickettsia*, descriptions of six new species combinations and designation of *Ehrlichia equi* and ‘HGE agent’ as subjective synonyms of *Ehrlichia phagocytophila*. Int. J. System. Evol. Microbiol. 51:2145-2165.

Dumler, J. S., E. R. Trigiani, J. S. Bakken, M. E. Aguero-Rosenfeld, and G. P. Wormser. 2000. Serum cytokine responses during acute human granulocytic ehrlichiosis. Clin. Diagnos. Lab. Immunol. 7:6-8.

Foley, J. 2000. Human ehrlichiosis: a review of clinical disease and epidemiology for the physician. Infect. Dis. Clin. Prac. 9:93-98.

Foley, J., J. Barlough, R. Kimsey, J. Madigan, E. DeRock, and A. Poland. 1998. *Ehrlichia* spp. in cervids from California. J. Wildl. Dis. 34:731-737.

Foley, J., L. Crawford-Miksza, J. Dumler, C. Glaser, J.-S. Chae, E. Yeh, D. Schurr, and J. Madigan. 1999a. Two cases of human granulocytic ehrlichiosis in northern California. Clin. Infect. Dis. 29:388-392.

Foley, J., P. Foley, M. Jecker, P. Swift, and J. Madigan. 1999b. Infection with granulocytic ehrlichia and infestation with the tick vector, *Ixodes pacificus*, in California mountains lions (*Puma concolor*). J. Wildl. Dis. 35:703-709.

Foley, J. E., P. Foley, and J. E. Madigan. 2001. The distribution of granulocytic ehrlichia seroreactive dogs in California. Am. J. Vet. Res. 62:1599-1605.

Foley, J. E., V. L. Kramer, and D. Weber. 2002. Experimental ehrlichiosis in dusky footed woodrats (*Neotoma fuscipes*). J. Wildl. Dis. 38:194-198.

Furman, D. P., and E. C. Loomis. 1984. The ticks of California (Acari: Ixodida). Bulletin of the California Insect Survey, Vol. 25. University of California Press, Berkeley, CA.

Goldman, E. E., E. B. Breitschwerdt, C. B. Grindem, B. C. Hegarty, J. J. Walls, and J. S. Dumler. 1998. Granulocytic ehrlichiosis in dogs from North Carolina and Virginia. J. Vet. Inter. Med. 12:61-70.

Goodman, J. L., C. Nelson, B. Vitale, J. E. Madigan, J. S. Dumler, T. J. Kurtti, and U. G. Munderloh. 1996. Direct cultivation of the causative agent of human granulocytic ehrlichiosis. N. Engl. J. Med. 334:209-215.

Greig, B., K. M. Asanovich, P. J. Armstrong, and J. S. Dumler. 1996. Geographic, clinical, serologic, and molecular evidence of granulocytic ehrlichiosis, a likely zoonotic disease, in Minnesota and Wisconsin dogs. J. Clin. Microbiol. 34:44-48.

Grible, D. 1969. Equine ehrlichiosis. J. Am. Vet. Med. Assoc. 155:462-469.

Klein, M. B., S. Hu, C. C. Chao, and J. L. Goodman. 2000. The agent of human granulocytic ehrlichiosis induces the production of myelosuppressing chemokines without induction of proinflammatory cytokines. J. Infect. Dis. 182:200-205.

Kramer, V. L., M. P. Randolph, L. T. Hui, W. E. Irwin, A. G. Gutierrez, and D. J. Vugia. 1999. Detection of the
agents of human ehrlichioses in ixodid ticks from California. Am. J. Trop. Med. Hyg. 60:62-65.

LANE, R. 1990. Seasonal activity of two human-biting ticks. Calif. Agric. 44:23-25.

LANE, R. 1994. Competence of ticks as vectors of microbial agents with an emphasis on *Borrelia burgdorferi*. Pp. 45-67 in: D. Sonenshine and T. Mather (Eds.), Ecological Dynamics of Tick-Borne Zoonoses. Oxford University Press, New York.

LANE, R. S., J. E. FOLEY, L. EISEN, E. T. LENNETTE, and M. A. PEOT. 2001. Acanthropic risk of exposure to emerging tick-borne bacterial pathogens in a semi-rural community in Northern California. J. Vector-borne and Zoonotic. Dis. 1: 197-210.

LEWIS, D. 1979. The detection of rickettsia-like microorganisms within the ovaries of female *Ixodes ricinus* ticks. Zeitschrift für Parasitenkunde 59:295-298.

LEWIS, G., D. HUXSOLL, M. RISTIC, and A. JOHNSON. 1975. Experimentally induced infection of dogs, cats, and nonhuman primates with *Ehrlichia equi*, etiologic agent of equine ehrlichiosis. Am. J. Vet. Res. 36:85-88.

MACLEOD, J., and W. GORDON. 1933. Studies in tick-borne fever of sheep. I. Transmission by the tick, *Ixodes ricinus*, with a description of the disease produced. Parasitol. 25: 273-285.

MADEWELL, B., and D. GRIBBLE. 1982. Infection in two dogs with an agent resembling *Ehrlichia equi*. J. Am. Vet. Med. Assoc. 180:512-514.

MADIGAN, J. 1993. Equine ehrlichiosis. Pp. 423-428 in: Veterinary Clinics of North America: Equine Practice 9.

MADIGAN, J., J. BARLOUGH, J. DUMLER, N. SCHANKMAN, and E. DE RoCK. 1996. Equine granulocytic ehrlichiosis in Connecticut caused by an agent resembling the human granulocytic ehrlichia. J. Clin. Microbiol. 34:434-435.

MADIGAN, J. E., and D. GRIBBLE. 1987. Equine ehrlichiosis in northern California: 49 cases (1968-1981). J. Am. Vet. Med. Assoc. 190:445-448.

MADIGAN, J., A. HIETALA, and S. CHAMBERS. 1990. Seroepidemiologic survey of antibodies to *Ehrlichia equi* in horses in northern California. J. Am. Vet. Med. Assoc. 196: 1962-1964.

MAGNARELLI, L., J. IIDO, K. ANDERSON, J. MADIGAN, J. DUMLER, and E. FIKKIRG. 1997. Antibodies to *Ehrlichia equi* in dogs from the northeastern United States. J. Am. Vet. Med. Assoc. 211:1134-1137.

MAGNARELLI, L. A., J. W. IIDO, K. C. STAFFORD 3rd, and E. FIKKIRG. 1999a. Infections of granulocytic ehrlichiae and *Borrelia burgdorferi* in white-tailed deer in Connecticut. J. Wildl. Dis. 35:266-274.

MAGNARELLI, L. A., K. C. STAFFORD 3rd, T. N. MATHER, M. T. YEH, K. D. HORN, and J. S. DUMLER. 1995. Hemocytic rickettsia-like organisms in ticks: serologic reactivity with antiserum to Ehrlichiae and detection of DNA of agent of human granulocytic ehrlichiosis by PCR. J. Clin. Microbiol. 33:2710-2714.

MAGNARELLI, L. A., A. VAN ANDEL, J. IIDO, R. HEIMER, and E. FIKKIRG. 1999b. Serologic testing of horses for granulocytic ehrlichiosis, using indirect fluorescent antibody staining and immunoblot analysis. Am. J. Vet. Res. 60:631-635.

MASSUNG, R. F., K. SLATER, J. H. OWENS, W. L. NICHOLSON, T. N. MATHER, V. B. SOLBERG, and J. G. OLSON. 1998. Nested PCR assay for detection of granulocytic ehrlichiae. J. Clin. Microbiol. 36:1090-1095.

MOTT, J., R. E. BARNEWALL, and Y. RIKHISSA. 1999. Human granulocytic ehrlichiosis agent and *Ehrlichia chaffeensis* reside in different cytoplasmic compartments in HL-60 cells. Infect. Immun. 67:1368-1378.

MUNDERLOH, U., and T. KURTZL. 1995. Cellular and molecular interrelationships between ticks and prokaryotic tick-borne pathogens. Ann. Rev. Entomol. 40:221-243.

NICHOLSON, W. 1998. Epidemiology of human granulocytic ehrlichiosis, with special reference to the role of wild rodents and ixodid ticks as natural hosts of *Ehrlichia phagocytophilia* sensu lato. Ph.D. dissert., Johns Hopkins University, Baltimore, MD.

NICHOLSON, W. L., M. B. CASTRO, V. L. KRAMER, J. W. SUMNER, and J. E. CHILDS. 1999. Dusky-footed wood rats (*Neotoma fuscipes*) as reservoirs of granulocytic *Ehrlichiae* (Rickettsiales: Ehrlichiae) in northern California. J. Clin. Microbiol. 37:3323-3327.

NICHOLSON, W. L., S. MUIR, J. W. SUMNER, and J. E. CHILDS. 1998. Serologic evidence of infection with *Ehrlichia* sp in wild rodents (Muridae: Sigmodontinae) in the United States. J. Clin. Microbiol. 36:695-700.

PANCHOLI, P., C. P. KOLBERT, P. D. MITCHELL, K. D. REED, J. S. DUMLER, J. S. BAKKEN, S. R. TELFORD, and D. H. PERSING. 1995. *Ixodes dammini* as a potential vector of human granulocytic ehrlichiosis. J. Infect. Dis. 172:1007-1012.

PETROVEC, M., S. L. FURLAN, T. A. ZUPANC, F. STRLE, P. BROUQUI, V. ROUX, and J. S. DUMLER. 1997. Human disease in Europe caused by a granulocytic *Ehrlichia* species. J. Clin. Microbiol. 35:1556-1559.

POPOV, V. L., V. C. HAN, S. M. CHEN, J. S. DUMLER, H. M. FENG, T. G. ANDREASIS, R. B. TESH, and D. H. WALKER. 1998. Ultrastructural differentiation of the genogroups in the genus *Ehrlichia*. J. Clin. Microbiol. 47:235-251.

PUSTERLA, N., C.-C. CHANG, B. CHOMEL, J.-S. CHAE, J. FOLEY, and J. MADIGAN. 2000. Serologic and molecular evidence of *Ehrlichia* spp in coyotes in California. J. Wild. Dis. 36: 494-499.

REUBEL, G., R. KIMSEY, J. BARLOUGH, and J. MADIGAN. 1998. Experimental transmission of *Ehrlichia equi* to horses through naturally infected ticks (*Ixodes pacificus*) from northern California. J. Clin. Microbiol. 36:2131-2134.

RICHTER, P. J., R. R. KIMSEY, J. E. MADIGAN, J. E. BARLOUGH, J. S. DUMLER, and D. L. BROOKS. 1996. *Ixodes pacificus* (Acarini: Ixodidae) as a vector of *Ehrlichia equi* (Rickettsiales: Ehrlichiae). J. Med. Entomol. 33:1-5.

RODGEERS, S. J., R. J. MORTON, and C. A. BALDWIN. 1989. A serological survey of *Ehrlichia canis*, *Ehrlichia equi*, *Rickettsia rickettsii*, and *Borrelia burgdorferi* in dogs in Oklahoma. J. Vet. Diag. Invest. 1:154-159.

STAFFORD, K. C., 3rd, R. F. MASSUNG, L. A. MAGNARELLI, J. W. IIDO, and J. F. ANDERSON. 1999. Infection with agents of human granulocytic ehrlichiosis, Lyme disease, and babesiosis in wild white-footed mice (*Peromyscus leucopus*) in Connecticut. J. Clin. Microbiol. 37:2887-2892.

TELFORD, S. R., J. E. DAWSON, P. KATAVOLOS, C. K. WARNER, C. P. KOLBERT, and D. H. PERSING. 1996. Perpetuation of the agent of human granulocytic ehrlichiosis in a deer tick-rodent cycle. Proc. Nat. Acad. Sci. USA 93:6209-6214.

TZYZZER, E. 1938. *Cytococcus microti*, n.g., n.sp., a parasite developing in granulocytes and infective for small rodents. Parasitol. 30:242-257.
Prevalence of tick-borne pathogens in *Ixodes scapularis* in a rural New Jersey County. Emerg. Infect. Dis. 4:97-99.

Vredenoo, L. K., P. J. Richter, Jr., J. E. Madigan, and R. B. Kimsey. 1999. Association of *Ixodes pacificus* (Acari: Ixodidae) with the spatial and temporal distribution of equine granulocytic ehrlichiosis in California. J. Med. Entomol. 36:551-561.

Walker, D., and S. Dumler. 1995. Emergence of the ehrlichioses as human health problems. Emerg. Infect. Dis. 2:18-29.

Walks, J., B. Greig, D. Neitzel, and J. Dumler. 1997. Natural infection of small mammal species in Minnesota with the agent of human granulocytic ehrlichiosis. J. Clin. Microbiol. 35:853-855.

Webster, P., J. W. Ido, L. M. Chicoine, and E. Fikrig. 1998. The agent of human granulocytic ehrlichiosis resides in an endosomal compartment. J. Clin. Investig. 101:1932-1941.

Westrom, D., R. Lane, and J. Anderson. 1985. *Ixodes pacificus* (Acari: Ixodidae): population dynamics and distribution on Columbian black-tailed deer (*Odocoileus hemionus columbianus*). J. Med. Entomol. 22:507-511.

Wikel, S. K. 1999. Tick modulation of host immunity: an important factor in pathogen transmission. Int. J. Parasitol. 29:851-859.

Zeidner, N. S., T. R. Burkot, R. Massung, W. L. Nicholson, M. C. Dolan, J. S. Rutherford, B. J. Biggerstaff, and G. O. Maupin. 2000. Transmission of the agent of human granulocytic ehrlichiosis by *Ixodes spinipalpis* ticks: evidence of an enzootic cycle of dual infection with *Borrelia burgdorferi* in Northern Colorado. J. Infect. Dis. 182:616-619.