

# The Taiga Tick *Ixodes Persulcatus* (Acari: Ixodidae), the Main Vector of *Borrelia Burgdorferi Sensu Lato* in Eurasia

**Igor Uspensky\***

The Alexander Silberman Institute of Life Sciences, Hebrew University of Jerusalem, Israel

\***Corresponding author:** Igor Uspensky, 16, Yustman Moshe St., Apt. 65, Jerusalem 9384208, Israel, Email: igorusp@mail.huji.ac.il; igorusp.acarina@gmail.com

**Published Date:** April 16, 2016

## ABSTRACT

The taiga tick *Ixodes persulcatus* Schulze, 1930 is considered to be one of the most important vectors of human pathogens. The tick is a temporary ectoparasite characterized by exophilic (pasture) type of host-seeking behavior and prolonged feeding (blood-sucking). The tick is a typical three-host species, i.e., all three parasitic stages of the tick feed on different hosts. Its geographic range extends as a broad belt from the Baltic Sea to the Pacific Ocean mainly through the zone of boreal coniferous (taiga) forests. The essential role of the taiga tick in transmission of the Lyme disease pathogen *Borrelia burgdorferi* s.l. was recognized in the 1980s and the following years have been characterized by efforts to clarify the importance of this species in epidemic and epizootic components of the infection. The chapter consists of two parts. The first part is dedicated to the general characteristics of this tick species, its systematic position, geographic range and biological and ecological patterns, such as seasonal activity, questing behavior, hosts, specificity of blood feeding etc. Nearly all of these data were obtained in the 1950-1980s by Russian scientists. The data accumulated during the three last decades of research into the relationships between *B. burgdorferi* and *I. persulcatus* are reviewed and discussed in the second part of this chapter. The chapter concludes with a brief discussion of directions and challenges for future research in this field.

The taiga tick *Ixodes persulcatus* was described by Schulze in 1930 and very soon thereafter this species became well known when its importance as the main vector of tick-borne encephalitis virus was revealed in the late 1930s [1,2]. Intensive and extensive studies of its biological characteristics as well as its role in epidemic and epizootic processes were carried out in the 1950-1980s by Russian scientists. In the 1980s the taiga tick was found to be a vector of human borreliosis (Lyme disease) and later its participation in the transmission of agents of human monocytic ehrlichiosis and human granulocytic anaplasmosis was also revealed [3]. Today *I. persulcatus* is considered to be one of the most important vectors of human pathogens. A special monograph dedicated to all aspects of taxonomy, biology, control and medical importance (concerning at that time only tick-borne encephalitis) of this species was published in the former USSR [4]. Various characteristics of this species were also analyzed in several reviews [3-6].

## TAXONOMIC STATUS

The taiga tick is a member of the family Ixodidae Murray, 1877, the subfamily Ixodinae Murray, 1877, the genus *Ixodes* Latreille, 1795 and the subgenus *Ixodes* (s.str.) Latreille, 1795. The subfamily Ixodinae (Prostriata group) is more ancient and more primitive morphologically and ecologically than subfamilies from Metastriata group. The origin of the subfamily Ixodinae is attributed to the Cretaceous while that of the genus *Ixodes* to the Paleogene. The subgenus *Ixodes* is considered to be the most progressive among other subgenera of the genus whereas *Ixodes persulcatus* is evolutionarily one of the youngest species originated in the late Paleogene [4,7].

It was recognized that several *Ixodes* species in the Asian part of the former USSR had been previously erroneously identified as *I. persulcatus* because of their morphological similarity. It was suggested [8] to integrate these species in a *I. persulcatus* group. Later this group was increased to incorporate up to 14 species, including species from Nearctic and Indo-Malayan faunal regions [9,10]. Such important vectors as European *I. ricinus* and North-American *I. scapularis* and *I. pacificus* also belong to this group. The most accepted name of the group is *I. ricinus*/*I. persulcatus* complex though in accordance with the International Code of Zoological Nomenclature [11] the correct name of the group should be *persulcatus* [12]\* (\*Nomination of *I. ricinus* as the leading species of the group (complex) seems to be inconsistent with established practice. Besides, this species is the type species of the subgenus *Ixodes* and additional nomination of it as the leading species of the group might create an erroneous impression that all species in the subgenus belong to this group).

## GEOGRAPHIC RANGE

The range of the taiga tick extends as a broad belt from the Baltic Sea to the Pacific Ocean mainly through the zone of boreal coniferous (taiga) forests. The northern border of the range is limited by the approximate value of the sum of temperatures for the period with the stable daily temperature above 5°C equal to 1,600°C. This roughly coincides with the southern border

of tundra and semi-tundra forests. Biotopes most suitable for *I. persulcatus* are located in mid- and southern-taiga forests whereas in the European part of the range such biotopes also exist in deciduous forests. Most often ticks exist in upland moraine and lowland glacial-lake landscapes. In the western part, the northern border of the range stretches along the latitudes of 62-63°N, in the Asian part it gradually moves southward and at the Far East the border lies at the latitudes of 52-54°N. The southern border of the range is defined by soil humidity [3,4,13].

The main part of the range of *I. persulcatus* lies on the territory of Russia. In the western part of the range the taiga tick presents in the eastern parts of Latvia and Estonia and in some areas of Lithuania; some findings of the species have been reported in Finland as well as in Belorussia, Poland and Ukraine.

Isolated populations of the taiga tick persist in mountain areas of Kazakhstan, Uzbekistan and Kirgizstan [3,4], in Mongolia, in 13 of 28 provinces of China including Tibet [14], apparently in North Korea, in northern part of South Korea [15], in Japan (Hokkaido Island but also mountain areas of Honshū and Kyūshū Islands) [16,17], and in mountain areas of Taiwan [18]. Regular findings of single *I. persulcatus* adults have been documented along the routes of bird migrations, mainly along the valleys of big Siberian rivers, even within the Arctic Circle [19-21].

In recent years, many authors have insisted that the northern border of the taiga tick range moves northwards. Regrettably, these conclusions have been made, with rare exceptions, on the basis of single tick collections on the territories where no previous surveys had been carried out. The question whether such shifts are the result of the global climate warming and have a steady tendency [22-24] or they only reflect regular fluctuations of tick abundance or they are simply the result of surveying the areas, which had not been surveyed previously, [3,25] remains to be open.

## BIOLOGICAL CHARACTERISTICS

The taiga tick *Ixodes persulcatus* is a temporary ectoparasite characterized by exophilic (pasture) type of host-seeking behavior and prolonged feeding (blood-sucking). The tick is a typical three-host species, i.e., all three parasitic stages of the tick feed on different hosts [4,7].

### Ecological Patterns

As the majority of tick species living in the temperate zone, *I. persulcatus* has a well-defined seasonality. Over the main part of the range, unfed ticks of all parasitic stages demonstrate host-seeking activity during the spring-summer season of the year. The very first adults appear when snow still lies and only thawed patches appear in well-warmed parts of tick biotopes [26]. I was attacked by such ticks on the northern slope of a mountain ridge in the Western Sayan mountains in the end of April when the air temperature was near 0°C. Not all ticks become active at once in the beginning of the activity season but they do it gradually: the main part of adult ticks become active during the first 15-30 days after the beginning of host-seeking activity but the entire period of tick appearance can continue for up to 85 days [27-30]. Apparently the appearance of unfed nymphs and larvae follows a similar pattern although this has never been tested experimentally.

It is difficult if at all possible to collect ticks of these stages by flagging or dragging as adults are collected [4], while collection of preadults on the hosts excludes their repeated findings.

The seasonal host-seeking activity of unfed adult ticks continues for 60 to 120 days but sometimes even shorter or longer depending on the meteorological conditions of a particular year [4,31,32]. In a typical case, activity accelerates rapidly to a peak in April-May with a gradual decline until the end of host-seeking activity later in the summer or even in the autumn. Sometimes people can be attacked by an adult female much later than the last tick was found by flagging. The pattern of tick activity strongly depends on meteorological conditions, so that its dynamics in a particular year can be completely unpredictable. The dynamics of host-seeking activity of nymphal and larval ticks follows, in general, that of adult ticks with some increases in preadult occurrence during the period of activity and perhaps a longer duration of activity by nymphs [4].

The activity period does not correspond to the life span of individual ticks. After hatching or molting, unfed preadults live about 14-15 months and unfed adults live about 12 months including post-molting development and diapause during hibernation when ticks do not seek hosts (see below). The life of host-seeking (questing) ticks is much shorter, from 1 day to about 75 days for unfed adults [27,33,34]. The adult ticks that become active earlier in the season live longer than those that become active later [29]; the latter begin their active life being physiologically older than the ticks which begin their activity earlier [33].

When seeking hosts, adult ticks use the so-called “ambush strategy”: unfed ticks are positioned on the vegetation scanning nearby spaces with their chemoreceptors, which are parts of Haller’s organs located on the dorsal surface of tarsus I [35,36]. They spend from several hours to several days in the questing position depending on the particular meteorological conditions. Adult ticks can sense the host stimuli from a distance of 5 to 10 m in still weather [37], and as far as 15 to 20 m from the windward direction under windy conditions [38]. They can also detect paths of regular host migrations, which explains their high concentration nearby. Questing ticks either catch onto a passing host or, sensing it from a distance, move in its direction. To maintain their water balance, ticks must regularly migrate down to the litter and soil where the temperature is lower and humidity higher. Unfed adult ticks have two peaks of activity during the day: in the morning (8-10 a.m.) and in the late afternoon (after 4 p.m.) [39,40]. Nymphal activity is maximal at dusk and the early hours of the night [41]. Cloudy weather, rain or high temperatures at nights can significantly alter this pattern. However, if a host appears close to an unfed tick, the latter becomes active and can attack the host at any time.

The capacity of *I. persulcatus* for active migrations is limited. The questing larvae usually can move up to 20 cm, nymphs up to 40-50 cm, and adults up to 1.0 m. The height of vertical movement is directly correlated with the air humidity being maximal in humid taiga forests of the Russian Far East [7,42]. Ticks also are unable to carry out long horizontal migrations; adults can migrate up to 10 m and larvae up to 1.5 m [43]. The rate of adult movement may be as high as 30 cm/min at 23°C but usually decreases with lower temperatures [42]. The taiga tick has no eyes though

it can distinguish between more and less illuminated areas, preferring the latter. Photosensitive cells were found in approximately the same area where eyes could be located [44]. The response of these photosensitive cells to light appears to be comparable to that in some species of ticks that have eyes [45].

Unfed host-seeking adults are characterized by a 1:1 sex ratio [4,30,46-48]. Only about 2% of active females are successful in finding hosts and engorgement [49-51]. The fraction of unfed larvae and nymphs that find hosts and engorge is higher because of greater number of host species and their higher abundance. It is estimated that more than 90% of larvae and more than 20 % of nymphs are successful in attaching to hosts and engorgement [49,50]. The fate of engorged ticks depends on the time of feeding. If the engorgement takes place in the first half of the activity season, larvae and nymphs molt into the next stage while females oviposit. Unfed nymphs and adults after ecdysis are able to enter behavioral diapause and overwinter. Unfed larvae emerging from eggs laid are also able to enter behavioral diapause. If the engorgement takes place in the second half of the activity season, engorged larvae and nymphs enter morphogenetic diapause and overwinter. Nymphal ticks start entering morphogenetic diapause in June whereas larval ticks do it in July [52,53]. In rare instances, engorged nymphs can survive for two winters being in diapause. Diapause is induced by declining photoperiod with an earlier beginning in more continental climate [4,54-56]. Eggs laid by engorged females are unable to overwinter and die. Thus, during the activity season there are simultaneously unfed ticks of several cohorts: those that were in behavioral and/or morphogenetic diapause and overwintered from the previous year and those that hatched (larvae) or emerged from engorged larvae or nymphs in the same year. Accordingly, adult ticks may be represented by specimens of up to 5 different cohorts.

The duration of life cycle (from eggs laid by an engorged female until the unfed adult ticks) can reach 3, 4 or 5 years (rarely 6 years) depending on the number of diapauses in a particular tick population. The maximal duration of life cycle has been observed in Siberian region and the western part of Far East while in the southern Far East or in the European part of the range this period is much shorter (sometimes only 2 years) [4,53,56,57]. The ratio between the parts of tick population developing with different duration depends on climatic conditions of particular years.

## Hosts and Feeding Specificity

The taiga tick is one of the most opportunistic (generalist) tick species, being able to use nearly 300 species of different vertebrates (about 100 species of mammals, more than 175 species of birds and a few species of reptiles) as hosts [4]. As a rule, each stage has hosts of preferential sizes: larvae feed on small mammals such as mice, voles and shrews; nymphs feed on small and medium-sized mammals such as chipmunks, squirrels, hedgehogs as well as on ground-dwelling birds; adults use as hosts medium-sized and large animals such as hares, deer, elk but also cattle and dogs. The questing height of ticks of each stage coincides with the size and location of their main hosts. Although larvae and nymphs can use the same hosts, nymphs demonstrate clear preference for medium-sized mammals and birds [49]. Apparently, the taiga tick employs

the strategy of partitioning resources (a case of classical niche partitioning [58,59]) in order to diminish interstage competition. All stages of *I. persulcatus* are active at the same time, so they should diversify their hosts (partitioning in space). In two other closely related vectors from the same group, *I. ricinus* and *I. scapularis*, the time of host-seeking activity of adults does not usually coincide with that of nymphal ticks, i.e. these species utilize partitioning in time. Perhaps, this phenomenon explains why only adult *I. persulcatus* attack humans (large animals) being more aggressive than adult *I. ricinus* [60] (nymphal *I. persulcatus* are also more aggressive towards their hosts than *I. ricinus* nymphs [61]). In this respect, *I. persulcatus* differ from *I. ricinus* and *I. scapularis*, where nymphal ticks, which seek hosts at the time of maximal human outdoor activity, are the main attackers and vectors of human pathogens. Preadult ticks can switch from their typical hosts for unusual ones under specific conditions such as depression in the abundance of small mammals [62,63] or on animal farms with a dominant host species [64].

Each parasitic stage feeds on a vertebrate host only once: the larva feeds for 3-5 days, the nymph for 3-6 days and an adult female for 6-10 days. The duration of feeding and the weight of engorged specimens strongly depend on the host species [65]. Males feed several times during their active life for 15-30 min each time. The obligatory condition for normal female engorgement is its insemination. The taiga tick females can be inseminated on the hosts as well as in nature, before finding a host. In the middle of the activity season up to 50% of unfed females collected from vegetation were inseminated [47,66,67]. Adult ticks produce an assembly pheromone which increases the probability of mating off hosts [68].

Larval and nymphal ticks increase their weight during feeding 15- to 30-fold, while engorged females are heavier than unfed ones 100- to 150-fold. The mass of an unfed larva is 0.03-0.045 mg, whereas the mass of fully engorged females reaches 250-470 mg [69]. Fully engorged females lay from 2,000 to 4,000 eggs. The minimal weight of engorgement, after which females are capable of laying single eggs, is about 20-35 mg. The heavier the engorged female becomes, the greater the ratio of the number of laid eggs/mg of the female's weight. When the female weight reaches 140-200 mg, the ratio reaches a plateau at approximately 8.5-9.5 eggs/mg [69]. The values of all of these parameters may differ between tick populations in different parts of the taiga tick range and strongly depend on the host species.

## **THE TAIGA TICK AS VECTOR OF *BORRELIA BURGDORFERI* S.L., THE CAUSATIVE AGENT OF TICK BORRELIOSIS**

Lyme disease was identified and described in the USA where the spirochete, *Borrelia burgdorferi* s.str., is the only causative agent of the disease. In Europe and Asia there is a set of closely related infections caused by several genospecies of *B. burgdorferi* s.l. At present, Lyme disease is the most common tick-borne zoonosis in temperate regions of the Northern Hemisphere. The pathogen is transmitted to humans by several species of hard ticks from the genus *Ixodes*, the taiga tick *I. persulcatus* being the main vector through its entire range in Eurasia [3,70].

## *B. burgdorferi* in infected ticks

The vector competence of *Ixodes persulcatus* for the causative agent of the disease was recognized in Russia in the middle of the 1980s [71]. Two genospecies of *Borrelia burgdorferi* s.l., which are absent in the USA, *B. garinii* and *B. afzelii*, are the most common pathogens of *I. persulcatus*, while the American genospecies, *B. burgdorferi* s.str., occurs only infrequently. *B. garinii* and *B. afzelii* are widespread over the entire range of the taiga tick [15,72,73]. The prevalence of ticks infected with *B. burgdorferi* s.l. varies by geographic areas and particular years being usually rather high.

The *Borrelia* spirochetes inhabit the gut of unfed ticks. A subset of unfed infected ticks demonstrates systemic (generalized) infection when *B. burgdorferi* penetrates into the body cavity, gonads and salivary glands. Such ticks are able to infect hosts soon after attachment [74]. It was shown that the number of *I. persulcatus* females with systemic infection positively correlates with the spirochete concentration in the tick gut [75]. The intensity of infection in physiologically older ticks is lower compared to physiologically younger specimens [76]. Intensive migration of spirochetes from the gut into salivary glands is initiated after the tick has been attached to the host for 2.5 days [3].

There is a very significant difference between *I. persulcatus* and the main vector of this pathogen in the USA and Canada, *I. scapularis*, with regard to the prevalence of ticks with systemic infection. The proportion of unfed *I. scapularis* with systemic infection was found to be much lower than that of *I. persulcatus* (2.4% and 12.9%, respectively) [77]. The small numbers of *I. scapularis* with systemic infection lead to a conclusion that attachment by this tick for less than 48 hours is not sufficient for human infection with *B. burgdorferi* [78,79]. In contrast, the taiga tick is able to infect humans within the first 24 hours after attachment [80]. The proportion of unfed *I. ricinus* with systemic infection is lower than that of *I. persulcatus* but higher than in *I. scapularis*, which leads to a higher rate of host infection during the first 24 hours after tick attachment [3,81,82]. However, even a small number of unfed ticks with systemic infection can be a source of human infection within a very short time after tick attachment. In some studies, the samples were too small to detect the ticks with systemic infection. It appears that host infection during the very first hours after tick attachment has not been studied [83].

*B. burgdorferi* spirochetes infect a number of eggs laid by engorged females but only a negligibly small number of larval ticks become infected [84,85]. (Some authors observed nearly 100% transovarial transmission by *I. persulcatus* [86], but this finding is likely attributable to methodological deficiencies). It is generally accepted that there is negligible if any transovarial transmission of *B. burgdorferi* in the main vectors from the genus *Ixodes*. Ticks mainly acquire the spirochetes during their larval or nymphal feeding on small mammals that are reservoir hosts for *B. burgdorferi*. The importance of reservoir hosts for infecting ticks is very high since they are able to preserve the spirochetes for a very long, perhaps lifelong, periods [3,87]. Larvae

and nymphs effectively transmit spirochetes to the next developmental stages (transstadial transmission) [88,89]. The infection rate of each subsequent stage with *B. burgdorferi* is higher than that of the preceding stage. An alternative route of tick infection by spirochete is the so-called co-feeding (distant) transmission, when uninfected larvae receive pathogen from infected nymphs feeding simultaneously on the same host [90,91]. Such transmission in *I. persulcatus* was found in only a single study with this species [92], while in *I. ricinus* it was demonstrated multiple times [93,94]. The significance of this route of infection is presently under discussion [87,95]. Sexual transmission by spirochetes between copulating adult partners [96] might be also of some, though probably minor, importance.

It was found that *I. persulcatus* is a more effective vector than *I. ricinus* not only because of its greater aggressiveness towards humans [60,61] but also because of a greater proportion of unfed specimens with systemic infection (see above) [3,70]. The suggestion of the positive influence of *I. persulcatus* on the infection rate of *I. ricinus* in their sympatry zones [97] was found to be incorrect [87,98,99].

### Influence of *B. burgdorferi* Infection on the Tick Hosts

It was postulated [100] that although the relationships of *Borrelia* with ixodid ticks are evolutionary younger and more primitive than its relationships with argasid ticks, the symbiotic interrelations *Borrelia*/ixodid ticks are well balanced. At the same time, it is widely accepted that microbial pathogens harbored by the tick vectors are parasites and as such are expected to have some negative effect on the ticks [101-103]. Only a small number of studies were carried out to elucidate any evidence of parasitic influence of *Borrelia burgdorferi* on the tick hosts.

In one study [104] no differences in tick development were found between *I. persulcatus* specimens infected and uninfected with *B. burgdorferi*. One study [105] found lower motor activity in infected ticks as compared to uninfected ones, although a more comprehensive study [106] of infected *I. persulcatus* demonstrated a greater questing activity than that of uninfected ticks, and this activity was positively correlated with the intensity of tick infection. It was also reported that there is a trend towards an increase in the longevity of infected adult *I. persulcatus* (and of *I. ricinus* too) [34]. The infection rate of adult ticks that were able to climb up the experimental rod to its maximal height of 30 cm was twice as high as that of the ticks that could not reach this height [107]. The above abnormalities in the behavior of infected ticks can be considered an example of the “parasite manipulation of the host” [108].

### Coinfection of *B. burgdorferi*-infected ticks with other pathogens

Until recently, the pathogen-vector relationships of the taiga tick *Ixodes persulcatus* were studied only with regard to the tick-borne encephalitis virus (TBEV). The discovery of *B. burgdorferi* and consequent detection of many other pathogens harbored by *I. persulcatus* (as well as by other ticks from *persulcatus* group) was followed by studies of coinfection of *B. burgdorferi*-

infected ticks with other pathogens. The development of molecular techniques for detection of pathogenic DNA and RNA gave an additional impetus to these studies. It was shown that one and the same adult *I. persulcatus* could be simultaneously infected with *B. garinii* of different genome groups (NT29 and 20047<sup>T</sup>), with *B. afzelii* and each of the groups of *B. garinii*, and with *B. afzelii* and the both groups of *B. garinii* [3,72,109]. Coinfection of *I. persulcatus* with both genospecies of *B. burgdorferi* was observed in several other studies [110,111]. Coexistence of *B. afzelii* and *B. garinii* with *B. miyamotoi*, a relapsing fever spirochete, which earlier was misidentified with *B. burgdorferi*, has also been reported [112, 113].

The most intriguing question for Russian scientists concerning *I. persulcatus* was whether *B. burgdorferi* can coexist with TBEV, the most intensively studied pathogen during the 1960s-1980s. It was suggested that the relationships between the virus and the spirochete function as a “one-sided antagonism”: the presence of spirochetes in tick body limits the virus circulation while the virus does not prevent, and possibly even stimulates, the transmission of spirochetes [105,114]. However, long-term observations carried out in different areas using a variety of techniques decisively demonstrated the absence of such “antagonism” between pathogens, or of any influence of pathogens on each other [87,115,116]. Coinfection of adult *I. persulcatus* by *B. burgdorferi* and TBEV was found in 18% of ticks examined in western Siberia [117].

*Babesia microti* infection was found in taiga tick adults near St. Petersburg in combination with one or both genospecies of *B. burgdorferi* or with *B. garinii* and TBEV (18 combinations in total) [118]. Coexistence of *B. burgdorferi* with rickettsiae of several genera in *I. persulcatus* adults was demonstrated in several studies. Since the prevalence of rickettsial agents in *I. persulcatus* is much lower than that of *B. burgdorferi*, coinfection has usually been registered only in a few ticks. Six of 1,146 adults and 1 of 199 nymphs (totally 0.5%) collected in northeastern China were infected with *B. burgdorferi* and *Anaplasma phagocytophilum* [119], whereas in western Siberia the prevalence of ticks coinfecting by this combination of pathogens reached 6% [117]. Several combinations of 2 to 4 pathogens were revealed in adult ticks in north-western regions of Russia including *B. burgdorferi*, *Ehrlichia muris*, *Rickettsia tarasevichiae* and *Rickettsia*-like endosymbiont *Montezuma* [120]. Coexistence of *B. burgdorferi* with the West Nile virus (WNV) or with *R. tarasevichiae* as well as with 2 other pathogens (TBEV+WNV, TBEV+ *R. tarasevichiae*, WNV+ *R. tarasevichiae*) was found in adult taiga ticks near Tomsk (West Siberia) [121]. Moreover, 17 combinations of DNA of different pathogens were revealed in adult taiga ticks in the Cis-Ural region (both genospecies of *B. burgdorferi*, *Ehrlichia muris*, *Anaplasma phagocytophilum* and *Rickettsia* spp.), and DNA of 4 or 5 agents being identified in 1.3% of ticks (5 out of 400) [122]. In fact, the larger the tick sample and the greater the number of PCR primers, specific for different pathogenic agents, the higher the chance to find multiple pathogens in a single tick.

Ultrastructural analysis confirmed the possibility of tick coinfection with borreliae (*B. burgdorferi* s.l.), rickettsiae (*E. muris* and *R. tarasevichiae*) and a flavivirus (apparently TBEV), and showed that different microorganisms are harbored by different organs of the same tick [123].

It appears that different pathogenic agents tend to localize to distinct cells, organs or tissues of the tick body thus avoiding antagonistic relationships with each other [3,109,124]. It is clear that the research on pathogen coexistence in ticks is still in its early stages, so it can be expected that the data reviewed here will be further expanded, and the conclusions may be refined or revised.

The phenomenon of coinfection of ticks with multiple pathogens necessitates that human protection be focused on prevention of tick bites rather than on elimination of tick-borne pathogens. The territorial principle of human protection through total tick control, as it was applied in the former Soviet Union [125,126], is unrealistic in the modern era. The modern strategy of human protection relies on individual protection of each person in the area where they can be attacked by infected ticks [127,128]. Protective clothes impregnated with acaricides with low toxicity for mammals were developed and successfully used in different areas of Russia [129].

## CONCLUSION

The discovery of Lyme disease and its causative agent, and the identification of ixodid ticks as its vectors ushered a new era in research on ticks and tick-borne diseases. In the three decades that followed, at least 10 microbial pathogens and a number of potential pathogens of humans and animals were identified in ticks of the *persulcatus* group, and in *I. persulcatus* in particular. This wealth of new information poses a multitude of questions concerning the relationships between ticks and pathogens, and especially between ticks and various combinations of different pathogens. In the absence of answers to these questions, it is impossible to reliably estimate the danger presented by particular areas populated by infected ticks (i.e., natural foci of tick-borne diseases), nor it is possible to forecast the rate of tick infection by a particular pathogen and, most importantly, the expected human morbidity. The answers for these questions are reasonably connected with in-depth investigation of ticks and pathogens using new molecular techniques. Likewise, numerous questions arise in connection with the appearance of tick populations at anthropogenically modified territories and in urban environment [130-132]. At the same time, it is important to keep in mind that in spite of decades of intensive research on the taiga tick at the population and organismal levels, some important questions are still awaiting answers. As one example, little is known about the biological mechanisms underlying the differences in aggressiveness of closely related tick species towards humans. Finding the answers to these questions would require the deployment of the whole arsenal of available approaches and methodologies to in-depth analysis of various aspects of tick and pathogen biology. Laboratory experiments and molecular methods are invaluable in addressing these issues; however, a thorough understanding of such highly complex problem cannot be attained without long-term observational studies of tick populations in nature.

## References

1. Mironov VS. Ticks as possible vectors of spring encephalitis. *Med Parazitol.* 1938; 7: 417-435. (in Russian).
2. Zilber LA. Spring (spring-summer) endemic tick-borne encephalitis. *Arkhiv Biol Nauk.* 1939; 56: 9-37. (in Russian).
3. Korenberg EI, Pomelova VG, Osin NS. Infections with natural focality transmitted by ixodid ticks. Moscow. 2013. (in Russian).
4. Filippova NA (editor). Taiga tick *Ixodes persulcatus* Schulze (Acarina, Ixodidae). Leningrad: Nauka. 1985 (in Russian).
5. Korenberg EI. Seasonal population dynamics of *Ixodes* ticks and tick-borne encephalitis virus. *Exp Appl Acarol.* 2000; 24: 665-681.
6. Uspensky I. Taiga tick, *Ixodes persulcatus* Schulze (Acari: Ixodida: Ixodidae). In: Capinera JL (editor). *Encyclopedia of Entomology*, 2<sup>nd</sup> Ed., Vol 4. Springer Science. 2008: 3687-3690.
7. Filippova NA. Ixodid ticks of subfamily Ixodinae. *Fauna of the USSR, Arachnoidea*, 4: 4. Leningrad: Nauka. 1977 (in Russian).
8. Filippova NA. Taxonomic aspects of studying ticks of the genus *Ixodes* Latr. (Ixodoidea, Ixodidae), vectors of the tick-borne encephalitis virus. *Entomol. Obozreniye* 1969; 48: 675-688 (in Russian).
9. Keirans JE, Needham GR, Oliver JH. The *Ixodes ricinus* complex worldwide: diagnosis of the species in the complex, host and distribution. In: Needham GR, et al. (editors) *Acarology IX. Symposia*. Columbus, Ohio. 1999: 341-347.
10. Filippova NA. Systematic relationships of the *Ixodes ricinus* complex in the Palearctic fauna region. In: Needham GR, et al. (editors) *Acarology IX. Symposia*. Columbus, Ohio. 1999: 355-361.
11. *International Code of Zoological Nomenclature*. 4<sup>th</sup> Ed. London: Natural History Museum. 1999.
12. Filippova NA. Characteristic features of the categories "genus" and "subgenus", and the intercalary category "group of species" in ixodid ticks (Acari: Ixodidae). *Parazitologiya.* 2008; 42: 249-263 (in Russian).
13. Korenberg EI. Biological and spatial structure of the species (with the taiga tick as a model). Moscow: Nauka. 1979 (in Russian).
14. Chen Z, Yang X, Bu F, Yang X, Yang X, Liu J, et al. Ticks (Acari: Ixodoidea: Argasidae, Ixodidae) of China. *Exp Appl Acarol.* 2010; 51: 393-404.
15. Masuzawa T. Terrestrial distribution of the *Lyme borreliosis* agent *Borrelia burgdorferi* sensu lato in East Asia. *Japan. J Infect Dis.* 2004; 57: 229-235.
16. Ishiguro F, Takada N, Masuzawa T, Fukui T. Prevalence of Lyme disease *Borrelia* spp. In ticks from migratory birds on the Japanese mainland. *Appl Environ Microbiol.* 2000; 66: 982-986.
17. Takada N, Nakao M, Ishiguro F, Fujita H, Yano Y, Toshiyuki M, et al. Prevalence of Lyme disease *Borrelia* in ticks and rodents in northern Kyūshū, Japan. *Med Entomol Zool.* 2001; 52: 117-123.
18. Robbins RG. The ticks (Acari: Ixodida: Argasidae, Ixodidae) of Taiwan: a synonymic checklist. *Proc Entomol Soc. Wash.* 2005; 107: 245-253.
19. Pospelova-Shtrom MV, Rashina MG (editors). *Problems of epidemiology of tick-borne encephalitis and biological regularities in its natural focus*. Moscow: Meditsina. 1968 (in Russian).
20. Egorov IY, Ochirov YD, Vershinin EA, Androssov IA, Mironchuk YV. Contacts of the human population of the Sakha Republic (Yakutia) with the tick *Ixodes persulcatus* Sch., 1930. *Med Parazitol.* 1996; 2: 37-40. (in Russian).
21. Uspensky I, Garruto RM, Goldfarb L. The taiga tick *Ixodes persulcatus* (Acari: Ixodidae) in the Sakha Republic (Yakutia) of Russia: Distributional and reproductive ranges. *J Med Entomol.* 2003; 40: 119-122.
22. Randolph SE, Rogers DJ. Fragile transmission cycles of tick-borne encephalitis virus may be disrupted by predicted climate change. *Proc R Soc London B.* 2000; 267: 1741-1744.
23. Brownstein JS, Holford TR, Fish D. Effect of climate change on Lyme disease risk in North America. *Ecohealth* 2005; 2: 38-46.
24. Popov IO, Yasyukevich VV. Taiga tick *Ixodes persulcatus*: distribution under conditions of changing climate of XXI century. *Meteorol Hydrol.* 2014; 8: 77-84. (in Russian).
25. Korenberg EI. Recent epidemiology of tick-borne encephalitis: An effect of climate change? *Adv Virus Research* 2009; 74: 123-144.
26. Kheisin EM. Behavior of adult *Ixodes persulcatus* depending on the environmental temperature and humidity. *Zool. Zhurnal* 1953; 32: 77-87 (in Russian).
27. Khzhinsky PG. Activation, abundance and duration of active life for *Ixodes persulcatus* ticks in the forests of the Krasnoyarsk Territory. *Med Parazitol.* 1963; 32: 6-13 (in Russian).

28. Lykov VA. After-winter activation, abundance and physiological age of newly-activated *Ixodes persulcatus* P.Sch. in the Perm' Region. Uchenye Zapiski Permskogo Univ. 1966; 130: 158-163 (in Russian).
29. Arumova EA, Rubina MA. The first manifestation of activity (activation) in *Ixodes persulcatus* P.Sch. and their life-span in the Western Sayan. Med Parazitol. 1974; 43: 179-186. (in Russian).
30. Korenberg EI, Baranovsky PM, Vinokurova NS. The estimation of results of a single registration of *Ixodes persulcatus* on experimental plots and some problems of ecology of this species (Ixodidae). Parazitologiya 1981; 15: 451-458. (in Russian).
31. Korenberg EI, Lebedeva NN, Zhukov VI. Geographic variability and the types of seasonal activity of adult *Ixodes persulcatus* P.Sch. Bull. MOIP, otd. biol. 1974; 4: 34-43. (in Russian).
32. Lykov VA, Mitrofanova YG. Materials on distribution and ecology of *Ixodes persulcatus* P.Sch. in the Perm' Region. Uchenye Zapiski Permskogo Univ. 1971; 249: 10-38. (in Russian).
33. Repkina LV, Uspensky IV. An attempt to find some ecological characteristics of *Ixodes persulcatus* populations (Ixodidae) by the changes in tick physiological age during the activity season. Parazitologiya 1980; 14: 118-125. (in Russian).
34. Naumov RL. The longevity of the sheep and taiga ticks (Ixodidae) infected and uninfected with borreliae of the *burgdorferi* group. Parazitologiya 2003; 37: 527-532. (in Russian).
35. Leonovich SA. Investigation of the Haller's organ in *Ixodes persulcatus* ticks (Ixodidae) using an electron microscope. Parazitologiya 1977; 11: 340-347. (in Russian).
36. Leonovich SA. Ethology of the taiga tick *Ixodes persulcatus* during spring activity. Parazitologiya 1989; 23: 11-19. (in Russian).
37. Elizarov YA, Vasyuta AA. Distant orientation of *Ixodes persulcatus* ticks on attractive factors of the target. Parazitologiya 1976; 10: 136-141. (in Russian).
38. Romanenko VN. The importance of chemical and vibrational stimuli in attracting *Ixodes persulcatus* P.Sch. ticks to paths. In: Spatial orientation of insects and ticks. Tomsk. 1984; 2: 124-127. (in Russian).
39. Mishin AV. Aggressiveness of *Ixodes persulcatus* ticks and methodology of its study. Zool. Zhurnal. 1956; 35: 978-985. (in Russian).
40. Babenko LV, Khizhinsky PG. Diurnal activity of *Ixodes persulcatus* P.Sch. ticks in the forests of the Krasnoyarsk Territory. In: Problems of medical parasitology and prophylaxis of infections. Moscow. 1964: 521-541. (in Russian).
41. Babenko LV. Diurnal fluctuations of activity of unfed nymphal *Ixodes ricinus* L. and *Ixodes persulcatus* P.Sch. (Parasitiformes: Ixodidae). Med Parazitol. 1974; 43: 520-527. (in Russian).
42. Okulova NM. Vertical and horizontal movements of ixodid ticks depending on the air temperature and humidity. Ecologiya. 1978; 2: 44-48. (in Russian).
43. Balashov YS. Active horizontal movements of the taiga tick *Ixodes persulcatus* P.Sch. Med Parazitol. 1958; 27: 481-484.
44. Ioffe ID. The size of olfactory and visual centers in three species of ixodid ticks (Parasitiformes, Ixodidae). Zool. Zhurnal 1976; 55: 526-530. (in Russian).
45. Panfilova IM. Relation of ixodid ticks (*Ixodes persulcatus*, *Dermacentor silvarum* and *Haemaphysalis concinna*) to the light. Zool. Zhurnal 1976; 55: 371-377. (in Russian).
46. Babenko LV, Arumova EA, Bush MA, Skadinsh EA. Sex ratio in natural populations of adult *Ixodes ricinus* L. and *Ixodes persulcatus* P.Sch. (Ixodoidea, Ixodidae). Med Parazitol. 1977; 46: 294-301. (in Russian).
47. Uspensky IV, Kachanko NI, Repkina LV. Materials on the ecology of ixodid ticks in the north of the Amur Region. Zool. Zhurnal 1978; 57: 391-397. (in Russian).
48. Kolonin GV. Sex structure of natural populations of ixodid ticks (Acarina, Ixodidae) in the Primorsky Territory. Ecologiya. 1987; 3: 84-86. (in Russian).
49. Korotkov YS, Kislenco GS. Demographic structure of the taiga tick population (Ixodidae) in valley dark coniferous forests of the Kemchug upland as of 1986-1991. Parazitologiya. 2001; 35: 265-274. (in Russian).
50. Korotkov YS, Kislenco GS. Causes of fluctuations in the demographic structure of the taiga tick population (Ixodidae) in dark coniferous-deciduous forests of the Kemchug upland. Parazitologiya. 2002; 36: 345-355. (in Russian).
51. Balashov YS. Demography and population models of ticks in the genus *Ixodes* with long-term life cycles. Parazitologiya. 2012; 46: 81-90. (in Russian).
52. Korotkov YS, Kislenco GS. Morphogenetic diapause of the taiga tick and methods of its quantitative estimation under conditions of field experiment. Parazitologiya. 1991; 25: 494-503. (in Russian).

53. Korotkov YS, Kislenco GS. Life cycle of the taiga tick *Ixodes persulcatus* in dark coniferous forests of low mountains of the Eastern Sayan Ridge. *Parazitologiya*. 2014; 48: 20-36. (in Russian).
54. Belozеров VN. 1982. Diapause and biological rhythms in ticks. In: Obenchain FD, Galun R (editors) *Physiology of ticks*. Oxford: Pergamon Press. 1982: 469-500.
55. Korotkov YS. Gradual variability of the parasitic system of tick-borne encephalitis. *Voprosy Virusol*. 2005; 3: 52-56. (in Russian).
56. Korotkov YS. Spatial and temporal variability of parasitic system of tick-borne encephalitis under conditions of global climate change. In: IV Congress of the Russian Society of Parasitologists, Proceedings. St-Petersburg. 2008: 88-91. (in Russian).
57. Kachanko NI. Development of ixodid ticks near the northern border of their range in the Amur Region. *Parazitologiya*. 1978; 12: 218-225. (in Russian).
58. Schoener TW. Resource partitioning in ecological communities. *Science*. 1974; 185: 27-39.
59. Finke DL, Snyder WE. Niche partitioning increases resource exploitation by diverse communities. *Science*. 2008; 321: 1488-1490.
60. Uspensky I. Ability of successful attack in two species of ixodid ticks (Acari: Ixodidae) as a manifestation of their aggressiveness. *Exp Appl Acarol*. 1993; 17: 673-683.
61. Alekseev AN, Jensen PM, Dubinina HV, Smirnova LA, Makrouchina NA, Zharkov SD, et al. Peculiarities of behavior of taiga (*Ixodes persulcatus*) and sheep (*Ixodes ricinus*) ticks (Acarina: Ixodidae) determined by different methods. *Folia Parasitol*. 2000; 47: 147-153.
62. Shilova SA, Mal'kov GB, Chabovsky VI, Meshcheryakova EV. Influence of depression in the abundance of forest murine rodents on feeding of larval and nymphal *Ixodes persulcatus*. *Bull MOIP, otd. biol*. 1956; 3: 27-34. (in Russian).
63. Uspensky I, Rubina M. Host substitution by *Ixodes persulcatus* (Acari: Ixodidae) larvae in the years of deep depression in the abundance of small mammals. *Folia Parasitol*. 1992; 39: 171-176.
64. Korenberg EI, Pchelkina AA, Soloshenko IZ, Dunayeva TN. Study of red deer (*Cervus elaphus*) in conjugate foci of tick-borne encephalitis, rickettsioses, leptospirosis and tularemia. *Zool Zhurnal*. 1975; 54: 1057-1065. (in Russian).
65. Balashov YS. Bloodsucking ticks (Ixodoidea), vectors of human and animal diseases. *Misc Publ Entomol Soc Am*. 1972; 8: 159-376.
66. Uspensky IV, Repkina LV. Some observations on mating and insemination of *Ixodes persulcatus*. *Zool Zhurnal*. 1978; 57: 1092-1095. (in Russian).
67. Babenko LV, Bush MA, Arumova EA, Skadinsh EA. Seasonal variations of the level of insemination in female *Ixodes ricinus* L. and *Ixodes persulcatus* P.Sch. before their attachment to hosts and the importance of this phenomenon in the life of tick populations. *Med Parazitol*. 1979; 5: 71-79. (in Russian).
68. Uspensky IV, Emelyanova OY. The existence of pheromone relationships in ticks of the genus *Ixodes*. *Zool. Zhurnal* 1980; 59: 699-704. (in Russian) (English translation: NAMRU 3-T1447).
69. Uspensky I, Ioffe-Uspensky I. The relationship between engorged female weight and egg number in ixodid ticks: A biological interpretation of linear regression parameters. *Acarologia*. 1999; 40: 9-17.
70. Korenberg EI, Gorelova NB, Kovalevskii YV. Ecology of *Borrelia burgdorferi* sensu lato in Russia. In: Grey J, Kahl O, Lane RS, Stanek G (editors) *Lyme borreliosis: Biology, epidemiology and control*. Wallingford: CAB International. 2002: 175-200.
71. Korenberg EI, Kryuchevnikov BN, Kovalevskii YV, Shcherbakov SV, Kuznetsova RI, et al. The tick *Ixodes persulcatus* Schulze – a new vector of *Borrelia burgdorferi*. *Doklady AN SSSR* 1987; 297: 1268-1270. (in Russian).
72. Postic D, Korenberg E, Gorelova N, Kovalevskii YV, Bellenger E, Baranton G, et al. *Borrelia burgdorferi* sensu lato in Russia and neighbouring countries: High incidence of mixed isolates. *Res Microbiol*. 1997; 148: 691-702.
73. Hao Q, Hou X, Geng Z, Wan K. Distribution of *Borrelia burgdorferi* sensu lato in China. *J Clin Microbiol*. 2011; 49: 647-650.
74. Korenberg EI, Moskvitina GG. Interrelationships between different *Borrelia* genospecies and their principal vectors. *J Vector Ecol*. 1996; 21: 178-185.
75. Moskvitina GG, Korenberg EI, Gorban' LY. The presence of borreliae in the gut and salivary glands of spontaneously infected adult *Ixodes persulcatus* Schulze ticks during bloodsucking. *Med Parazitol*. 1995; 3: 16-20.
76. Uspensky I, Kovalevskii YV, Korenberg EI. Physiological age of field-collected female taiga ticks, *Ixodes persulcatus* (Acari: Ixodidae), and their infection with *Borrelia burgdorferi* sensu lato. *Exp Appl Acarol*. 2006; 38: 201-209.
77. Moskvitina GG, Korenberg EI, Spielman A, Shchyogoleva TV. Frequencies of generalized infection in unfed adult ticks of the genus *Ixodes* in Russian and American foci of borreliosis. *Parazitologiya* 1995; 29: 353-360. (in Russian).

78. Piesman J, Mather TN, Sinsky RJ, Spielman A. Duration of tick attachment and *Borrelia burgdorferi* transmission. J Clin Microbiol. 1987; 25: 557-558.
79. Piesman J. Dynamics of *Borrelia burgdorferi* transmission by nymphal *Ixodes dammini* ticks. J Infect Dis. 1993; 167: 1082-1085.
80. Korenberg EI, Moskvitina GG, Vorobyeva NN. Prevention of human borreliosis after infected tick bite. In: Advances in Lyme borreliosis research. VI International Conference on Lyme Borreliosis. Proceedings. Bologna. 1994: 209-211.
81. Lebet N, Gern L. Histological examination of *Borrelia burgdorferi* infections in unfed *Ixodes ricinus* nymphs. Exp. Appl. Acarol. 1994; 18: 177-183.
82. Kahl O, Janetzki-Mittmann C, Gray JS, Jonas R, Stein J, de Boer R, et al. Risk of infection with *Borrelia burgdorferi* sensu lato for a host in relation to the duration of nymphal *Ixodes ricinus* feeding and the method of tick removal. Zentralbl Bakteriell. 1998; 287: 41-52.
83. Cook MJ. Lyme borreliosis: A review of data on transmission time after tick attachment. Int J General Microbiol. 2015; 8: 1-8.
84. Nakao M, Miyamoto K. Negative finding in detection of transovarial transmission of *Borrelia burgdorferi* in Japanese ixodid ticks, *Ixodes persulcatus* and *Ixodes ovatus*. Japan J Sanit Zool. 1992; 43: 343-345.
85. Nefedova VV, Korenberg EI, Gorelova NB, Kovalevskii YV. Studies on the transovarial transmission of *Borrelia burgdorferi* sensu lato in the taiga tick *Ixodes persulcatus*. Folia Parasitol. 2004; 51: 67-71.
86. Balashov YS, Amosova LI, Grigor'eva LA. Transovarial and transphasic transmission of *Borrelia* by the taiga tick *Ixodes persulcatus* (Ixodidae). Parazitologiya 1998; 32: 130-132. (in Russian).
87. Vasilieva IS, Naumov RL. Lyme disease parasitosis system, the state of the problem. Communication I. Pathogenes and vectors. Acarina. 1996; 4: 53-75.
88. Naumov RL, Vasilieva IS, Gutova VP, Ershova AS. Reproduction of the Lyme disease pathogen *Borrelia burgdorferi* in *Ixodes persulcatus* ticks. Parazitologiya 1998; 32: 412-421. (in Russian).
89. Sun Y, Xu R. Ability of *Ixodes persulcatus*, *Haemaphysalis concinna* and *Dermacentor silvarum* ticks to acquire and transstadially transmit *Borrelia garinii*. Exp Appl Acarol. 2003; 31: 151-160.
90. Randolph SE, Gern L, Nuttall PA. Co-feeding ticks: Epidemiological significance for tick-borne pathogen transmission. Parasitology Today. 1996; 12: 472-479.
91. Ogden NH, Nuttall PA, Randolph SE. Natural Lyme disease cycle maintained via sheep by co-feeding ticks. Parasitology. 1997; 115: 591-599.
92. Sato Y, Nakao M. Transmission of the Lyme disease spirochete, *Borrelia garinii*, between infected and uninfected immature *Ixodes persulcatus*, during co-feeding on mice. J Parasitol. 1997; 83: 547-550.
93. Gern L, Rais O. Efficient transmission of *Borrelia burgdorferi* between co-feeding *Ixodes ricinus* ticks (Acari: Ixodidae). J Med Entomol. 1996; 33: 189-192.
94. Richter D, Allgöwer R, Matuschka FR. Co-feeding transmission and its contribution to the perpetuation of the Lyme disease spirochete *Borrelia afzelii*. Emerg Infect Dis. 2002; 8: 1421-1425.
95. Voordouw MJ. Co-feeding transmission in Lyme disease pathogens. Parasitology. 2015; 142: 290-302.
96. Alekseev AN, Dubinina HV. Exchange of *Borrelia burgdorferi* between *Ixodes persulcatus* (Ixodidae: Acarina) sexual partners. J Med Entomol. 1996; 33: 351-354.
97. Alekseev AN, Arumova EA, Burenkova LA, Chunikhin SP. Some peculiarities of the Lyme disease agent distribution and of the behavior of *Ixodes* ticks infected with it. Parazitologiya. 1993; 27: 389-398. (in Russian).
98. Korenberg EI, Kovalevskii YV, Levin ML, Shchyogoleva TV. The prevalence of *Borrelia burgdorferi* sensu lato in *Ixodes persulcatus* and *I. ricinus* ticks in the zone of their sympatry. Folia Parasitol. 2001; 48: 63-68.
99. Korotkov YS, Kislenco GS, Burenkova LA, Rudnikova NA, Karan' LS. Spatial and temporal variability of the infection of *Ixodes ricinus* and *Ixodes persulcatus* ticks with Lyme disease pathogen in the Moscow Region. Parazitologiya 2008; 42: 441-451. (in Russian).
100. Korenberg EI. Taxonomy, phylogenetic interrelations and areas of form-forming in spirochetes of the genus *Borrelia* transmitted by ixodid ticks. Uspekhi Sovremen. Biol. 1996; 116: 389-406. (in Russian).
101. Friedhoff KT. Interaction between parasites and tick vector. Int J Parasitol. 1990; 20: 525-535.
102. Walker AR. Parasitic adaptations in the transmission of theileria by ticks. A review Trop. Animal Health Prod. 1990; 22: 23-33.

103. Balashov YS. Relationships between ixodid ticks (Ixodidae) and agents of arthropod-transmitted infections of vertebrates. *Parazitologiya*. 1995; 29: 337-352. (in Russian).
104. Nakao M. *Ixodes persulcatus* and Lyme disease spirochete: Comparison of development between infected and noninfected ticks. *Japan J Sanit Zool*. 1995; 46: 241-247.
105. Alekseev AN, Burenkova LA, Vasilieva IS, Dubinina EV, Chunikhin SP. The functioning of mixed tick-borne infection foci over Russia. *Med Parazitol*. 1996; 4: 9-16. (in Russian).
106. Naumov RL. The questing activity of the taiga tick *Ixodes persulcatus* infected with borreliae. *Parazitologiya*. 1999; 33: 251-256. (in Russian).
107. Romashchenko AV, Ratushnyak AS, Zapara TA, Tkachev SE, Moshkin MP. Behavioral and electrophysiological responses of the taiga tick (*Ixodes persulcatus*) to synthetic human sex pheromones. *Zool Zhurnal*. 2010; 89: 682-693. (in Russian).
108. Hurd H. Manipulation of medically important insect vectors by their parasites. *Annu Rev Entomol*. 2003; 48: 141-161.
109. Korenberg EI. Interrelations between transmissible disease agents in ixodid ticks (Ixodidae) coinfecting with them. *Parazitologiya*. 1999; 33: 273-289. (in Russian).
110. Alekseev AN, Dubinina HV, Antykova LP, Dzhivnyan TI, Rijpkema SGT, Kruij NV, et al. Tick-borne borreliosis pathogen identification in *Ixodes* ticks (Acarina, Ixodidae) collected in St. Petersburg and Kaliningrad Baltic regions of Russia. *J Med Entomol*. 1998; 35: 136-142.
111. Alekseev AN, Dubinina HV, Van de Pol I, Schouls LM. Identification of *Ehrlichia* spp. and *Borrelia burgdorferi* in *Ixodes* ticks in the Baltic regions of Russia. *J Clin Microbiol*. 2001; 39: 2237-2242.
112. Fomenko NV, Livanova NN, Borgoyakov VY, Kozlova IV, Shulaykina IV, et al. Detection of *Borrelia miyamotoi* in *Ixodes persulcatus* ticks in Russia. *Entomol. Rev*. 2010; 90: 1088-1094.
113. Geller J, Nazarova L, Katargina O, Järvekülg L, Fomenko N, Golovljova I, et al. Detection and genetic characterization of relapsing fever spirochete *Borrelia miyamotoi* in Estonian ticks. *PLoS ONE*. 2012; 7:12.
114. Alekseev AN. The pathogen-vector interface: A history of paradigms. *Acarina*. 1999; 7: 111-120.
115. Korenberg EI, Shcherbakov SV, Bannova GG, Levin ML, Karavanov AS. Simultaneous infection of *Ixodes persulcatus* ticks with agents of Lyme disease and tick-borne encephalitis. *Parazitologiya*. 1990; 24: 102-105. (in Russian).
116. Korenberg EI, Gorban' LY, Kovalevskii YV, Frizen VI, Karavanov AS. Risk for human tick-borne encephalitis, borreliosis, and double infection in the Pre-Ural region of Russia. *Emerg Infect Dis*. 2001; 7: 459-462.
117. Morozova OV, Dobrotvorskij AK, Livanova NN, Tkachev SE, Bakhvalova VN, Beklemishev AB, et al. PCR detection of *Borrelia burgdorferi* sensu lato, tick-borne encephalitis virus, and the human granulocytic ehrlichiosis agent in *Ixodes persulcatus* ticks from Western Siberia, Russia. *J Clin Microbiol*. 2002; 40: 3802-3804.
118. Alekseev AN, Semenov AV, Dubinina HV. Evidence of *Babesia microti* infection in multi-infected *Ixodes persulcatus* ticks in Russia. *Exp Appl Acarol*. 2003; 29: 345-353.
119. Cao WC, Zhao QM, Zhang PH, Yang H, Wu XM, Wen BH, et al. Prevalence of *Anaplasma phagocytophila* and *Borrelia burgdorferi* in *Ixodes persulcatus* ticks from northeastern China. *Am J Trop Med Hyg*. 2003; 68: 547-550.
120. Eremeeva ME, Oliveira A, Moriarity J, Robinson JB, Tokarevich NK, Antyukova LP, et al. Detection and identification of bacterial agents in *Ixodes persulcatus* Schulze ticks from the North Western region of Russia. *Vector-Borne Zoonot. Dis*. 2007; 7: 426-436.
121. Chausov EV, Ternovoi VA, Protopopova EV, Konovalova SN, Kononova YV, Pershikova NL, et al. Genetic diversity of infectious agents transmitted by ixodid ticks in Tomsk and its suburbs. *Parazitologiya* 2009; 43: 374-388. (in Russian).
122. Korenberg EI, Nefedova VV, Kovalevskii YV, Gorelova NB. The tick *Ixodes persulcatus* (Acari: Ixodidae) is a vector of various disease agents in the Cisural region, Russia. In: *Trends in acarology. The 12<sup>th</sup> International Congress of Acarology, Proceedings*. Amsterdam: Springer. 2010: 533-535.
123. Popov VL, Korenberg EI, Nefedova VV, Han VC, Wen JW, Kovalevskii YV, et al. Ultrastructural evidence of the ehrlichial developmental cycle in naturally infected *Ixodes persulcatus* ticks in the course of coinfection with *Rickettsia*, *Borrelia*, and a flavivirus. *Vector-Borne Zoonot Dis*. 2007; 7: 699-716.
124. Balashov YS. The tick body as a habitat of the agents of arthropod-borne diseases. *Parazitol Sbornik* 1987; 34: 48-69. (in Russian).
125. Uspensky I. Tick-borne encephalitis prevention through vector control in Russia: An historical review. *Rev Med. Vet Entomol*. 1996; 84: 679-689.
126. Uspensky I. Comparison of main approaches to human tick-borne disease prevention. *Zentralbl Bakteriol*. 1999; 289: 765-767.

127. Shashina NI, Germant OM, Luboshnikova VM. Nonspecific prevention of tick-borne encephalitis in the beginning of the XXI century. Bull. SO RAMN 2007; 4: 111-115. (in Russian).
128. Korenberg EI. Infections transmitted by ixodid ticks in forest areas and the strategy of prevention: changing of priorities. Epidemiol Vaksinoprofilaktika 2013; 5: 7-17. (in Russian).
129. Shashina NI, Germant OM. Biological peculiarities of the taiga tick (*Ixodes persulcatus*, Ixodidae) and methods of human protection. Zool Zhurnal. 2010; 89: 115-120. (in Russian).
130. Uspensky I. Ticks (Acari: Ixodoidea) as urban pests and vectors with special emphasis on ticks outside their geographical range. In: 6<sup>th</sup> International Conference on Urban Pests, Proceedings. OOK-Press Kft., Veszprém, Hungary. 2008: 333-347.
131. Uspensky I. Tick pests and vectors (Acari: Ixodoidea) in European towns: introduction, persistence and management. Ticks Tick-Borne Dis. 2014; 5: 41-47.
132. Uspensky I. Blood-sucking ticks (Acari: Ixodoidea) and their mammalian hosts in the urban environment: A review. Research & Reviews: J. Zool. Sci. 2016; 4: 8-16.