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Lyme Borreliosis: is there a preexisting (natural) variation in antimicrobial susceptibility among *Borrelia burgdorferi* strains?

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ABSTRACT

The development of antibiotics changed the world of medicine and has saved countless human and animal lives. Bacterial resistance/tolerance to antibiotics have spread silently across the world and has emerged as a major public health concern. The recent emergence of pan-resistant bacteria can overcome virtually any antibiotic and poses a major problem for their successful control. Selection for antibiotic resistance may take place where an antibiotic is present: in the skin, gut, and other tissues of humans and animals and in the environment. *Borrelia burgdorferi*, the etiological agents of Lyme borreliosis, evades host immunity and establishes persistent infections in its mammalian hosts. The persistent infection poses a challenge to the effective antibiotic treatment, as demonstrated in various animal models. An increasingly heterogeneous sub-population of replicatively attenuated spirochetes arises following treatment, and these persistent antimicrobial tolerant/resistant spirochetes are non-cultivable. The non-cultivable spirochetes resurge in multiple tissues at 12 months after treatment, with *B. burgdorferi*-specific DNA copy levels nearly equivalent to those found in shame-treated experimental animals. These attenuated spirochetes remain viable, but divide slowly, thereby being tolerant to antibiotics. Despite the continued non-cultivable state, RNA transcription of multiple *B. burgdorferi* genes was detected in host tissues, spirochetes were acquired by xenodiagnostic ticks, and spirochetal forms could be visualized within ticks and mouse tissues. A number of host cytokines were up- or down-regulated in tissues of both shame- and antibiotic-treated mice in the absence of histopathology, indicating a lack of host response to the presence of antimicrobial tolerant/resistant spirochetes.

KEYWORDS: *Borrelia burgdorferi*; antibiotics, persistence; antimicrobial resistance; antimicrobial tolerance; ticks; small mammals

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INTRODUCTION

Lyme disease, or Lyme borreliosis, was first described in 1977 as a distinctive entity in a cluster of children from Lyme, Connecticut, U.S. These children had symptoms resembling juvenile rheumatoid arthritis, a disease that does not cluster and is rare in children [1]. Based upon similarities with recognized human clinical syndromes in Europe that were of unknown etiology, but associated with the bite of *Ixodes ricinus* ticks, the causative agent was isolated from North

American *Ixodes scapularis* ticks in 1982 [2], and subsequently named *Borrelia burgdorferi* [3, 4]. Once the connection was made between vector, agent, and the human disease, Lyme borreliosis has been diagnosed throughout the world, but its significance is greatest in North America and Europe [5-10]. Since its discovery, the importance of Lyme borreliosis has led to evolution of all aspects of bacterial pathogenesis research.

The association of Lyme disease in humans has been demonstrated with *B. burgdorferi* sensu stricto (s.s.), *B. afzelii*, and *B. garinii*, and possibly with *B. valaisiana*. *B. burgdorferi* s.s., *B. afzelii*, and *B. garinii* have been associated with Lyme disease in livestock [11-13]. *B. burgdorferi* belongs to a guild of pathogens, including Ehrlichia, Babesia, and tick-borne encephalitis viruses that are maintained within the same vector-reservoir niches [14]. Thus, co-infection with one or more of these agents can occur and may be responsible for "para-Lyme disease" syndromes as these other agents have a wide host range.

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Borreliae are unique among the pathogenic spirochetes by requiring obligate blood-feeding arthropods for their transmission and maintenance in susceptible vertebrate host populations. With one exception, ticks transmit all borreliae and nearly all species are maintained in enzootic foci with humans being only accidental victims to infection. The wide geographic distribution and the broad host range of both the vector and the bacterium provide ample opportunity for wild mammal species to be infected with *B. burgdorferi*. However, most of what is known about Lyme borreliosis is based upon human clinical studies, and experimental studies in laboratory rodents. The amount of well-documented information on Lyme borreliosis in wild mammals is quite limited, even though wild rodents are considered as the main reservoir host for *B. burgdorferi*.

ETIOLOGY

Borrelia burgdorferi was first described as a gram-negative treponema-like organism with irregular coils, 10 to 30 nm in length and 0.2 to 0.3 nm in diameter, with outer membrane and periplasmic flagella [4, 15]. For culture in vitro, this microaerophilic slow growing organism requires a complex liquid medium, and an optimal temperature of 33 to 35°C [16]. Based on 16S ribosomal DNA gene sequences, the Genus *Borrelia* belongs to the Order *Spirochaetales*, family *Spirochetaceae* along with other genera, including *Spirochaeta*, *Cristispira*, *Treponema* and *Brachyspira* (formerly *Serpulina*). It was first believed that *B. burgdorferi* was the only bacterium that could cause Lyme disease, but differences in morphology among isolates from diverse geographic locations suggested that additional spirochetes may be involved in the etiology of Lyme disease [17].

A major effort has been undertaken to analyze the phenotypic and genotypic diversity of *B. burgdorferi* isolates from around the world, using PCR techniques, targeting 16S and 23S ribosomal DNA, *flagellin*, *OspA*, and *bdr* genes, as well as intergenic spacers. It is now apparent that *B. burgdorferi* is genetically diverse, and belongs to a *B. burgdorferi* sensu lato genospecies complex composed of several different species including: *B. burgdorferi* s.s., present in the USA and Europe (but not in Euroasia and Asia); *B. afzelii*, *B. garinii*, *B. valaisiana*, and *B. lusitaniae* in Euroasia; *B. japonica*, *B. turdae*, and *B. tanukii* in Japan; and *B. bissettii* and *B. andersoni* in the U.S. [7, 18, 19]. Evolutionary changes: mutation, genetic drift, migration, and natural selection created macro evolutionary divergence of species. The prevailing data suggest that *B. burgdorferi* s.l. was once a wide-ranging species in the Northern Hemisphere that rapidly separated into the species present today [19].

Lyme disease *Borrelia* has developed an unusual life-style in that they alternate between vertebrate and arthropod hosts. In addition, they belong to a group of organisms that produce no known toxins yet are capable of invading virtually any mammalian tissue and causing infection and disease manifestations for months to years. *Borrelias* are host-dependent, tick-transmitted, invasive, non-toxicogenic, persistent pathogens that cause disease in humans and other mammals primarily through the induction of inflammatory reactions. During transmission from the infected tick, dissemination within infected host, and acquisition by a tick-vector, the bacteria undergo dramatic changes in gene expression, resulting in adaptation to the host environment [20].

EPIZOOTIOLOGY

B. burgdorferi s.l. is spread by ticks in the *Ixodes ricinus* species complex [21]. Ticks complete their two-year life cycle in four developmental stages: eggs, larva, nymph, and adult. Female adult ticks lay eggs in the spring. Larvae emerge from eggs in summer and seek a host, usually small rodents (mice, squirrels) and birds, which are common natural hosts of *B. burgdorferi*. Each larva obtains a single blood meal then drops off and molts into the nymphal stage. The nymphal stage overwinters, and seeks a host (a variety of birds, reptiles and mammals, including large animals) the following spring or early summer. After a single blood meal, the nymph drops off and molts an adult. Adult ticks are not important for maintaining *B. burgdorferi* in the wild, as they typically feed on incompetent reservoir hosts such as deer or livestock, but females serve a role in the transmission of the pathogen to humans (Figure 1). While *B. burgdorferi* is transmitted transtadially within individual ticks, the pathogen is rarely, if ever, transmitted transovarially [22].

Although all three stages can feed on humans, nymphs are responsible for the vast majority of spirochete transmission to humans [23], but adult *I. scapularis*, *I. ricinus*, and *I. persulcatus* ticks seek and parasitize large mammals, including deer or livestock, and are considered to be the most common vector for Lyme disease in large animals [24-26]. Clinical cases of Lyme borreliosis in large animals could therefore be expected in localities where these *Ixodes* ticks are common. *B. burgdorferi* and its vector ticks tend to be non-selective in their host range, as *B. burgdorferi* has been isolated from a wide variety of birds and mammals [27]. Many hosts harbor subclinical infections. For example, in hyper-endemic areas such as New York and Connecticut, a high percentage of dogs are seropositive (and probably infected), but only a small fraction manifest clinical signs [12].

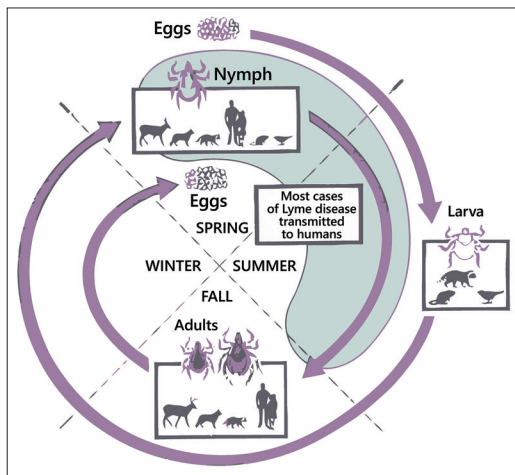


FIGURE 1. The enzootic cycle of *B. burgdorferi*. *Ixodes* spp. ticks undergo a three life cycle – larva, nymph and adult – with one blood meal per stage. Larval ticks feed on many different animals (mice, squirrel, birds), so they acquire *B. burgdorferi* from infected reservoir animals. There is no transovarial transmission. After molt nymphs can transmit spirochetes to a competent reservoir host (small mammals). Adult ticks are not important for maintenance of *B. burgdorferi* in the wild, as they feed on large animals such as deer, which are incompetent hosts for *B. burgdorferi*. However, deer are important for maintenance of the tick population. Although all three stages can feed on humans, nymphs are responsible for the vast majority of spirochetes transmission to humans [22].

Among a large number of hard tick species, *B. burgdorferi* has been primarily detected in *Ixodes ricinus*, which is prevalent in Europe, *I. persulcatus*, which is prevalent in Eastern Europe and Asia, and *I. scapularis* and *I. pacificus* in Northern America [23, 28, 29].

Lyme borreliosis shows strong spatial clustering, geographically distributed in temperate regions of the northern hemispheres. This range does not extend beyond northern Africa at its most southern extreme [27]. In the U.S. Lyme borreliosis is mainly reported from the eastern part of the country, the upper Midwest, and occasionally from the West Coast. Nevertheless, migratory birds, particularly seabirds, contribute to the opportunity for *B. burgdorferi* to expand its geographic distribution, with documentation of *Ixodes* sp. ticks, and *B. burgdorferi* s.l. DNA within some of them, as far south as the Falkland Islands, Crozet Islands, and off-shore islands of New Zealand [30]. Lyme borreliosis is emerging across much of the northern hemisphere, causing considerable morbidity and in some cases mortality in humans, domestic animals, and occasionally wildlife. It is the most frequently diagnosed tick-borne disease in the United States. According to the Centers for Disease Control and Prevention (CDC) there were over 240,000 reported cases of Lyme borreliosis in the United States from 1992-2006 [31]. However, the CDC estimates there are greater than 300,000 human cases of Lyme borreliosis annually (<http://www.cdc.gov/lyme/stats/humanCases.html>).

PATHOGENESIS

Transmission by the vector (nymphal or adult ticks) to the host is a complex three-way interaction between the tick, the host, and the pathogen. Hosts mount local inflammatory, hemostatic and immune responses to the feeding tick, while tick saliva contains substances that counter the host response, thereby facilitating a successful blood meal and transmission of the pathogens [32]. After tick attachment, *B. burgdorferi* spirochetes undergo striking variations in the expression of antigens, and migrate from the tick midgut to its salivary glands [20, 33-35]. After being transmitted, spirochetes stay in the skin at the attachment site for several days, then disseminate throughout host [36-38]. As a result of spirochete multiplication at the tick attachment site, the host reacts with a local rash (erythema migrans), generally weeks after tick detachment. The rash is observed in the majority of human cases [39-42].

Following local replication in the skin, spirochetes disseminate widely to multiple organs. Clinical signs of illness are generally most apparent during the early stages of disseminated infection, when spirochetes are believed to elaborate pro-inflammatory lipoproteins that appear to facilitate the process of dissemination through host tissues. Despite the highly immunogenic nature of these lipoproteins, spirochetes very effectively evade host immune clearance by yet to be understood mechanisms [43]. Whatever the mechanism, it is clear that spirochetes undergo dramatic shifts in protein expression. For example, outer surface protein A (OspA), is a highly immunogenic lipoprotein that is expressed in the midgut of flat ticks, but is rapidly down-regulated upon onset of feeding, and is minimally expressed in the host. In contrast, OspC is up regulated under similar circumstances [34, 44-46]. Up- and down-regulation have also been documented for several other lipoproteins, some of which are expressed exclusively in vivo, but their role is still unclear [20, 43, 47]. Other possible explanations of immune evasion by *B. burgdorferi* spirochetes have been proposed, including intracellular localization [48, 49], formation of cystic-like forms found in vivo [50], and in vitro [51, 52], existence of complement-resistant strains that regulate and control complement activation [53], and a biofilm formation [54]. Once spirochetes have disseminated, humans develop clinical signs of Lyme disease, including fever, lethargy, weight loss, swollen joints, uveitis, and sometimes encephalitis. The most common clinical feature of late-stage *B. burgdorferi* infection is arthritis, which usually begins months after tick bite [55]. Lyme borreliosis uncommonly affects the heart. Because of the rarity of this diagnosis and the frequent absence of other concurrent clinical manifestations of early infection, consideration of Lyme carditis demands a high level of suspicion when patients in

endemic areas come to attention with cardiovascular symptoms and evidence of higher-order heart block [56].

The mechanisms by which *B. burgdorferi* spirochetes cause disease in infected hosts are being studied in animal models. It is suspected that the approximately 150 lipoproteins that are encoded by the *B. burgdorferi* genome play an important role in not only disease pathogenesis, but also host immunity. Differential expressions of pro-inflammatory lipoproteins, of which the majority are outer surface proteins, in various tissues and at different times during persistent infection appear to be critical determinants of disease [57, 58]. The genome has 12 linear and 9 circular plasmids, and loss of plasmids has been correlated with decreased infectivity and pathogenicity [59-65].

Persistence

A basic feature of Lyme borreliosis (without antibiotics) is that persistent infection is the rule, not the norm. This occurs in *B. burgdorferi*'s many reservoir hosts, and has been proven experimentally in *Peromyscus* mice [66], laboratory mice [67], rats [68], hamsters [69], gerbils [70], guinea pigs [71], dogs [72], and non-human primates [73]. Humans appear to be no different, as there are a number of documented case reports of persistent infection based on culture [74-80] and PCR [81-85].

B. burgdorferi has evolved to persist in immunologically competent hosts as a survival strategy for maintaining its natural host-vector life cycle. Natural reservoir hosts and small laboratory animals are generally rodents. In such hosts, infection is generalized and persistent, including in the skin, wherein spirochetes can most efficiently interface with the vector tick. Both in vivo animal model studies and in vitro studies have shown that *B. burgdorferi* spirochetes utilize an array of adhesins that engage virtually every component of the extracellular matrix to facilitate their dissemination [86], and sequester within collagen as their preferred site of persistence [87-89].

Dissemination is also facilitated by bacteremia during early infection, which is generally cleared during the immune persistent phase of infection, and intermittent thereafter. Because humans are much larger, they experience localized infections, as evidenced by erythema migrans, and sometimes disseminated, but randomly multifocal infection through bacteremia, which may result in pauciarticular arthritis, secondary erythema migrans, carditis, peripheral neuropathy, meningitis, and other objective clinical signs. It should be emphasized that Lyme disease in untreated humans (and experimental animals) is ephemeral, with "spontaneous" resolution (without antibiotic treatment) of erythema migrans, carditis, arthritis, and other signs [90, 91]. Studies in animal models have shown that resolution of arthritis and carditis is mediated by the acquired humoral immune response of the host. Under these conditions, anatomically defined inflammation resolves, but

infection persists [88, 92, 93]. Indeed, even during the pre-immune phase of infection, spirochetes populate many tissues with no evidence of inflammation (thus inflammation does not necessarily correlate with spirochete presence).

CONTROL

Antibiotics such as penicillin, amoxicillin, ceftriaxone, doxycycline, and erythromycin, as the most commonly prescribed antibiotics for the treatment of human Lyme borreliosis, have shown to be effective against *B. burgdorferi* [55, 94]. Early treatment is desirable, and most effective when treatment is given during the early stages of infection [95]. Chronic cases require prolonged treatment, and treatment success is often less effective [39, 96-98].

There is widespread consensus among the mainstream medical community that relatively short-term courses of antibiotics can eliminate objective signs of Lyme borreliosis in patients, with the assumption that patients have been cured of infection. This has been articulated in the Infectious Diseases Society of America (IDSA) Guidelines in 2006 [99] and reaffirmed by an expert Lyme disease review panel in 2010 [100]. The IDSA Guidelines are in agreement with position statements of other medical and scientific organizations, including the European Federation of Neurological Societies, The European Union of Concerted Action on Lyme Borreliosis, the American Academy of Neurology, the Canadian Public Health Network, the German Society for Hygiene and Microbiology, several expert panels in various different countries, the American Lyme Disease Foundation, the CDC and NIH. An Ad Hoc International Lyme Disease Group has also affirmed this position [97, 101].

This consensus is based upon clinically objective criteria, in keeping with sound medical practice. However, it is well established that patients with objective criteria of Lyme borreliosis may also have widely varied and subjective manifestations that do not necessarily fit objective clinical criteria [90, 102, 103]. There is agreement that when objective clinical signs are persistent, a rare patient may have chronic Lyme disease, and when objective clinical signs return in a treated patient, a rare patient may have recurrent Lyme disease. Under both circumstances, repeated antibiotic treatment is advised. A principal area of continuing but unresolved debate involves patients who experience disabling subjective symptoms following completion of appropriate antibiotic therapy. This has been recognized by the term "post-Lyme disease syndrome" (PLDS). IDSA Guidelines state that there is "no well-accepted definition of the PLDS", and that "there is no convincing biologic evidence for the existence of systemic chronic *B. burgdorferi* infection among patients after receipt of recommended treatment regimens for Lyme disease." [99].

population, and their relative abundance rises (reaching 1% at the late-exponential phase of growth [135, 136, 138, 139]. Persisters are non-growing dormant cells [138, 140], which explains their tolerance to bactericidal antibiotics that depend on the presence of active targets for killing the cell [139]. All of the pathogens examined so far form persisters [137, 141]. Recently, significant progress was made in the study of persisters, but the importance of the persisters has not been recognized appropriately [142] and the mechanisms of their formation are largely unknown. Persisters also have an important role in the development of conventional antibiotic-resistant mutants. Persisters are killed only slowly, if at all, and resume growth when antibiotic concentrations fall [143].

Numerous studies have shown differences between antimicrobial resistance and antimicrobial persister tolerance [137, 138, 144]. These two traits are independent, and persisters represent a small subpopulation of cells that spontaneously enter a dormant, non-dividing state. Treatment with antimicrobial agents of a bacterial population results in death of regular cells, whereas persisters survive. Antimicrobial agents require active targets to be effective, which explains persister tolerance (Figure 3). In contrast, antimicrobial resistance prevents antimicrobial agents from binding to their targets [136]. An important characteristic of resistance is the ability of bacteria to continue to grow at elevated concentrations of antimicrobial agents [118, 136]. Bacterial resistance to antimicrobial agents can be defined as: (a) clinical resistance, (b) microbiological resistance, (c) inherent resistance, (d) acquired resistance, (e) cross-resistance, (f) co-resistance, and (g) multiple resistance [107, 118, 145].

ANTIMICROBIAL RESISTANCE/ TOLERANCE OF *B. BURGDORFERI*

In a recent critical review of studies involving antibiotic treatment of *B. burgdorferi*-infected animal models, it was stated, “in the treatment of other infections it is probably unrealistic to expect that antimicrobial therapy per se will eliminate every single microorganism from an infected host, and moreover, such an action would rarely if ever be required for a successful outcome...the role of antimicrobial therapy in vivo can be thought of in terms of “tipping the balance” in favor of the host’s own defenses against a particular pathogen” [146]. This may be true for “other infections” but when treating for *B. burgdorferi*, which persists in fully immunocompetent hosts as the rule of its natural behavior, “tipping the balance” in favor of the host may be a challenge.

Several reports, including those generated in our laboratory, have provided evidence of *B. burgdorferi* presence in collagenous tissues, following antimicrobial therapy during chronic infection in animals [63, 87, 147-151], and in

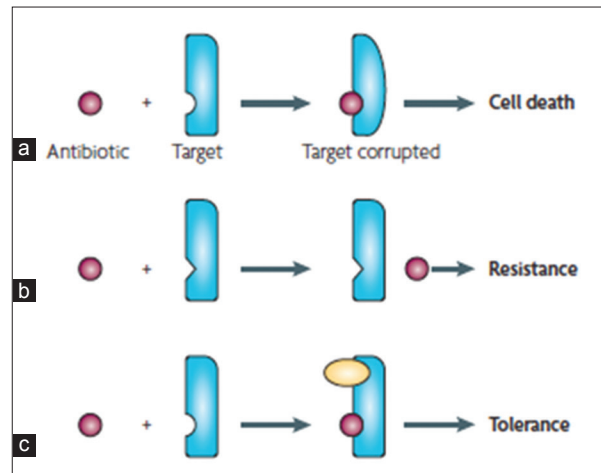


FIGURE 3. Resistance versus tolerance to antimicrobial agents. a) The antimicrobial agent (purple) binds to the target (blue) altering its function, which causes bacterial death. b) The target of the antimicrobial agents has been altered so that it fails to bind to the agent and the cell becomes resistant to treatment with the agent. c) A different molecule (yellow) inhibits the antimicrobial target. This prevents the antimicrobial agent from corrupting its functions, resulting in tolerance [136].

humans [152-156]. One interesting finding was that uninfected ticks were able to acquire antibiotic-tolerant *B. burgdorferi* and transmit spirochetes to naïve hosts following the molt to the next stage. We have found no differences in the feeding efficacy and the numbers of acquired spirochetes between ticks that fed on antibiotic treated and saline treated mice [149]. Thus, seemingly adequate treatment with a variety of antimicrobial agents may not eliminate infection in some patients, which was confirmed in animal models. There is clear scientific evidence that a small heterogeneous subpopulation of surviving spirochetes shows tolerance to antimicrobial agents and can persist in a host for a prolonged period following therapy.

What is unique about all of these studies is that spirochetes can be detected by PCR for *B. burgdorferi*-specific DNA (BbDNA), but not by culture. In mouse studies performed in this laboratory [87, 149, 157], mice were treated with ceftriaxone, doxycycline, or tigecycline at various intervals of infection, and tissues were tested at intervals after treatment. Tissues remained BbDNA PCR-positive up to 12 months, but were consistently culture-negative. Morphologically intact spirochetes could be visualized by immunohistochemistry in tissues from treated mice; ticks could acquire morphologically intact *B. burgdorferi* and BbDNA from treated mice; ticks remained BbDNA-positive through molting into nymphs and adults; nymphs transmitted BbDNA to recipient immunocompromised mice; allografts from treated mice transplanted into recipient immunocompromised mice transferred BbDNA to recipient mice; and both tick- and transplant-inoculated mice had disseminated BbDNA. BbDNA-positive tissues were also positive for *B. burgdorferi*-specific

RNA transcription. Furthermore, quantitative PCR indicated low-levels of replication during these various stages.

The IDSA Guidelines have stated, “the significance of continued PCR positivity needs to be better understood, but this phenomenon should not necessarily be construed to indicate persistence of viable *B. burgdorferi*” [99]. The above summarized behavior of PCR-positivity, RNA transcription, BbDNA transmission, BbDNA amplification, BbDNA dissemination, and morphologically intact spirochetes in both mouse tissues and ticks strongly indicate the presence of persistent, viable, but uncultivable spirochetes.

IDSA Guidelines also state “unless proven otherwise, culture should be regarded as the gold-standard to address viability of *B. burgdorferi*” [99]. Culture may indeed be a gold standard when it is positive, but it is often not. Having worked with for over 20 years, it is apparent that not all isolates or strains can be easily cultured, and this is especially apparent during long-term infection. Thus, culture cannot be relied upon as a gold standard of viability. As noted above, our studies and those of others in mice, dogs and non-human primates have all reached similar conclusions: spirochetes are persisting, but are paradoxically non-cultivable. A very intriguing observation in the recent study was the resurgence of non-cultivable spirochetes in all assessed tissues of antimicrobial treated mice after 12 months, and the overall tissue spirochete burden reached the levels detected in sham-treated mice at the same time point (Figure 4). Despite the continued non-cultivable state, RNA transcription of multiple *B. burgdorferi* genes was detected in host tissues, *flaB* DNA was acquired by xenodiagnostic ticks, and spirochetal forms could be visualized within ticks and mouse tissues by immunofluorescence and immunohistochemistry, respectively (Figure 5). A number of host cytokines were up- or down-regulated in tissues of both saline- and antibiotic-treated mice in the absence of histopathology, indicating host response to the presence of non-cultivable, despite the lack of inflammation in tissues [149].

During the course of infection, *B. burgdorferi* proliferates and incidentally generates an increasingly heterogeneous population of replicatively attenuated spirochetes that have lost one or more small plasmids. These “attenuated” spirochetes remain viable, but because of their plasmid loss, they divide slowly, thereby being tolerant to the effects of antibiotics, as well as being non-cultivable (unpublished data). Because persistence of non-cultivable spirochetes has been shown to occur following treatment with several different classes of antibiotics, the phenomenon is likely explained by antimicrobial tolerance (in contrast to antibiotic resistance or inadequate antibiotic treatment), in which all classes of antibiotics fail to completely eliminate non-dividing or slowly dividing subpopulations of a broad array of bacteria and fungi [136, 158]. It has been known for decades that during

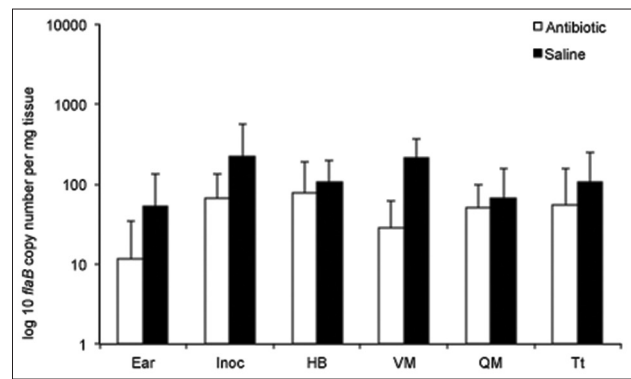


FIGURE 4. *B. burgdorferi* levels resurge in tissues at 12 months after antibiotic treatment. Copy numbers of *B. burgdorferi flab* DNA, determined by quantitative PCR, in ear, inoculation site (Inoc), heart base (HB), ventricular muscle (VM), quadriceps muscle (QM), and tibiotarsus (Tt) tissues of saline- and antibiotic-treated mice at 12 months after treatment [149].

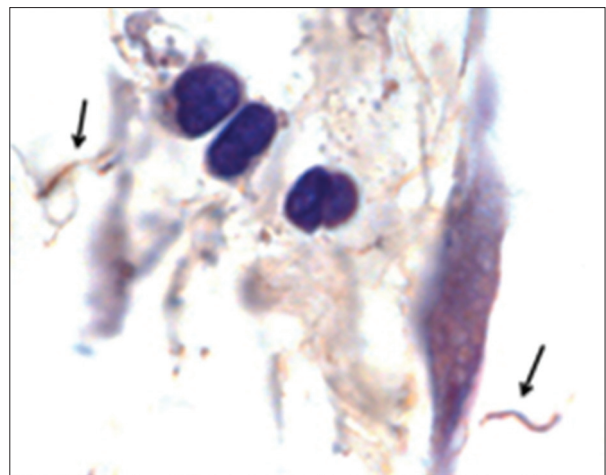


FIGURE 5. Spirochetes can be visualized within tissue of a mouse at 12 months following antibiotic treatment. Indirect immunohistochemical staining of *B. burgdorferi* spirochetes (arrows) in the heart base connective tissue [149].

in vitro passage, *B. burgdorferi* is highly prone to plasmid loss [61, 159, 160], and therefore plasmid loss is likely to also occur during the course of infection and increase over time. This may explain why treatment success in humans [99, 103] and laboratory mice [87, 157] appears to be most effective during early infection. Treatment success is inversely correlated with spirochete populations, since spirochete burdens in mouse tissues are highest during early infection [35], when antibiotics work best. The biological (in contrast to medical) significance of attenuated spirochetes is probably insignificant, in that robustly dividing-, genetically-intact spirochetes would be selectively favored upon tick acquisition, transmission, and survival in reservoir hosts. The medical significance of attenuated persisting spirochetes is another matter, and compels further investigation.

Another interesting point is the finding of antimicrobial resistant/tolerant microorganisms, resistant genes, and integrons in wild animals [115, 123, 161-168], after being exposed

to antimicrobial agents present in natural environments, most notably sewage and surface water sediments. Some such wildlife species animals are natural reservoir hosts for *B. burgdorferi*. These findings further support the concept that small mammals as natural hosts for *B. burgdorferi* could be exploited for selection of antimicrobial resistant/tolerant phenotypes. Such spirochete phenotypes could contribute to the intensity of transmission and the overall risk of Lyme borreliosis.

Based on these observations and recent evidence of persisting *B. burgdorferi* present in tissues of treated hosts during chronic infection, it will be plausible to speculate that *there is preexisting (natural) variation in antimicrobial susceptibility among bacterial strains*, which could be an alternative phenotype that offers an appreciable survival advantage within the pathogen's original population.

CONCLUSIONS

Based on the observations stated above it can be concluded that: 1) a small population of persistent spirochetes survive antimicrobial treatment, as demonstrated in various animal models. *B. burgdorferi* gDNA was readily detected in tissues of mice as late as 12 months after treatment with antimicrobial agents, even after using a new class of antibiotics, tigecycline, which has a longer half-life in mice compared to ceftriaxone. 2) Morphologically intact spirochetes were visualized by immunohistochemistry in collagen rich tissues of treated mice. Transcriptional activity of antimicrobial-tolerant persistent *B. burgdorferi* mRNA was detected for several target genes as well as the ability to replicate at low levels. Recently published data have confirmed previous findings and showed transcriptional activity of numerous genes in spirochetes that survived for 12 months after antimicrobial treatment. These results indicate viability and metabolic activity among the persisting spirochetes. 3) It has been demonstrated that spirochetes that survived antimicrobial treatment in mice could be acquired by larval ticks, passed transtadially to the nymphs, and transmitted into naïve C3H-scid mice. Multiple tissues in the mice were PCR-positive, although inflammation was not observed. 4) A possible mechanism for the reduced infectivity of residual spirochetes might be a lack of two undetected plasmids, lp25 and lp28-1, probably due to mutation of certain genes, plasmid loss or recombination events as a result of antimicrobial treatment. The results suggest that the population of spirochetes detected after antimicrobial therapy is genetically different from the infecting population. 5) The resurgence of spirochetes in all assessed tissues of antimicrobial treated mice after 12 months was observed, and the overall tissue spirochete burden reached the levels detected in sham-treated mice at the same time point. 6) It has been shown that the

antimicrobial tolerant/resistant persisters are uncultivable. These findings create an obstacle in studying the molecular mechanisms involved in persistence and properly addressing their significance in chronic Lyme borreliosis. 7) The characteristics and the role of this rare, uncultivable population are poorly understood.

DECLARATION OF INTERESTS

The author declares no competing interests.

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