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Personal protection measures to prevent tick bites in the United States: Knowledge gaps, challenges, and opportunities

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Abstract

Personal protection measures to prevent human tick encounters from resulting in bites are widely recommended as the first line of defense against health impacts associated with ticks. This includes using repellents, wearing untreated or permethrin-treated protective clothing, and conducting tick checks after coming inside, aided by removing outdoor clothing articles and running them in a dryer on high heat (to kill undetected ticks) and taking a shower/bath (to aid in detecting ticks on the skin). These measures have the benefit of incurring no or low cost, but they need to be used consistently to be most effective. In this paper, I review the level of use (acceptability combined with behavior) of the above-mentioned personal protection measures and their effectiveness to prevent tick bites and tick-borne disease. Studies on the level of use of personal protection measures to prevent tick bites have used different recruitment strategies, focused on different types of respondent populations, employed variable phrasings of survey questions relating to a given personal protection measure, and presented results based on variable frequencies of taking action. This complicates the synthesis of the findings, but the studies collectively indicate that members of the public commonly take action to prevent tick bites, most frequently by wearing untreated protective clothing or conducting tick checks (done routinely by 30 to 70% of respondents in most studies of the public), followed by showering/bathing after being outdoors or using repellents on skin/clothing (15 to 40% range), and with permethrin-treated clothing being the least frequently used tick bite prevention method (<5 to 20% range). A suite of experimental studies have shown that applying repellents or permethrin to coveralls or uniform-style clothing can result in decreased numbers of tick bites, but similar studies are lacking for members of the public wearing summer-weight clothing during normal daily activities. Moreover, a set of case-control and cross-sectional studies have explored associations between use of different personal protection measures to prevent tick bites and Lyme disease or other tick-borne infections. The results are mixed for each personal protection measure, with some studies indicating that regular use of the measure is associated with a reduction in tick-borne disease

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Supplementary materials

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while other studies found no similar protective effect. One possible interpretation is that these personal protection measures can protect against tick-borne infection but the information gathered to date has not been sufficiently detailed to clarify the circumstances under which protection is achieved, especially with regards to frequency of use, parts of the body being protected, and use of combinations of two or more potentially protective measures. In conclusion, personal protection measures to prevent tick bites are used by the public and merit further study to better understand how they need to be used to have the greatest public health impact.

Keywords

Tick bite; Tick-borne disease; Personal protection; United States

1. Background

Hard ticks and their associated human health impacts are negatively influencing the quality of life in the United States. Humans are bitten by a suite of North American generalist tick species for which at least one life stage quests for hosts openly in the environment: these include *Amblyomma americanum* (lone star tick), *Amblyomma maculatum* (Gulf Coast tick), *Dermacentor andersoni* (Rocky Mountain wood tick), *Dermacentor occidentalis* (Pacific Coast tick), *Dermacentor variabilis* (American dog tick), *Haemaphysalis longicornis* (Asian longhorned tick), *Ixodes pacificus* (western blacklegged tick), and *Ixodes scapularis* (blacklegged tick) (Merten and Durden, 2000; Guglielmone and Robbins, 2018). Additional human bites are associated with a specialist tick species, *Rhipicephalus sanguineus* sensu lato (brown dog tick), primarily infesting dogs and thus readily coming into contact with humans (Guglielmone and Robbins, 2018). Human bites can also be associated with cryptic *Ixodes* species with more limited potential for contacting humans due to their host preference and questing behavior (Merten and Durden, 2000; Guglielmone and Robbins, 2018). Negative effects on humans resulting from tick bites include infection with viral, bacterial, and parasitic disease agents (Eisen et al., 2017b; Rosenberg et al., 2018). Human pathogens transmitted by the above-mentioned tick species include, among others: *Anaplasma phagocytophilum* causing anaplasmosis (*I. pacificus* and *I. scapularis*); *Babesia microti* causing babesiosis (*I. scapularis*); *Borrelia burgdorferi* sensu stricto causing Lyme disease (LD) (*I. pacificus* and *I. scapularis*); *Ehrlichia chaffeensis* and *Ehrlichia ewingii* causing ehrlichiosis (*A. americanum*); *Rickettsia parkeri* causing spotted fever group rickettsiosis (*A. maculatum*); and *Rickettsia rickettsii* causing Rocky Mountain spotted fever (*D. andersoni, D. variabilis*, and *R. sanguineus* s.l.) (Eisen and Paddock, 2021). Additional health impacts associated with tick bites include tick paralysis and Alpha-gal syndrome/red meat allergy (Edlow and McGillicuddy, 2008; Mitchell et al., 2020a; Young et al., 2021).

The difficulty in countering the increasing problem with hard ticks and their associated human health impacts in the United States has been addressed in numerous reviews and perspectives over the years (see Eisen 2021 for a comprehensive list of these publications). Recent overviews focusing on how to counter the ongoing increase in human tick bites and tick-borne disease (TBD) cases have addressed vaccine-based solutions (vaccines to protect against tick-borne pathogens in humans, domestic animals, or natural reservoirs;

and anti-tick vaccines intended for use in humans, domestic animals, or wildlife) and environmentally-based tick management approaches targeting ticks off-host or on-host (Eisen and Dolan, 2016; de la Fuente et al., 2017; Stafford et al., 2017; Eisen and Eisen, 2018; White and Gaff, 2018; Rego et al., 2019; Gomes-Solecki et al., 2020; Eisen, 2021; Eisen and Stafford, 2021). Other recent papers have addressed spatial and temporal risk patterns for exposure to human biting ticks and their associated pathogens at different spatial scales in the United States, based on collection of host-seeking ticks or recovery of ticks from human hosts, to facilitate avoidance of high risk areas during the times of year when host-seeking ticks are most active (Eisen et al., 2017b; Nieto et al., 2018; Jordan and Egizi, 2019; Little et al., 2019; Porter et al., 2019; Salkeld et al., 2019; Xu et al., 2019; Fleshman et al., 2021; Lehane et al., 2021). However, one topic has received insufficient attention despite its importance as a first line of defense against health impacts associated with ticks: personal protection measures to prevent human tick encounters from resulting in bites or to shorten the duration a biting tick is allowed to stay attached. Despite a weak evidence base for the effectiveness of commonly recommended personal protection measures to prevent tick bites and tick-borne infections (as noted by Mead 2011, Eisen and Gray 2016, Eisen and Mead 2020, Lantos et al. 2021), this topic has been addressed only in a cursory fashion in recent papers broadly discussing prevention of TBDs. Since the review on education, behavior change, and other non-pharmaceutical measures to prevent LD and other TBDs presented by Mead in 2011, numerous new research studies on these topics have been published. Previous reviews also have been lacking in considering personal protection measures from the perspective of dealing with a suite of human biting tick species with variable behaviors both while questing for hosts and when attempting to locate a suitable bite site on a host.

The present paper therefore aims to summarize the state of the science and explore knowledge gaps, challenges, and opportunities relating to personal protection measures focused on preventing human tick encounters from resulting in bites. Section 2 provides an overview of personal protection measures to prevent human tick bites; Section 3 addresses the level of use (acceptability combined with behavior) for different personal protection measures; Section 4 focuses on the evidence base for the effectiveness of these personal protection measures to prevent human tick bites and TBD; and Section 5 summarizes knowledge gaps and challenges and opportunities for moving forward. Published literature was queried by searching the Scopus database using combinations of the key words "personal protection", "clothing", "repellent", "permethrin", or "tick check" together with "tick", "tick bite", "tickborne disease" or "Lyme disease". The snowball technique, which identifies additional publications based on referenced materials, was then employed to identify additional publications of interest. For discussion of personal protection measures either preceding the human tick encounter (e.g., avoidance of high-risk habitats for tick exposure) or occurring after a tick is detected and removed (e.g., antibiotic prophylaxis), I refer to previous overviews of these topics (Eisen and Eisen, 2016; Eisen and Mead, 2020; Lantos et al., 2021).

2. Overview of personal protection measures to prevent human tick encounters from resulting in bites or reducing tick attachment time

The personal protection measures outlined below and summarized in Table 1 focus on the chain of events from when human tick contact first occurs to when an attached tick is detected and removed, or when an undetected tick detaches naturally when the blood meal is complete. These measures can be broadly classified as actions that: (i) prevent a human tick encounter from resulting in a bite (see Sections 2.1 and 2.2); (ii) shorten the duration of time before an attached tick is detected and removed (Section 2.3); and (iii) disrupt feeding by ticks that go undetected (Section 2.4).

2.1. Preventing a human tick encounter from resulting in a bite

Several types of actions can prevent a tick having made contact with a human from reaching a suitable location on the skin to bite (Table 1). The most basic action is to conduct regular tick checks on clothing and exposed skin while outside in tick habitat and to remove crawling ticks before they have a chance to bite. Two additional commonly recommended no-cost protection measures may aid in detecting crawling ticks on clothing when outside: (i) wearing light-colored clothing to provide contrast with dark-colored ticks and making them easier to spot during a quick, cursory scan in the field; and (ii) wearing long pants tucked into socks and a long-sleeved shirt tucked into the pants, to maximize the distance ticks are forced to walk on clothing before reaching skin and thus increase the chance they are detected while still on the clothing. It should be noted here that one study from Europe (Stjernberg and Berglund, 2005) found a similar likelihood of detecting experimentally introduced *Ixodes ricinus* (castor bean tick) on light-colored and dark-colored clothing. However, this finding was based on two persons thoroughly examining a subject which they knew to have ticks present on the clothing. This scenario is not representative of how a quick, cursory tick check of clothing is likely to be conducted by a member of the public while outdoors, for example doing a quick scan of clothing while walking without certain knowledge that ticks are present on the clothing. The study by Stjernberg and Berglund (2005) also recorded larger numbers of ticks from subjects walking through vegetation wearing light-colored compared to dark-colored clothing, and the authors speculated that the ticks may have been more attracted to light-colored clothing. A biological rationale for such a phenomenon is elusive as *I. ricinus* ticks would not perceive clothing color as light or dark until after they made contract with the textile, and then would need to preferentially dislodge from dark clothing, presumably due to dark-colored clothing lacking some characteristic found in a natural host animal.

Additional protection from ticks while outdoors can be achieved by applying a United States Environmental Protection Agency (EPA)-approved tick repellent product to skin and clothing, treating clothing with an EPA-approved permethrin-based product acting as a contact irritant for ticks, or purchasing pre-treated permethrin-impregnated clothing. EPA provides an online search tool for approved tick repellent products to use on skin and clothing, with search filters for active ingredient (2-undecanone, citronella, DEET, IR3535, oil of lemon eucalyptus, picaridin, and p-menthane-3,8-diol) and protection time (≤4, 5–8, 9–12, or 13–16 h) to help the user select an acceptable and appropriate product (EPA, 2021).

There is also an increasing number of marketed tick repellent products that are based on other active ingredients, including various botanical oils, and not registered by the EPA; the efficacy of these products to repel ticks is unclear and merits further investigation. Use of tick repellents can be considered a low-cost personal protection method. In contrast to the suite of repellent active ingredients outlined above, which can be formulated into products applied to skin as well as clothing, the synthetic pyrethroid, permethrin is used to impregnate shoes and clothing articles for protection against ticks but should never be applied directly to skin. Impregnation with permethrin can be achieved at low cost with do-it-yourself spray products. A more convenient but also substantially more costly alternative is to purchase pre-treated permethrin-impregnated clothing articles, which are available in the form of socks, long pants, shorts, short-sleeved shirts, long-sleeved shirts, and outerwear.

After returning inside, additional actions can be taken to further reduce the risk of a human tick encounter resulting in a bite. Removing the clothing worn outdoors and running it (dry) in a dryer on high heat has the three-fold benefit of removing clothing on which ticks may still be crawling, exposing skin to reveal potentially crawling ticks, and killing ticks still present on the clothes by means of high, dry heat in the dryer (Carroll, 2003; Nelson et al., 2016). Showering or bathing when coming indoors could similarly lead to a change of potentially tick-infested clothing and increased probability of detecting crawling ticks previously hidden under the clothing, and contact with water could perhaps cause ticks to lose contact with the skin if they are still moving toward a suitable bite site (Mead, 2011). These actions can be part of conducting a thorough tick check, which is recommended when coming indoors after spending time in tick habitat. Additionally, there is need for awareness of the potential for transfer of crawling ticks from pets having been outdoors to household residents (Jones et al., 2018; de Wet et al., 2020). For information on tick bite prevention measures for companion animals, I refer to Stafford (2017).

2.2. Initial contact of a host-seeking tick with a person

The details of the initial contact a host-seeking tick makes with a person remains a knowledge gap across human biting tick species. Data for specific bite sites on the bodies of human hosts are available for *I. ricinus* in Europe (Berglund et al., 1995; Hügli et al., 2009; Wilhelmsson et al., 2013; Cull et al., 2020) and a suite of human biting tick species in North America (Falco and Fish, 1988; Falco et al., 1996; Felz and Durden, 1999; Gleim et al., 2016; Slaff and Newton, 1993; Xu et al., 2016, 2019; Jordan and Egizi, 2019). Some general patterns are evident after a review of the North American publications: (i) bites by all tick species were distributed across the human body; (ii) *A. americanum* and *I. scapularis* females tended to more frequently be found biting on the upper part of the body compared with nymphs; and (iii) *D. variabilis* females were commonly found biting on the head. Factors underlying these observed patterns include tick questing height on natural vegetation (Goddard, 1992; Mejlon and Jaenson, 1997; Tsunoda and Mori, 2000; Goddard et al., 2011), types of human activity and clothing worn (Carroll and Kramer, 2001; Lane et al., 2004; Wierzbicka et al., 2016), and differences in mobility across tick species and life stages. Consequently, it should not be assumed that the most frequent bite sites on the human body for a given tick species and life stage necessarily reflect where on the body initial tick contact most often occurs.

Taking the vegetation height in the frequented area and the type of planned outdoor activity into consideration when deciding on the specifics of application of repellents and use of permethrin-treatment garments could help to ensure that an adequate portion of the body is protected. Walking through short vegetation should result in ticks making contact primarily with shoes and the lower parts of the legs whereas walking through taller vegetation or engaging in activities that involve kneeling down or handling things on the ground (such as yardwork or backyard play) will present risk for ticks making contact with a much wider range of portions of the body. The initial contact of a host-seeking tick with a person may involve the tick encountering untreated skin, untreated clothing, skin treated with a repellent, or clothing treated with a repellent or an acaricide (permethrin). These scenarios are considered in detail in Sections 2.2.1 to 2.2.2.

2.2.1. Initial contact with untreated skin or clothing—The worst-case scenario for a human tick encounter is that the tick makes initial contact with untreated skin or clothing and then continues to move without being impeded by either skin repellents or treated clothing before it locates a suitable bite site. This could for example include ticks that make initial contact with skin on the legs of a person wearing shorts and then proceed up the legs, under the shorts, to bite in the groin area. Here, spotting the crawling tick before it bites is the only purposeful action that can prevent a bite. An alternative scenario is that ticks make initial contact with untreated skin or clothing but then encounter repellent-treated skin or clothing. In this case, the ticks can: (i) retreat and attempt to find another route to an optimal bite site without being impeded by a repellent, for example if only one side of an arm or shirt-sleeve is treated; (ii) retreat and settle for a suboptimal, more exposed bite site on untreated skin; or (iii) make an attempt to cross the repellent-treated surface. Ticks approaching a repellent-treated surface, including human skin, often stop moving as they reach the edge of the treated surface and sense the repellent, and then change movement direction (Carroll et al., 1989, 2005; Dautel et al., 1999; Carroll, 2008; Büchel et al., 2015; Foster et al., 2020).

The first two (i, ii) tick response actions outlined above would result in longer time spent crawling on clothing and skin, in turn leading to increased risk of accidentally losing contact with the host or being spotted and removed before biting. It also should be noted that the behavior upon encountering a repellent may differ among tick species: *A. americanum* nymphs were noted to more frequently dislodge from a vertically oriented surface after approaching a repellent compared to *I. scapularis* nymphs, which tended to retreat but remain on the untreated portion of the vertical surface (Carroll et al., 2010). Ticks that instead choose to attempt to cross a repellent-treated surface (response action iii) can either fail in doing so, leading them to retreat to untreated skin/clothing or to dislodge from the host due to the repellent, or succeed in moving through the treated area to reach an untreated surface. Based on results from experimental studies, there are differences between North American human biting tick species in their willingness to move onto repellent-treated substrates, including for treated skin (Schreck et al., 1995; Carroll et al., 2004, 2007, 2010, 2016; Bissinger et al., 2009; Zhang et al., 2009). The likelihood of a tick successfully crossing a stretch of repellent-treated skin or clothing depends on multiple factors, including the inherent sensitivity of a given tick species and life stage to the repellent active ingredient, the speed at which the tick is traveling combined with the length of the treated surface (i.e., the time it will remain in contact with the repellent), and characteristics of the repellent product and its application, including the concentration of active ingredient and the amount of time elapsed since the repellent was applied. One reasonable assumption is that more mobile, fast-moving ticks are more likely to be able to cross repellent-treated surfaces compared with slower moving ticks. In the case where a tick is successful in crossing a repellent-treated surface to reach untreated skin, the impact of the physical contact with the repellent-treated surface on the willingness and ability of the tick to bite and feed at different points after contacting the repellent remains unknown.

The final scenario is when ticks make initial contact with untreated clothing or skin but thereafter encounter permethrin-treated clothing before reaching a bite site. As they reach the edge of a permethrin-treated clothing surface, ticks tend to continue moving due to the weak non-contact repellency of permethrin and then dislodge from the clothing as they start to experience the contact irritancy caused by the permethrin (Eisen et al., 2017a). As for repellents, the impact of permethrin-treated clothing varies across different tick species and life stages. For example, Prose et al. (2018) found that shorter exposure times on permethrin-treated textile are required to incapacitate nymphs versus adults of either *A. americanum* or *I. scapularis*; nymphs of *I. scapularis* versus *A. americanum*; and females of *I. scapularis* versus *A. americanum* or *D. variabilis*. Ticks that remain alive on the host after exposure to permethrin-treated clothing may display reduced willingness or ability to bite (Eisen et al., 2017a; Prose et al., 2018; Connally et al., 2019) or perish in the early stages of their blood meal due to more slowly developing toxic effects (Miller et al., 2011).

2.2.2. Initial contact with repellent-treated skin, repellent-treated clothing, or permethrin-treated clothing—The best-case scenario for a human tick encounter is when ticks make initial contact with repellent-treated skin or clothing, or with permethrin-treated clothing. Ticks actively moving toward a stationary person could conceivably sense a repellent as they attempt to ascend onto a repellent-treated surface and abort the attempt. In contrast, ticks that quest from a stationary position in leaf litter or from vegetation and then make contact with a human brushing by are unlikely to be able to sense a repellent before the physical contact is made. However, ticks making initial contact with vertically oriented repellent-treated skin or clothing (such as on a leg) are likely to actively dislodge from that surface and fall off the person (Schreck et al., 1986). Ticks instead making initial contact with permethrin-treated clothing likewise will attempt to actively dislodge from the surface as they start to experience contact irritancy (Prose et al., 2018), and if failing to dislodge before losing the ability to move they will most likely perish from extended permethrin exposure (Schreck et al., 1982a, 1986; Lane and Anderson, 1984; Lane, 1989; Evans et al., 1990; Miller et al., 2011).

The likelihood of ticks making initial contact with a surface treated with repellent or permethrin to succeed in moving across the surface until they reach untreated skin or clothing, and still be physiologically capable of biting, depends on the inherent sensitivity of the tick species and life stage to the repellent or permethrin and the speed at which the tick is traveling combined with the length of the treated surface (i.e., the time it will remain in contact with the repellent or permethrin). As a practical example, wearing permethrin-treated shoes and/or ankle socks but not protecting any other part of the body can be assumed to provide less effective tick bite protection compared with also wearing permethrin-treated pants because: (i) ticks are more likely to make initial contact above a treated shoe or ankle sock compared to above the waist of a treated pair of pants based on their typical questing heights in the vegetation (Goddard, 1992; Mejlon and Jaenson, 1997; Tsunoda and Mori, 2000; Goddard et al., 2011); and (ii) ticks making initial contact with a treated shoe or ankle sock are more likely to reach untreated skin and survive to bite if the person is not also wearing treated pants. Increasing the length of time a moving tick is forced to stay in contact with permethrin-treated clothing before reaching untreated clothing or skin is important because the proportions of ticks either dislodging from a vertically oriented treated surface (mimicking a pant leg) or becoming incapacitated due to the permethrin contact increases with exposure time (Eisen et al., 2017a; Prose et al., 2018).

2.3. Shortening the duration of time before an attached tick is detected and removed

If a tick bite occurs, it is beneficial to take action to shorten the duration of time the tick remains attached before it is detected and removed. Viral pathogens may be transmitted as soon as the tick attaches and starts to inject saliva (Alekseev et al., 1996; Ebel and Kramer, 2004) but the probability of transmission of many, albeit not all (Levin et al., 2020), bacterial or parasitic pathogens increases with the amount of time an infected, feeding tick is allowed to remain attached, especially during the first 1–3 days of its blood meal (see Eisen 2018). Conducting daily, thorough tick checks after spending time in tick habitat, and for several days thereafter, is therefore recommended to increase the likelihood of detecting and removing infected ticks before they have a chance to transmit disease agents (CDC, 2021a). The difficulty in detecting attached ticks is underscored by that comparisons of self-assessed durations of attachment by *Ixodes* ticks and attachment durations based on tick engorgement indices indicate that people consistently underestimate the actual duration of time ticks were attached prior to being discovered (Sood et al., 1997; Logar et al., 2002; Wilhelmsson et al., 2013). The probability of detecting a biting tick is influenced by a variety of factors, including the location of the bite site on the human body, the sensitivity of the bitten person to tick bites, the size of the tick, the duration of time required to complete the blood meal, and potentially also factors such as tick species-specific salivary components to reduce host inflammatory responses. Biting ticks should be removed as soon as possible after being discovered using recommended tick removal techniques (CDC, 2021b), which are supported by empirical data (Needham, 1985; de Boer and van den Bogaard, 1993; Stewart et al., 1998; Piesman and Dolan, 2002; Akin Belli et al., 2016; Coleman and Coleman, 2017; Huygelen et al., 2017).

2.4. Disrupting feeding by ticks that go undetected

Some ticks biting humans do remain undetected throughout their blood meal. Of the tick life stages, it stands to reason that adult females are most likely to be detected while attached as they are much larger, especially when partially or fully engorged, and feed for a longer duration of time (≥1 wk) compared to immatures. *Ixodes scapularis* nymphs are assumed to be responsible for the majority of bites in the 30–50% of LD cases in the United States where the patient had no knowledge of a tick bite prior to symptom onset (see review by Eisen and Eisen 2016). Future emergence of products capable of disrupting feeding by ticks that go undetected could therefore be of great value to complement existing personal protection measures. A pathogen transmission-blocking anti-tick vaccine, ideally impacting a broad range of tick vector species, is one promising approach to achieve this, but despite identification of numerous potential targets, it has proven difficult to move the field from discovery and basic research to translation into products capable of preventing pathogen transmission (de la Fuente et al., 2017; Rego et al., 2019; Gomes-Solecki et al., 2020; Narasimhan et al., 2020, 2021). Another possible approach to disrupt feeding by ticks that go undetected is a skin lotion or shower soap containing an active ingredient that is feasible to apply to human skin but also has acaricidal properties, such as nootkatone (Panella et al., 2005; Dolan and Panella, 2011; Evolva, 2021).

3. Evidence base for level of use (acceptability combined with behavior) of personal protection measures intended to prevent tick bites

Numerous studies have presented data on the level of use of personal protection measures taken by the public or outdoor workers to prevent tick bites (Table 2). These studies have included populations at the geographical scales of the United States (4 studies); states, or local areas within states, where LD and other *Ixodes*-associated infections predominate (28 studies); and states where tick-borne infections associated with *Amblyomma* or *Dermacentor* ticks are of greatest concern (5 studies). The frequent use of LD endemicity or incidence to define geographical study areas stems from the prominence of this disease among tick-borne infections in the United States (Rosenberg et al., 2018). In the specific case of tick bite prevention, it is worth considering the full range of human biting tick species, rather than only *Ixodes* spp. vectors of LD spirochetes, when selecting extents of geographical areas to include in a survey or use for data presentation broken down by sub-areas of the overall study area. Some geographical areas in the United States present risk for a single commonly human biting tick species (e.g., *D. variabilis* in the northern parts of the Great Plains, *D. andersoni* in the Rocky Mountain region, or *R. sanguineus* s.l. in parts of the arid Southwest), whereas other areas present risk for bites by two commonly human biting tick species (e.g., *D. occidentalis* and *I. pacificus* in California, and *D. variabilis* and *I. scapularis* in parts of the Northeast and Upper Midwest) or three or more such tick species (e.g., *A. americanum, D. variabilis*, and *I. scapularis* in the Mid-Atlantic region; and *A. americanum, A. maculatum, D. variabilis*, and the adult stage of *I. scapularis* in parts of the Southeast). Based on variable habitat preferences and seasonal activity patterns across human biting tick species, areas with multiple species present can include a broader range of habitat types with elevated risk for tick encounters as well as a longer period of the year when ticks are seeking hosts. Both factors may influence the level of use of personal protection measures against tick bites.

National surveys that include information on use of tick bite prevention measures (Herrington, 2004; Hook et al., 2015; Beck et al., 2021; Nawrocki and Hinckley, 2021) used variable breakdowns for presentation of results at sub-national scale. As these studies are featured prominently in Sections 3.1–3.6, their respective sub-national scale geographical breakdowns in relation to the presence of human biting tick species are worth outlining here. The study by Hook et al. (2015) used geographical regions defined in 2010 by the United

States Census Bureau (USCB, 2021). From east to west these include: New England, Mid-Atlantic, and South Atlantic along the Eastern Seaboard; East North Central and East South Central; West North Central and West South Central; Mountain; and Pacific. However, these regions only partly align with key human biting tick species in the eastern United States. For example, *I. scapularis* is highly abundant in most of the New England and Mid-Atlantic regions, but only in limited portions of the East North Central region (primarily Wisconsin) and West North Central region (primarily Minnesota). Likewise, *A. americanum* is highly abundant across the South Atlantic and East South Central regions, and in most of the West South Central region, but only in the southernmost parts of the Mid-Atlantic, East North Central, and West North Central regions.

The other national surveys (Herrington, 2004; Beck et al., 2021; Nawrocki and Hinckley, 2021) used state level LD incidence for the sub-national breakdown but approached this differently. As detailed in Table 3, Herrington (2004) used two groupings of states representing high and low LD incidence states, whereas the other two studies (Beck et al., 2021; Nawrocki and Hinckley, 2021) used three groupings of states representing high LD incidence states, neighboring states with low LD incidence but sharing a border with a high LD incidence state, and low LD incidence states (not sharing a border with a high LD incidence state). Both approaches share the problem that the low LD incidence groupings (including the neighboring states grouping) consist of a combination of states where human biting tick species other than *Ixodes* vectors of LD spirochetes are ubiquitous and abundant (e.g., in the South Atlantic and East South Central regions) versus less abundant near human population centers (e.g., in the Mountain and Pacific regions). As a case in point, personal protection measures against tick bites were routinely used less frequently in the Mountain and Pacific regions, where 65–76% of respondents reported taking no action to prevent tick bites, compared to the South Atlantic and East South Central regions where the percentage of respondents taking no action to prevent tick bites (34–45%) was similar to the LD endemic Mid-Atlantic and New England regions (36–45%) (Hook et al., 2015). Moreover, the neighboring states grouping include states in the Great Plains (North Dakota and South Dakota) where, rather than *I. scapularis, D. variabilis* is the dominant human biting tick and states in the southeast (Kentucky, Tennessee, and North Carolina) where *A. americanum* is the dominant human biting tick. One additional study (Kopsco and Mather, 2021) included participants across the United States but the majority of responses came from northeastern and Mid-Atlantic states, and the results are therefore most representative of areas where *Ixodes*-associated diseases predominate. This study included two distinct groups of respondents: public users of TickSpotters (https://web.uri.edu/tickencounter/tickspotters/) and outdoor workers represented by master gardeners.

Comparisons across studies for use of specific personal protection measures to prevent tick bites are further complicated by changes in local risk for exposure to ticks and TBD agents over time in some areas, as well as variable survey participant recruitment strategies, respondent sample sizes, and context of survey questions. Over the 30-yr period covered by the studies summarized in this Section, several human biting tick species have expanded their ranges in the United States (Sonen-shine, 2018; Molaei et al., 2019; Eisen and Paddock, 2020) and the previously most prominent local human biting tick species has been supplanted by another species in some areas (Jordan and Egizi, 2019). The public's level of knowledge about the risk for tick bites and actions that can be taken to prevent this from happening likely have increased over time in areas where tick species established and then proliferated, and perhaps also in response to more ready access to information via the internet from local, state, and national public health agencies or other sources (Journault et al., 2020). These factors complicate comparisons of older and more recent studies.

Breaking down studies by type of sampling strategy and respondent population is useful but not always straightforward. One important set of studies have used participant recruitment strategies designed to survey a random sample of the public representing adults ≥18 years of age at national level (Herrington, 2004; Hook et al., 2015; Nawrocki and Hinckley, 2021) or at state/local level either without consideration of TBD incidence (Jones et al., 2002; Omodior et al., 2021a) or focusing on portions of states with elevated TBD incidence (Niesobecki et al., 2019). It should be noted, however, that the surveys in some of these studies were focused solely on TBD (Herrington, 2004; Niesobecki et al., 2019; Omodior et al., 2021a), whereas in other studies the questions about TBD were part of broader surveys (Jones et al., 2002; Hook et al., 2015; Nawrocki and Hinckley, 2021). This may have influenced the composition of individuals electing to participate in the surveys and thus how representative they were of the general population.

Another set of studies focusing on the public has specifically recruited participants representing subsets of the population that are active outdoors (visitors to recreation areas; Hallman et al., 1995; Bayles et al., 2013; Jones et al., 2015); may have a particular interest in TBDs (convenience samples including health care seekers or users of information resources relating to ticks and TBDs, or samples of residents in areas with community-wide education campaigns; Gould et al., 2008; Butler et al., 2016; Gupta et al., 2018; Hu et al., 2019; Bron et al., 2020; Kopsco and Mather, 2021); or reside in or visit islands along the New England coast with a history as LD hot-spots, such as Martha’s Vineyard or Nantucket Island (Shadick et al., 1997; Phillips et al., 2001; Finch et al., 2014; Valente et al., 2015). The populations sampled in these studies may have greater motivation to take action to prevent tick bites compared with a randomly selected sample of the overall population in the same areas. Additional studies have focused entirely or partly on children ≤17 years of age (Cartter et al., 1989; Valente et al., 2015; Omodior et al., 2021a); outdoor workers (Smith et al., 1988; Goldstein et al., 1990; Parrott et al., 1993; Nolan and Mauer, 2006; Han et al., 2014; Jones et al., 2015; Valente et al., 2015; Donohoe et al., 2018; Noden et al., 2020; Schotthoefer et al., 2020; Kopsco and Mather, 2021); or subsets of the overall population represented by Hispanic persons nationwide or at state level (Hu et al., 2019; Beck et al., 2021), or a Brazilian immigrant population in Massachusetts (Heller et al., 2010). Finally, information on use of tick bite prevention measures can also be found in studies on LD/TBD case patients and matched control individuals (Orloski et al., 1998; Smith et al., 2001; Vázquez et al., 2008; Connally et al., 2009), and in educational intervention studies focused on children (Shadick et al., 2016), children and adults (Daltroy et al., 2007), or adults (Malouin et al., 2003). Across these numerous studies, respondent sample sizes have been highly variable, ranging from <100 to >30,000. Moreover, for use of a given personal protection measure, some surveys have included questions, or presented results, based on a Yes/No binary response (in some cases without clarifying the frequency of use but more often based on terms such as regular, routine, or consistent use), whereas other surveys presented data to further qualify the frequency of taking action, such as Always / Most of the time / Sometimes / Rarely / Never.

Bearing in mind these caveats, Sections 3.2–3.6 summarize the results from surveys on use of specific personal protection measures to prevent tick bites. The presentation is broken down by (i) randomized surveys of the public conducted nationwide or at state/local level; (ii) surveys of populations representing the public at state/local level that can be expected to have elevated interest in tick bite prevention (including control group participants in TBD case-control studies or pre-intervention baseline surveys in educational intervention studies); and (iii) state/local level surveys of outdoor workers. For LD/TBD case-control studies, the presented data are restricted to the control groups. For educational intervention studies, presented data are restricted to the control/comparison groups, using data from the first survey instance if applicable, or pre-intervention baseline surveys if there was no control/ comparison group. The presentation is further broken down to separate studies conducted in states where LD and other *Ixodes*-associated infections are the primary concern versus states where TBDs associated with *Amblyomma* or *Dermacentor* ticks predominate. For all data presented below, survey responses are assumed to refer to activities taking place in settings where the respondents think that ticks may occur during times of year when ticks are active.

3.1. No use/routine use of personal protection measures

The proportion of individuals not taking any action to prevent tick bites, based on the specific set of actions outlined in Sections 3.2–3.6, is difficult to discern from published studies. The majority of studies include avoidance of tick habitat as an additional personal protection measure, and other studies present data for not taking routine tick bite prevention action versus never taking such action. However, results from national surveys on lack of routine use of tick bite prevention measures are worth mentioning here. Two national surveys (Hook et al., 2015; Nawrocki and Hinckley, 2021) found that 51–58% of respondents in the United States take no routine action to prevent tick bites. A similar study focusing specifically on the Hispanic population in the United States reported a similar level (56%) of respondents taking no routine action to prevent tick bites (Beck et al., 2021). Hook et al. (2015) further found that not taking routine tick bite prevention action was least frequently (32–36%) reported from the New England region (where *D. variabilis* and *I. scapularis* are the dominant human biting ticks), West North Central region (*D. variabilis* and *I. scapularis*, and *A. americanum* in the southernmost part), and East South Central region (*A. americanum, A. maculatum, D. variabilis*, and the adult stage of *I. scapularis*); and most frequently (65–76%) from the Mountain region (*D. andersoni*) and Pacific region (*D. occidentalis* and *I. pacificus*). Moreover, Nawrocki and Hinckley (2021) reported that not routinely taking tick bite prevention action was less frequently (47%) reported for high LD incidence states compared with groupings of states that included low LD incidence states (54–65%).

3.2. Untreated protective clothing

A total of 29 surveys include information relating to use of untreated protective clothing to prevent tick bites (Table 2). Specific actions falling under use of untreated protective clothing to prevent tick bites in these studies include wearing light-colored clothing, wearing long pants and long-sleeved shirts, and tucking pants into socks and shirts into pants. These actions are presented individually in most studies but grouped as protective clothing in some studies. The context of survey questions has been variable across studies, ranging from broad (e.g., wearing light-colored clothing; wearing long pants/long-sleeved shirt) to more specific by defining the frequency of wearing untreated protective clothing or the specific circumstances when the clothing was worn (e.g., in the yard). Although survey questions were specific to tick bite prevention, there is potential for untreated protective clothing to be worn for other primary purposes, such as light-colored clothing being cooler than dark-colored clothing in the summer and long pants/long-sleeved shirt being worn to protect arms and legs during yardwork.

3.2.1. Randomized national surveys of the public—One national survey (Herrington, 2004) included questions regarding use of untreated protective clothing to prevent tick bites. Wearing long pants/long sleeves was reportedly done often by 12% of respondents and at least some of the time by 23%. Tucking pants into socks or boots was slightly less common as this action was taken often by 8% of respondents and at least some of the time by 16%. Moreover, often wearing long pants/long sleeves was more commonly reported by respondents in high LD incidence states versus low LD incidence states (19 and 11%, respectively), and the same was true for often tucking pants into socks or boots (15 and 7%, respectively).

3.2.2. Randomized state/local surveys of the public in areas where Ixodes-associated TBDs predominate—Published studies are lacking.

3.2.3. Randomized state/local surveys of the public in areas where Amblyomma/Dermacentor-associated TBDs predominate—Data are restricted to a single survey from Indiana that included both adults and children (Omodior et al., 2021a). Use of light-colored clothing to facilitate tick detection was reported for 55% of adults and 59% of children; and tucking shirt into pants and pants into socks for 52% of adults and 48% of children. However, the frequency of taking these actions was not specified.

3.2.4. Targeted state/local surveys of subsets of the public with presumed elevated concern about tick-borne illness in areas where Ixodes-associated tick-borne diseases predominate—Data are available from 16 studies focusing on visitors to recreation areas or including other respondent populations with potentially elevated level of concern about TBDs (including control populations in LD case-control studies or education intervention studies). One set of five studies, conducted in Connecticut, Massachusetts, New Jersey, New York, Rhode Island, and Wisconsin, did not specify the type of untreated protective clothing used (Phillips et al., 2001; Vázquez et al., 2008; Finch et al., 2014; Butler et al., 2016; Bron et al., 2020). In these studies, which reported on regular use (usually; always/most of the time; all of the time) of untreated protective clothing or in one case (Bron et al., 2020) did not define the frequency of use, the proportion of respondents taking action ranged from 44 to 58%. Another set of nine studies, conducted in Connecticut, Delaware, Maryland, Massachusetts, New Jersey, or primarily in the Northeast/Mid-Atlantic states, did specify the type of untreated protective clothing used (Shadick et al., 1997; Orloski et al., 1998; Gould et al., 2008; Connally et al., 2009; Heller et al., 2010; Jones et al., 2015; Valente et al., 2015; Gupta et al., 2018; Kopsco and Mather, 2021). Three of these studies (from Connecticut, Maryland, and Massachusetts) defined the frequency of use as regular (usually; always/-most of the time), and recorded such use for 52–71% of respondents for light-colored clothing, 14–43% for wearing long pants/long sleeves, and 16–48% for tucking pants into socks (Orloski et al., 1998; Jones et al., 2015; Valente et al., 2015). Studies from Delaware (Gupta et al., 2018) or primarily the Northeast/Mid-Atlantic states (Kopsco and Mather, 2021) presented more detailed data for frequency of use. Gupta et al. (2018) found that wearing light-colored clothing (specifically to facilitate detection of ticks) or tucking pants into socks always or most of the time when outdoors was reported by 17 and 7% of respondents, respectively, but this increased substantially to 48 and 26%, respectively, when instead considering use half the time or more. Kopsco and Mather (2021) found that wearing long pants when entering a tick-infested area, and tucking pants into socks to keep ticks on the outside of clothes, was done always or most of the time by 67 and 28% of respondents, respectively, and this increased to 78 and 34%, respectively, when instead considering use half the time or more. Categorizing use as always, sometimes, or never, Gould et al. (2008) reported that roughly 60% of respondents in Connecticut always wore long pants in wooded or brushy areas whereas only 20% always tucked pant legs into socks. A unique study on a Brazilian immigrant population in Massachusetts found that 78% of respondents, including both outdoor and indoor workers, always or usually wore long pants when walking out in the woods or working outdoors (Heller et al., 2010).

Based on data from the control group in a LD case-control study, Connally et al. (2009) reported high proportions of Connecticut respondents using light-colored clothing (90%) and long pants (70%) at least on some occasion while in the yard in the month prior to onset of symptoms in their matched case patients. Finally, Shadick et al. (1997) found that 30–40% of Massachusetts respondents wore long pants/long sleeves and tucked pants into socks, but did not define the frequency of use. For studies on school-age children, 32% of high school students in Connecticut reported always or often wearing long pants/long-sleeved shirt when in wooded or grassy areas (Cartter et al., 1989), whereas approximately 50% of elementary school students in Massachusetts reported always or usually wearing long pants just to keep ticks off (Shadick et al., 2016). In a few other relevant studies presenting information on untreated protective clothing, data were not collected or presented in a manner that allows for clear interpretation of the results (Hallman et al., 1995; Smith et al., 2001).

3.2.5. Targeted state/local surveys of subsets of the public with presumed elevated concern about tick-borne illness in areas where Amblyomma/ Dermacentor-associated TBDs predominate—Data are restricted to a single survey of adults visiting recreational areas in Missouri (Bayles et al., 2013). Regular use (always or most of the time) of light-colored clothing was reported by 34% of respondents, as compared to 25% for wearing long pants/long sleeves and 17% for tucking pants into socks.

3.2.6. Targeted surveys of outdoor workers in areas where Ixodes-associated TBDs predominate—Studies of outdoor workers, primarily employees in outdoor recreation areas, were conducted in Maryland, New Jersey, New York, Pennsylvania, Wisconsin, or primarily the Northeast/Mid-Atlantic states (Smith et al., 1988; Goldstein et al., 1990; Parrott et al., 1993; Han et al., 2014; Jones et al., 2015; Schotthoefer et al., 2020; Kopsco and Mather, 2021). Of the seven studies presenting data for use of untreated protective clothing, one presented multiple categories for frequency of use (Kopsco and Mather, 2021) and four defined the frequency of use as always (Schotthoefer et al., 2020) or always/usually (Goldstein et al., 1990; Han et al., 2014; Jones et al., 2015), whereas no similar distinction for frequency of use was made in two studies (Smith et al., 1988; Parrott et al., 1993). As results nevertheless were similar across all studies, they are presented collectively below. While at work, the proportion of respondents that reported regularly wearing long pants ranged from roughly 65–85%, whereas it was less common to wear a long-sleeved shirt (10–28%) or tuck pants into socks (<5 to 38%). In the subset of studies also reporting on wearing light-colored clothing, which may not be possible to use for some groups due to uniform requirements, this action was taken by 10–30% of respondents (Parrott et al., 1993; Han et al., 2014; Jones et al., 2015). Three studies (Smith et al., 1988; Goldstein et al., 1990; Parrott et al., 1993) also included information for use of untreated protective clothing while at work versus at leisure. Wearing long pants, long sleeves, or tucking pants into socks was 1.5 to 3-fold less likely at leisure, compared to at work, whereas wearing light-colored clothing was 2-fold more likely when at leisure. In another relevant study presenting information on untreated protective clothing, data were not collected and presented in a manner that allows for clear interpretation of the results (Nolan and Mauer, 2006).

3.2.7. Targeted surveys of outdoor workers in areas where Amblyomma/ Dermacentor-associated TBDs predominate—Data are available from two studies in Florida and Oklahoma. A survey of Florida Fish and Wildlife/Florida State Parks employees found that 58% always wear long pants and long-sleeved shirts, 59% always tuck the shirt into pants, and 25% always tuck pants into socks (Donohoe et al., 2018). A study on beef producers in Oklahoma reported that 33% of respondents used untreated protective clothing, such as wearing long pants/long-sleeved shirts and tucking pants into socks, but the frequency of use was not defined (Noden et al., 2020).

3.2.8. Surveys from Canada and Europe—Surveys that include questions about use of untreated protective clothing also have been conducted in Canada and Europe, with the proportion of respondents regularly taking this action most often in the range of 30–65% (Bartosik et al., 2008; Beaujean et al., 2013a, b; Mowbray et al., 2014; Aenishaenslin et al., 2015, 2017; Zöldi et al., 2017; Slunge and Boman, 2018; Buczek et al., 2020).

3.2.9. Conclusions and future directions—Use of untreated protective clothing to prevent tick bites has been omitted from recent national surveys of the public in the United States, but data from state or local surveys conducted over the last decade indicate regular use by half or more of the respondents in some areas (Bayles et al., 2013; Jones et al., 2015; Valente et al., 2015; Butler et al., 2016; Gupta et al., 2018; Kopsco and Mather, 2021). However, quantifying the use of untreated protective clothing is complicated by that data are presented broadly as untreated protective clothing in some studies, whereas other studies break down different types of untreated protective clothing but without making it clear which proportion of the overall respondent population used at least one type of untreated protective clothing. It would be useful in future surveys to collect data for the frequency of use of untreated protective clothing, as well as which specific actions falling under use of untreated protective clothing (light-colored clothing, long pants, long-sleeved shirt, tucking shirt into pants, and tucking pant legs into socks) are used by individual respondents. As wearing a long-sleeved shirt tucked into long pants, in turn tucked into socks, may not be pleasant during outdoor activities in warm weather, it also would be useful in future surveys to clarify which specific outdoor activities, weather conditions or other factors cause respondents to forgo this low-cost, non-chemical personal protection measure against tick bites.

3.3. Repellents for skin and clothing

A total of 32 surveys include information relating to use of repellents that can be applied to both skin and clothing to prevent tick bites (Table 2). The context of survey questions has been variable across studies, ranging from broad (e.g., using an insect repellent on your skin or clothes) to more specific (e.g., distinguishing between repellent use on skin versus clothing, defining where the activity prompting the use of repellent took place, or defining the frequency of repellent use). The emergence of natural product-based repellents during the latter part of the time period when data for repellent use were reported may have contributed to variable results across older and more recent studies, as natural product-based repellents may be acceptable for use by some individuals who are hesitant to use synthetic repellents. Although survey questions were specific to tick bite prevention, there is potential for use of repellents to primarily protect against mosquitoes depending on the time of day the outdoor activity took place.

3.3.1. Randomized national surveys of the public—Four national surveys have included questions regarding use of skin/clothing repellents to prevent tick bites. Herrington (2004) reported repellents to be used often by 5% of respondents on skin and 4% on clothing, and this increased to 13% of respondents for skin and 12% for clothing when considering application at least some of the time. The proportions of respondents wearing repellent often on skin or clothing was similar for high LD incidence states (5–6%) compared to low LD incidence states (4–5%). More recent surveys have reported that 20–21% of respondents in the United States routinely use skin/clothing repellents to prevent tick bites (Hook et al., 2015; Nawrocki and Hinckley, 2021), and a similar study focusing specifically on the Hispanic population in the United States showed a higher level (28%) of respondents routinely using repellents (Beck et al., 2021). Moreover, Hook et al. (2015) reported lower routine repellent use to prevent tick bites for respondents in the Mountain and Pacific regions (6–12%) compared with the rest of the United States (21–30%). Nawrocki and Hinckley (2021) reported routine repellent use for 25% of respondents in high LD incidence states compared to 17–24% for groupings of states that included low LD incidence states.

3.3.2. Randomized state/local surveys of the public in areas where Ixodes-associated TBDs predominate—Data are restricted to a single survey of adults in parts of Connecticut and Maryland with elevated LD incidence (Niesobecki et al., 2019). In both states, 31% of respondents applied repellents always or most of the time when outdoors in places where you could get ticks.

3.3.3. Randomized state/local surveys of the public in areas where Amblyomma/Dermacentor-associated TBDs predominate—Data are available from two studies in Tennessee and Indiana that included both adults and children. Jones et al. (2002) reported that 29% of respondents in Tennessee always use repellent in tick-infested areas, and this increased to 40% for using repellent always or usually. Omodior et al., 2021a reported use of repellents on exposed skin for 78% of adults and 90% of children when outdoors during summer months in Indiana, but the frequency of taking this action was not specified. For clothing, the survey question in the Indiana study was phrased so that answers may have included treatment of clothing with either skin/clothing repellents or permethrin.

3.3.4. Targeted state/local surveys of subsets of the public with presumed elevated concern about tick-borne illness in areas where Ixodes-associated TBDs predominate—Data are available from 17 studies focusing on visitors to recreation areas or including other respondent populations with potentially elevated level of concern about TBDs (including control populations in LD case-control studies or education intervention studies). Eight of these studies reported on consistent repellent use (e.g., usually, regularly, routinely, or always/most of the time), which ranged from 10 to 20% among respondents in studies from New Jersey, Massachusetts, and Rhode Island (Orloski et al., 1998; Phillips et al., 2001; Finch et al., 2014; Valente et al., 2015) to 30–40% in studies from Connecticut, Maryland, and Maryland/Virginia (Vázquez et al., 2008; Jones et al., 2015; Butler et al., 2016; Hu et al., 2019). Studies from Delaware (Gupta et al., 2018) or primarily the Northeast/Mid-Atlantic states (Kopsco and Mather, 2021) presented more detailed data for frequency of use. Applying repellents to skin always or more than half of the time when outdoors during the summer months was reported by 22% of respondents in Delaware, and this increased to 56% for doing so half the time or more. Application of repellents to clothing in this study by Gupta et al. (2018) is not considered here because the survey question was phrased as to potentially include both application of skin/clothing repellents and permethrin to clothing. For the study primarily including Northeast/Mid-Atlantic states (Kopsco and Mather, 2021), applying repellents with DEET to exposed skin before working or playing in tick habitat always or more than half of the time was reported by 26% of respondents, and this increased to 37% for doing so half the time or more. Categorizing use as always, sometimes, or never, another study from Connecticut reported that roughly 25% of respondents always used repellents (Gould et al., 2008). A unique study on a Brazilian immigrant population in Massachusetts found that 12% of respondents, including both outdoor and indoor workers, always or usually wore repellents when walking out in the woods or working outdoors (Heller et al., 2010).

Based on data from the control group in a LD case-control study, Connally et al. (2009) reported that 41% of Connecticut respondents wore repellent on at least some occasion while in the yard in the month prior to onset of symptoms in their matched case patients.

Two other studies did not define the frequency of using repellent: in these surveys the proportions of respondents taking this action ranged from 15% in Maryland (Malouin et al., 2003) to 50–60% in New Jersey/New York and Wisconsin (Bron et al., 2020). For the single study on school-age children, 17% of high school students in Connecticut reported always or often wearing repellent on skin and clothes when at risk for tick bites (Cartter et al., 1989). It also should be noted that Smith et al. (2001) reported more frequent use of repellents by Pennsylvania respondents during recreational activities or outdoor work away from home compared to during yardwork at home (44% and 22% of respondents, respectively); and that Jones et al. (2015) found a similar level of application of repellents to skin and clothing (33% and 31% of respondents, respectively) for park visitors in Maryland. In a few other relevant studies presenting information on repellent use, data were not collected or presented in a manner that allows for clear interpretation of the results (Hallman et al., 1995; Shadick et al., 1997).

3.3.5. Targeted state/local surveys of subsets of the public with presumed elevated concern about tick-borne illness in areas where Amblyomma/ Dermacentor-associated TBDs predominate—Data are restricted to a single survey of adult visitors to recreational areas in Missouri (Bayles et al., 2013). Regular use (always or most of the time) of skin/clothing repellents for tick bite prevention was reported by 43% of the respondents, with 35% using repellents containing DEET and 8% using organic repellents.

3.3.6. Targeted surveys of outdoor workers in areas where Ixodes-associated TBDs predominate—Studies of outdoor workers, primarily employees in outdoor recreation areas, were conducted in Maryland, Massachusetts, New Jersey, New York, Pennsylvania, or primarily the Northeast/Mid-Atlantic states (Smith et al., 1988; Goldstein et al., 1990; Parrott et al., 1993; Han et al., 2014; Jones et al., 2015; Valente et al., 2015; Kopsco and Mather, 2021). Of the seven studies presenting data, one presented multiple categories for frequency of use (Kopsco and Mather, 2021) and four defined the frequency of using repellents as regularly or always/usually (Goldstein et al., 1990; Han et al., 2014; Jones et al., 2015; Valente et al., 2015), whereas no such distinction for frequency of use was made in two studies (Smith et al., 1988; Parrott et al., 1993). The proportion of respondents always/usually wearing repellent ranged from 10 to 38% for application to skin and 19–47% for application to clothing for studies from Maryland, New Jersey, Pennsylvania, or primarily the Northeast/Mid-Atlantic states (Goldstein et al., 1990; Han et al., 2014; Jones et al., 2015; Kopsco and Mather, 2021). Valente et al. (2015) reported that 8% of respondents in Massachusetts regularly used repellent but did not distinguish between use on skin versus clothing. For the studies where frequency of use was not defined, Smith et al. (1988) reported equal percentages (21%) for use of repellents on skin versus clothing in New York, whereas Parrott et al. (1993) reported larger proportions of respondents using repellents on skin (73%) or clothing (59%) in Maryland. Use of repellents while at work versus at leisure was similar in two studies (Smith et al., 1988; Goldstein et al., 1990) but roughly 1.5-fold more common at work in another study (Parrott et al., 1993).

3.3.7. Targeted surveys of outdoor workers in areas where Amblyomma/ Dermacentor-associated TBDs predominate—
Data are restricted to a single survey of Florida Fish and Wildlife/Florida State Parks employees, which found that 47% of respondents always apply repellent when at risk for tick bites (Donohoe et al., 2018).

3.3.8. Surveys from Canada and Europe—
Surveys that include questions about use of repellents for skin and clothing also have been conducted in Canada and Europe, with the proportion of respondents regularly taking this action ranging from 6 to 47% (Bartosik et al., 2008; Beaujean et al., 2013a, b; Mowbray et al., 2014; Aenishaenslin et al., 2015, 2017; Zöldi et al., 2017; Slunge and Boman, 2018; Buczek et al., 2020).

3.3.9. Conclusions and future directions—
Regular use of skin/clothing repellents to prevent tick bites has been reported by 15–40% of respondents in most studies of the public in the United States conducted over the last decade. Assessing factors underlying change in the level of repellent use over the last three decades is complicated by an increase over time in options for repellent active ingredients, including the more recent emergence of natural product-based repellents. In addition to some studies failing to define the critically important frequency of repellent use, not a single study has spec-ified which portions of the body, or types of clothing, most commonly are treated with repellents. In future surveys, it would be useful to: (i) separate out the use of permethrin treatment on clothing from use of skin/clothing repellents applied to clothing; (ii) define the frequency of repellent use; (iii) distinguish between use of repellents with synthetic chemical active ingredients versus natural product-based active ingredients; and (iv) clarify which type of skin surfaces (e.g., legs, hands, arms, and neck) and clothing articles (e.g., shoes, socks, pants, shorts, short-sleeved shirts, and long-sleeved shirts) are treated.

3.4. Permethrin-treated clothing

Information regarding use of permethrin-treated clothing to prevent tick bites has been included in 10 surveys (Table 2). Two additional surveys included permethrin treatment of clothing but the questions were phrased so that answers also may have included treatment of clothing with skin/clothing repellents (Table 2; Gupta et al., 2018; Omodior et al., 2021a). The context of survey questions has been variable across studies, ranging from broad (e.g., wearing permethrin-treated clothing) to more specific by defining the frequency of use. Although survey questions were specific to tick bite prevention, there is potential for use of permethrin-treated clothing to primarily protect against mosquitoes depending on the time of day the outdoor activity took place.

3.4.1. Randomized national surveys of the public—
Two national surveys have included data on use of permethrin-treated clothing to prevent tick bites. Nawrocki and Hinckley (2021) reported that 3% of respondents routinely used permethrin-treated clothing to prevent tick bites, with slightly higher levels of use for high LD incidence states (4%) compared to groupings of states that included low LD incidence states (1–2%). Beck et al. (2021) reported a similar level (3%) of routine use of permethrin-treated clothing for the Hispanic population in the United States.

3.4.2. Randomized state/local surveys of the public in areas where Ixodes-associated TBDs predominate—Published studies are lacking.

3.4.3. Randomized state/local surveys of the public in areas where Amblyomma/Dermacentor-associated TBDs predominate—The study by Omodior et al., 2021a in Indiana included a survey question mentioning treatment of clothing with permethrin but with a phrasing (insect repellent, e.g., permethrin) that likely led to responses also including treatment with skin/clothing repellents such as DEET. Bearing this in mind, use of treated clothing was reported for 48% of adults, without defining the frequency of taking this action.

3.4.4. Targeted state/local surveys of subsets of the public with presumed elevated concern about tick-borne illness in areas where Ixodes-associated TBDs predominate—Data are available from seven studies focusing on visitors to recreation areas or including other respondent populations with potentially elevated level of concern about TBDs (including control populations in LD case-control studies and education intervention studies). A study of visitors in a recreational area in Maryland found 3% of respondents to always or usually wear permethrin-treated clothing while spending time in the park (Jones et al., 2015). A similar level of routine use (<5%) of permethrin-treated clothing was reported by respondents from Maryland/Virginia (Hu et al., 2019). A recent study conducted primarily in the Northeast/Mid-Atlantic states (Kopsco and Mather, 2021) presented more detailed data for frequency of use: wearing permethrin-treated clothing always or more than half of the time was reported by 19% of respondents, and this increased to 29% for doing so half the time or more. In this study, using at-home permethrin clothing treatment was twice as common as purchasing and wearing pre-treated permethrin clothing. Two additional studies reported on use of permethrin-treated clothing without defining the frequency of use. A low level of use (2%) was reported from Maryland (Malouin et al., 2003), whereas a higher level of use (10–15%) was reported from New Jersey/New York and Wisconsin (Bron et al., 2020). Based on data from the control group in a LD case-control study, Connally et al. (2009) reported a low proportion (<1%) of Connecticut respondents wearing permethrin-treated clothing in the yard on at least some occasion in the month prior to onset of symptoms in their matched case patients. Finally, the study by Gupta et al. (2018) in Delaware included a survey question phrased as follows: How often do you treat your outdoor clothing with special bug spray (insect repellants) made for clothing (such as permethrin)? Bearing in mind that this likely includes answers relating to treatment of clothing with skin/clothing repellents rather than only with permethrin, 12% of respondents reported taking this action always or more than half of the time.

3.4.5. Targeted state/local surveys of subsets of the public with presumed elevated concern about tick-borne illness in areas where Amblyomma/Dermacentor-associated TBDs predominate—Data are available from a single survey of adult visitors to recreational areas in Missouri, where 8% of respondents reported using permethrin to repel ticks, presumably by treating clothing, always or most of the time (Bayles et al., 2013).

3.4.6. Targeted surveys of outdoor workers in areas where Ixodes-associated TBDs predominate—Data are available from three surveys. In an early study, Parrot et al. (1993) reported that 5% of outdoor workers in a Maryland recreation area used permethrin-treated clothing but the frequency of use was not defined. A later study (Jones et al., 2015) from another recreation area in Maryland found that permethrin-treated clothing was used routinely (always or usually) by 22% of outdoor workers. The most recent study, conducted primarily in the Northeast/Mid-Atlantic states (Kopsco and Mather, 2021), found that wearing permethrin-treated clothing always or more than half of the time was reported by 23% of master gardeners, and this increased to 32% for doing so half the time or more.

3.4.7. Targeted surveys of outdoor workers in areas where Amblyomma/ Dermacentor-associated TBDs predominate—Published studies are lacking

3.4.8. Surveys from Canada and Europe—Published studies are lacking.

3.4.9. Conclusions and future directions—Regular use of permethrin-treated clothing to prevent tick bites has been reported by <5 to 20% of respondents in studies of the public conducted over the last decade, making permethrin-treated clothing the least commonly used personal protection measure to prevent tick bites. Assessing factors underlying change in the level of use of permethrin-treated clothing over the last three decades is complicated by the recent emergence of pre-treated permethrin-impregnated clothing articles as an alternative to do-it-yourself permethrin spray-on treatment. In future surveys, it would be useful to: (i) separate out the use of skin/clothing repellents applied to clothing from use of permethrin treatment on clothing; (ii) make the distinction between do-it-yourself treatment of clothing with permethrin spray versus purchasing clothing articles already impregnated with permethrin; (iii) define the frequency of use of permethrin-treated clothing; and (iv) clarify which type of clothing articles (e.g., shoes, socks, pants, shorts, short-sleeved shirts, and long-sleeved shirts) are treated.

3.5. Tick checks

A total of 35 surveys include information relating to use of tick checks to prevent tick bites and reduce the duration of attachment for biting ticks (Table 2). The context of survey questions has been variable across studies, ranging from broad (e.g., performing tick checks after being outdoors; checking the body for ticks when coming in) to more specific (e.g., distinguishing between tick checks done while outdoors versus when coming inside; specifying an outdoor environment related to the tick checks, such as after spending time in the yard; checking for ticks on skin versus clothing; or defining how commonly tick checks are performed after being outdoors). Of the personal protection measures described in Section 3, this is the only one without another potential primary purpose.

3.5.1. Randomized national surveys of the public—Three national surveys have presented data for tick checks. Hook et al. (2015) reported that 31% of respondents routinely checked their bodies for ticks when coming inside during the warm part of the year, whereas Nawrocki and Hinckley (2021) reported that 19% of respondents routinely checked their bodies for ticks daily. The discrepancy in the level of use of tick checks between these studies may in part have resulted from variable phrasing of survey questions, including the mention of daily tick checks in the latter survey. A similar study focusing specifically on the Hispanic population in the United States showed a lower level (12%) of respondents routinely conducting daily tick checks (Beck et al., 2021). Moreover, Hook et al. (2015) reported the highest routine use of tick checks when coming inside from the New England, East South Central, and West North Central regions (43–48%); and the lowest routine use of tick checks in the West South Central, Mountain, and Pacific regions (12–26%). Nawrocki and Hinckley (2021) reported higher routine use of daily tick checks for high LD incidence states (29%) compared to groupings including low LD incidence states (13–23%).

3.5.2. Randomized state/local surveys of the public in areas where Ixodes-associated TBDs predominate—Data are restricted to a single survey of adults in parts of Connecticut and Maryland with elevated LD incidence (Niesobecki et al., 2019). Conducting tick checks always or most of the time after being outdoors in places where you could get ticks was reported by 55% of respondents in Maryland and 62% in Connecticut.

3.5.3. Randomized state/local surveys of the public in areas where Amblyomma/Dermacentor-associated TBDs predominate—Data are available from two studies in Tennessee and Indiana that included both adults and children. Jones et al. (2002) reported that 54% of respondents in Tennessee always check their bodies carefully for ticks after being in tick-infested areas. Omodior et al., 2021a reported that a thorough check of clothing and the body for ticks after returning from the outdoors was done by 81% of adults and for 85% of children in Indiana, but the frequency of taking this action was not specified.

3.5.4. Targeted state/local surveys of subsets of the public with presumed elevated concern about tick-borne illness in areas where Ixodes-associated TBDs predominate—Data are available from 21 studies focusing on visitors to recreation areas or including other respondent populations with potentially elevated level of concern about TBDs (including control populations in LD case-control studies or education intervention studies). Nine of these studies reported on consistent use of tick checks (e.g., usually, regularly, always/most of the time, daily, or every day or most days), which ranged from 25 to 45% for respondents in Maryland, Maryland/Virginia, and Massachusetts (Daltroy et al., 2007; Valente et al., 2015; Hu et al., 2019), 50–60% for park visitors in Maryland and respondents in Rhode Island (Finch et al., 2014; Jones et al., 2015), and 68–79% for respondents in Connecticut, Massachusetts, and New Jersey (Orloski et al., 1998; Phillips et al., 2001; Vázquez et al., 2008; Butler et al., 2016). Studies from Delaware (Gupta et al., 2018) or primarily the Northeast/Mid-Atlantic states (Kopsco and Mather, 2021) presented more detailed data for frequency of use. Conducting tick checks always or more than half of the time when returning from outdoors was reported by 22% of Delaware respondents, and this increased to 53% for doing so half the time or more (Gupta et al., 2018). In contrast, conducting tick checks always or more than half of the time after being outdoors was reported by 77% of respondents residing primarily the Northeast/Mid-Atlantic states, and this increased to 87% for doing so half the time or more (Kopsco and Mather, 2021). Categorizing use as always, sometimes, or never, another study from Connecticut reported that roughly 50% of respondents always conducted tick checks (Gould et al., 2008). A unique study on a Brazilian immigrant population in Massachusetts found that 28% of respondents, including both outdoor and indoor workers, always or usually checked for ticks after walking out in the woods or working outdoors (Heller et al., 2010).

Based on data from the control group in a LD case-control study, Connally et al. (2009) reported that 65% of Connecticut respondents performed tick checks within 36 h after spending time in the yard on at least some occasion in the month prior to onset of symptoms in their matched case patients. Three other studies conducted in Maryland, Massachusetts, New Jersey/New York, and Wisconsin did not define the frequency of checking for ticks: in these surveys the proportions of respondents taking this action ranged from 66 to 85% (Shadick et al., 1997; Malouin et al., 2003; Bron et al., 2020). For studies on high school students, 48% of Connecticut students reported always or often doing tick checks after walking in wooded areas or grass (Cartter et al., 1989), whereas 30% of students in Massachusetts checked their skin for tick most of the time (Valente et al., 2015). In another study from Massachusetts on elementary school students, 34% reported always or usually checking themselves for ticks (Shadick et al., 2016). In a final study presenting information on tick checks, data were not collected or presented in a manner that allows for clear interpretation of the results (Hallman et al., 1995).

Some studies provided additional notable information about tick checks. With regards to conducting tick checks outdoors versus after coming inside, Smith et al. (2001) found that Pennsylvania respondents most commonly did both (54%), followed by checking for ticks only when coming inside (44%) and rarely reporting checking for ticks only while outdoors (2%). Malouin et al. (2003) reported that similar proportions of respondents checked for ticks at home (65%) and away from home (59%), and noted that 13% of respondents used a handheld mirror to check for ticks. Shadick et al. (1997) found that of the respondents conducting tick checks, approximately 60% reported examining the entire body whereas 40% conducted more cursory tick checks focusing on feet and legs or exposed skin. Finally, Jones et al. (2015) reported that park visitors in Maryland more commonly checked for ticks on the body (61%) than on clothing (51%).

3.5.5. Targeted state/local surveys of subsets of the public with presumed elevated concern about tick-borne illness in areas where Amblyomma/ Dermacentor-associated TBDs predominate—Data are restricted to a single survey of adult visitors to recreational areas in Missouri, where 52% of respondents reported checking for ticks regularly (always or most of the time) after spending time in the recreational area (Bayles et al., 2013).

3.5.6. Targeted surveys of outdoor workers in areas where Ixodes-associated TBDs predominate—Of the seven studies of outdoor workers, primarily employees in outdoor recreation areas, one presented multiple categories for frequency of use (Kopsco and Mather, 2021) and four defined the frequency of checking for ticks as always (Schotthoefer et al., 2020) or always/usually (Goldstein et al., 1990; Han et al., 2014; Jones et al., 2015), whereas the other two studies did not define the frequency of use (Smith et al., 1988; Nolan and Mauer, 2006). As results nevertheless were similar across all studies, they are presented collectively below. While at work, the proportion of respondents that reported regularly checking for ticks on their clothes and body ranged from roughly 70 to 90%. Tick checks focusing on the body were slightly more common than checks focusing on clothing (Han et al., 2014; Jones et al., 2015). Three studies also included information for tick checks while at work versus at leisure: Smith et al. (1988) reported similar proportions of respondents checking for ticks at work and at leisure, whereas Goldstein et al. (1990) found checking for ticks to be slightly more likely at work and Nolan and Mauer (2006) reported tick checks being slightly more common at leisure.

3.5.7. Targeted surveys of outdoor workers in areas where Amblyomma/ Dermacentor-associated TBDs predominate—Data are available from two studies in Florida and Oklahoma. A survey of Florida Fish and Wildlife/Florida State Parks employees found that 73% always check for ticks on their skin (Donohoe et al., 2018). A study on beef producers in Oklahoma similarly reported that 67% of respondents check their body for ticks when leaving the field (Noden et al., 2020).

3.5.8. Surveys from Canada and Europe—Surveys that include questions about tick checks also have been conducted in Canada and Europe, with the proportion of respondents regularly taking this action most often in the range of 30–70% (Bartosik et al., 2008; Beaujean et al., 2013a, b; Mowbray et al., 2014; Aenishaenslin et al., 2015, 2017; Antonise-Kamp et al., 2017; Zöldi et al., 2017; Slunge and Boman, 2018; Buczek et al., 2020).

3.5.9. Conclusions and future directions—Regular use of tick checks has been reported by 30–70% of respondents in most studies of the public in the United States conducted over the last decade. One complication is that recent surveys tend to focus solely on (thorough) tick checks conducted when coming indoors rather than also considering (quick and cursory) checks of clothing and skin for ticks while still outdoors in tick habitat. This could be addressed in future surveys. As a thorough tick check is difficult to conduct, it also would be useful in future surveys to clarify the details of how such checks typically are conducted for children of different age groups and adults (for example if clothes are removed and which parts of the body are examined). It stands to reason that tick checks would be most effective when conducted for small children, for example while they are taking a daily bath. Finally, as for all other personal protection measures, it would be useful in future surveys to consistently evaluate and present data for how frequently tick checks are conducted.

3.6. Showering/bathing after coming indoors

Showering/bathing after spending time outdoors has been included in 11 surveys (Table 2). The context of survey questions has been variable across studies, including for the definition of the time period after coming indoors when the shower/bath took place (e.g., immediately; soon; within 2 h of being outdoors), the specific purpose of the shower/bath (e.g., shower soon after coming indoors; shower or bathe to remove ticks; shower immediately after returning from the outdoors, specifically because of concern for ticks), or the spatial scope of the outdoor activity (e.g., in the yard; outdoors). Although survey questions were specific to tick bite prevention, showering/bathing after spending time outdoors is also routinely done to clean off sweat, grime, sunscreen, and repellent.

3.6.1. Randomized national surveys of the public—Three national surveys have presented data for showering/bathing to prevent tick bites. Two of these studies (Hook et al., 2015; Nawrocki and Hinckley, 2021) reported that 15–16% of respondents routinely shower/bathe soon after coming inside to prevent tick bites, whereas the third study (Beck et al., 2021) focusing specifically on the Hispanic population in the United States showed a slightly lower level (11%) of respondents routinely showering/bathing soon after coming inside to prevent tick bites. In the studies focusing broadly on the population of the United States, variation in routine use of showering/bathing to prevent tick bites was recorded across geographical regions (ranging from 6 to 7% in the Mountain and Pacific regions to 19–27% in the South Atlantic, Mid-Atlantic, East South Central, and West North Central regions) but not for groupings of high LD incidence states (16%) versus groupings that included low incidence states (14–18%).

3.6.2. Randomized state/local surveys of the public in areas where Ixodes-associated TBDs predominate—Data are restricted to a single survey of adults in parts of Connecticut and Maryland with elevated LD incidence (Niesobecki et al., 2019). Showering/bathing within 2 h always or most of the time after being outdoors in places where you could get ticks was reported by 40% of respondents in Connecticut and 43% in Maryland.

3.6.3. Randomized state/local surveys of the public in areas where Amblyomma/Dermacentor- associated TBDs predominate—Data are restricted to a single survey from Indiana that included both adults and children (Omodior et al., 2021a). Taking showers immediately after returning from the outdoors (specifically because of concern for ticks) was reported by 62% of adults and for 67% of children, but the frequency of taking this action was not specified.

3.6.4. Targeted state/local surveys of subsets of the public with presumed elevated concern about tick-borne illness in areas where Ixodes-associated TBDs predominate—Data are available from six studies focusing on visitors to recreation areas or including other respondent populations with potentially elevated level of concern about TBDs (including control populations in LD case-control studies). Three of these studies reported on regular/consistent practice (routinely; or always or usually) of showering/bathing when coming indoors: proportions of respondents taking this action ranged from roughly 30% for respondents in a Maryland/Virginia study (Hu et al., 2019) to 53% for day visitors to a recreational area in Maryland (Jones et al., 2015) and 59% for a study from Connecticut (Butler et al., 2016). A study from Delaware that included all age groups presented more detailed data for frequency of use (Gupta et al., 2018). Showering always or more than half of the time immediately after returning indoors was reported by 40% of respondents, and this increased to 74% for doing so half the time or more. As presented here, the survey question (from Appendix A in Gupta et al. 2018) used the phrase shower immediately after returning indoors whereas the publication used the phrase shower within 2 h after returning indoors. Bron et al. (2020) reported that roughly 40–50% of respondents in New Jersey/New York and Wisconsin shower/bathe to remove ticks, but did not define the frequency of use. Finally, based on data from the control group in a LD case-control study, Connally et al. (2009) reported a high proportion (85%) of Connecticut respondents bathing within 2 h after spending time in the yard on at least some occasion in the month prior to onset of symptoms in their matched case patients.

3.6.5. Targeted state/local surveys of subsets of the public with presumed elevated concern about tick-borne illness in areas where Amblyomma/ Dermacentor-associated TBDs predominate—Published studies are lacking.

3.6.6. Targeted surveys of outdoor workers in areas where Ixodes-associated TBDs predominate—Data are available from one study of outdoor workers in a Maryland recreation area, where 38% of respondents reported showering/bathing within 2 h after coming indoors (Jones et al., 2015).

3.6.7. Targeted surveys of outdoor workers in areas where Amblyomma/ Dermacentor-associated TBDs predominate—Published studies are lacking.

3.6.8. Surveys from Canada and Europe—A national survey from Canada (Aenishaenslin et al., 2017) found that 36–53% of respondents across provinces take a shower or bath after activities occurring in a wooded area where ticks may occur.

3.6.9. Conclusions and future directions—Regular use of showering/bathing after coming indoors to prevent tick bites has been reported by 15–40% of respondents in most studies of the public in the United States conducted over the last decade. Part of the observed variation could have resulted from variable context of survey questions, such as defining different limits of time for when the shower/bath took place after coming indoors and more or less clearly defining the specific purpose of why the respondent took a shower/bath. The action of showering/bathing in the context of preventing tick bites may also be difficult to separate from a tick check if removing outdoor clothing and showering/bathing are part of a thorough tick check of the skin. As for the other personal protection measures, it would be useful in future surveys to consistently evaluate and present data for how frequently respondents shower/bathe to prevent tick bites or detect attached ticks. It also would be beneficial to better understand how removed clothing is handled as part of the showering/ bathing activity, such as being run in a dryer at high heat to kill ticks still on the clothing or immediately washed and then placed in the dryer when being removed versus simply being placed in a laundry hamper until the next load of laundry is due.

3.7. Comparison across personal protection measures

Studies on the level of use of different personal protection measures to prevent tick bites have used different recruitment strategies, focused on different types of respondent populations, employed variable phrasings of survey questions relating to a given personal protection measure, and presented results based on variable frequencies of taking action. Although this complicates the synthesis of the findings, the studies collectively indicate that members of the public commonly take action to prevent tick bites, most frequently by wearing untreated protective clothing or conducting tick checks (done routinely by 30–70% of respondents in most studies of the public), followed by showering/bathing after being outdoors or using repellents on skin/clothing (15–40% range), and with permethrin-treated clothing being the least frequently used tick bite prevention method (<5 to 20%). In the majority of individual studies focusing on the public and evaluating routine use of multiple personal prevention measures, the level of use is greater for the non-chemical approaches of wearing untreated protective clothing or conducting tick checks compared to applying repellents (Orloski et al., 1998; Phillips et al., 2001; Smith et al., 2001; Jones et al., 2002; Herrington, 2004; Gould et al., 2008; Vázquez et al., 2008; Connally et al., 2009; Finch et al., 2014; Hook et al., 2015; Jones et al., 2015; Valente et al., 2015; Butler et al., 2016; Niesobecki et al., 2019; Kopsco and Mather, 2021). Notable exceptions include the study by Gupta et al. (2018) in Delaware, a study focusing on visitors to recreation areas in Missouri (Bayles et al., 2013), and three recent surveys that introduced the phrase “check for ticks daily/check my body for ticks daily” for tick checks but used the less specific phrase “wear repellent” for application of repellent (Hu et al., 2019; Beck et al., 2021; Nawrocki and Hinckley, 2021).

4. Evidence base for the effectiveness of personal protection measures to prevent human tick bites and TBD

As shown in Section 3, widely recommended personal protection measures for tick bite prevention are used by the public. However, the evidence base for the effectiveness of these measures to prevent tick bites and TBD is weak (Mead, 2011; Eisen and Gray, 2016; Eisen and Mead, 2020; Lantos et al., 2021). Sections 4.1 to 4.5 provide an overview of studies from the United States on associations between use of specific personal protection measures and the frequency of tick bites or occurrence of TBD cases. Data for impact of personal protection measures on the frequency of tick bites come from a set of experimental field or semi-field studies (Schreck et al., 1980, 1982a, 1982b, 1986; Mount and Snoddy, 1983; Lane and Anderson, 1984; Lane, 1989; Evans et al., 1990; Vaughn and Meshnick, 2011; Jordan et al., 2012; Vaughn et al., 2014; Richards et al., 2015; Mitchell et al., 2020b) and one cross-sectional study (Mead et al., 2018). Data for impact on occurrence of cases of LD and other TBDs come from a set of 13 case-control studies or cross-sectional studies focused on outdoor workers or the public (Table 4). Only five of these studies presented statistical analyses accounting for frequency of use of personal protection measures, defined as regular (Orloski et al., 1998; Finch et al., 2014), routine (Vázquez et al., 2008), always/usually (Phillips et al., 2001), or broken down by percentage classes of time used (Ley et al., 1995). Another potential issue is that the strength of the association between use of a single personal protection measure aiming to prevent tick bites and infection with TBD may be confounded by use of one or several other actions also serving the purpose of preventing tick bites. Analyses taking into account the full range of personal protection measures to prevent tick bites taken by each surveyed individual are lacking from the published literature. Terms written as abbreviations in Sections 4.1–4.5 include Odds Ratio (OR), Relative Risk (RR) and Confidence Interval (CI).

4.1. Untreated protective clothing

No prospective experimental study in the United States has evaluated the protective effect against tick bites or tick-borne infections of wearing untreated protective clothing (light-colored clothing; long pants/long-sleeved shirt; shirt tucked into pants/pants tucked into socks). However, data for use of this personal protection measure collected as part of 12 case-control or cross-sectional studies (Table 4) provide insights into the potential to prevent tick-borne infections, including LD. The context of survey questions has been variable across studies, ranging from general without qualifiers for circumstance or frequency of use (wearing protective clothing; wearing light-colored clothing; wearing long pants/long-sleeved shirt; tucking pants into socks) to more specific by defining the circumstance of use (e.g., working or playing in your yard; while in yard; during work or recreation outdoors away from home) or the frequency of use (e.g., untreated protective clothing used 0–5, 6–50, 51–90, or 91–100% of the time when outside).

Of the 12 studies presenting data on associations between use of untreated protective clothing and TBD, nine found no significant beneficial effect of wearing untreated protective clothing on the probability of acquiring LD or another TBD for outdoor workers (Smith et al., 1988) or the public (Lane et al., 1992; Klein et al., 1996; Orloski et al., 1998; Armstrong et al., 2001; Phillips et al., 2001; Smith et al., 2001; Connally et al., 2009; Kianersi et al., 2020). However, only two of these studies (Orloski et al., 1998; Phillips et al., 2001) included analyses that took the frequency of wearing untreated protective clothing into account. Four studies focusing on the public did show a protective ($n = 3$) or borderline protective ($n = 1$) effect and these deserve further mention. Ley et al. (1995) found that wearing long pants ≤5% of the time when outdoors, compared to 91–100% of the time, was associated with increased risk for LD, based on physician-diagnosed erythema migrans, for a set of participants living primarily in north coastal California (OR = 4.8; 95% CI = 1.0–22.4). Less frequent use of long pants (6–50 or 51–90%) was not protective compared to use ≤5% of the time. No significant differences were recorded across use frequency classes for wearing light-colored clothing, long-sleeved shirts, or tucking pant legs into socks (Ley et al., 1995). Vázquez et al. (2008) found routine use of protective clothing while outdoors to reduce the risk of definite physician-diagnosed LD in Connecticut (OR = 0.6; 95% CI = 0.5–0.7). Finch et al. (2014) reported that regular use of protective clothing was associated with reduced probability of being seropositive for LD in Rhode Island (OR = 0.5; 95% CI = 0.3–0.8). Finally, Orloski et al. (1998) reported borderline protective effects against physician-diagnosed LD for members of the public in New Jersey reporting regularly wearing light-colored clothing (OR = 0.4; 95% CI = 0.2–1.1) or tucking pant legs into socks (OR = 0.3; 95% CI = 0.1–1.2), but not for those wearing long pants.

The overall results are contradictory for all types of untreated protective clothing, with a few studies indicating a protective effect against TBDs but most studies failing to find such an effect. However, it is worth noting that studies assessing the protective effect of regular/routine use appear more likely to show a protective or borderline protective effect of wearing different types of untreated protective clothing against TBD compared with studies where the frequency of use was not defined in the publication. It would be beneficial in future studies to: (i) explore the impact of frequency of use of untreated protective clothing on the level of protection against TBD; (ii) include an analysis for a composite of untreated protective clothing (as attempted by Lane et al. 1992) in addition to analyzing each subtype of untreated protective clothing separately; and (iii) account for the potentially confounding effect of repellent use on exposed skin, when wearing shorts and a short-sleeved shirt, as a means to avoid wearing warm, uncomfortable untreated protective clothing but still be protected against tick bites. These types of analyses could help to define the circumstances under which untreated protective clothing fail or succeed to protect against TBD.

4.2. Repellents for skin and clothing

There are several excellent reviews on active ingredients used in tick repellents, including those based on natural products, as well as the benefits and drawbacks of different laboratory bioassays used to quantify the efficacy of active ingredients or commercial repellent formulations against ticks (Dautel et al., 1999, 2013; Bissinger and Roe, 2010; Carroll et al., 2011; Dolan and Panella, 2011; Pages et al., 2014; Benelli et al., 2016; Adenubi et al., 2018; Nwanade et al., 2020). These topics will not be discussed further here; the following Sections will focus on use of repellents to protect humans from tick bites and tick-borne infections in natural settings.

4.2.1. Experimental field studies to evaluate the impact of repellents on the frequency of human tick encounters or tick bites—A suite of experimental field studies have assessed protection afforded by repellents applied to clothing against different human biting tick species, including for DEET against *A. americanum* (Schreck et al., 1980; Mount and Snoddy, 1983; Evans et al., 1990), *D. variabilis* (Mount and Snoddy, 1983; Evans et al., 1990), and *I. scapularis* (Schreck et al., 1986; Evans et al., 1990); and for plant-derived compounds against *A. americanum* and *I. scapularis* (Jordan et al., 2012). All studies focused on use of repellent-treated coveralls or military uniforms, thus covering a very large portion of the body, and were limited by small (n = 3–6) participant sample sizes and inclusion of experimental field activities rather than normal daily outdoor activities. Use of DEET-treated clothing, compared to similar but untreated clothing, was found to reduce the frequency of finding crawling or attached ticks on the subjects by 50–90% across studies for *A. americanum* nymphs and adults, by 50–95% for *D. variabilis* adults, and by 80–100% for *I. scapularis* nymphs and adults. Coverall treatments with solutions containing plant-based active ingredients (nootkatone or a mixture of rosemary, cinnamon leaf, lemongrass oils, and geraniol) also were found to provide a high level of protection (>90% reduction in numbers of crawling ticks) against *A. americanum* and *I. scapularis* nymphs up to 3 d after treatment (Jordan et al., 2012).

Although these studies clearly demonstrate the value of repellents for personal protection against human biting ticks, there is a lack of prospective experimental studies from the United States to evaluate the protective effect of repellents against tick bites and tick-borne infections when applied by members of the public to skin or summer-weight clothing during normal daily activities. One example of such a study comes from Sweden, where a cross-over field trial demonstrated a 3-fold reduction in *I. ricinus* bites for use of a lemon eucalyptus-based repellent formulation, compared with no repellent use, in members of the public engaging in various outdoor activities (Gardulf et al., 2004). Another notable finding was that application of repellent only to the lower extremities resulted in 5.6-fold reduction in tick bites located below the waist but only 1.5-fold reduction in tick bites located above the waist, underscoring the importance not only of using repellents but also how they are applied across the body.

4.2.2. Studies on associations between repellent use and TBDs—

Data for use of repellents collected as part of 12 case-control or cross-sectional studies (Table 4) provide additional insights into the potential to prevent tick-borne infections, including LD. The context of survey questions has been variable across studies, ranging from general without qualifiers for circumstance or frequency of use (use of repellent) to more specific by defining the circumstance of use (e.g., in the yard versus elsewhere), or how the repellent was applied (e.g., to skin versus clothing).

Of the 12 studies presenting data on associations between use of repellents and TBD, eight found no significant beneficial effect of applying repellents to skin or clothing on the probability of acquiring LD or other TBDs for outdoor workers (Smith et al., 1988) or the public (Ley et al., al.,1995; Klein et al., 1996; Orloski et al., 1998; Armstrong et al., 2001; Phillips et al., 2001; Connally et al., 2009; Finch et al., 2014). However, only four of these studies (Ley et al., 1995; Orloski et al., 1998; Phillips et al., 2001; Finch et al., 2014) included analyses that took the frequency of using repellents into account. Six studies involving outdoor workers or the public did show a protective ($n = 4$) or borderline protective ($n = 2$) effect. Schwartz and Goldstein (1990) reported that outdoor workers in New Jersey choosing to not use repellents were at increased risk for acquiring LD, based on serological evidence, compared to those who wore repellent at some undefined level of frequency (Adjusted OR = 2.0; 95% CI = 1.0–4.0). Moreover, although the results were not statistically significant, a similar study on outdoor workers in New York (Smith et al., 1988) showed a tendency toward increased risk for acquiring LD for those choosing not to apply repellents to clothing at work or at leisure (RR = 3.3; 95% CI = 0.9–12.2; and RR = 4.5; 95% CI = 0.8–26.2, respectively) compared to those using repellents at some undefined level of frequency. Focusing on the public in Pennsylvania, Smith et al. (2001) found use of repellents (without defining the frequency of use) to be protective against physician-diagnosed LD for recreation away from the home (OR = 0.7; 90% CI = 0.56–0.95) but not for activities taking place in the yard. In Connecticut, Vázquez et al. (2008) found routine use of repellents to reduce the risk of definite physician-diagnosed LD (OR = 0.8; 95% CI = 0.6–0.9), and Connally et al. (2009) found wearing repellent while in the yard (at least on some occasion in the month prior to onset of symptoms for case patients, or during the same time period for their matched controls) to be borderline protective against physician-diagnosed LD (OR = 0.7; 95% CI = 0.5–1.02). Finally, Kianersi et al. (2020) found use of repellent on exposed skin (without defining the frequency of use) to be protective against self-reported TBD in Indiana (Doubly Robust Adjusted OR = 0.6; 95% CI = 0.4–0.9).

The overall results for repellents are contradictory, with a mix of studies indicating a protective or borderline protective effect against TBD but other studies failing to find such an effect. It would be beneficial in future studies to: (i) better define the impact of frequency of use of repellents on the level of protection against TBD; (ii) include an analysis for overall use of repellents (on skin and clothing) in addition to analyzing repellent application to skin and clothing separately; (iii) account for which body parts or pieces of clothing typically are treated with repellents, which may be relevant to the questing behavior of different tick species and life stages; (iv) account for whether or not the repellent products used are registered by the EPA and thus known to be effective against ticks; and (iv) determine whether individuals choosing not to use repellents instead are using untreated protective clothing or permethrin-treated clothing for tick bite prevention. These types of analyses could help to define the circumstances under which use of repellents fail or succeed to protect against TBD.

4.3. Permethrin-treated clothing

Different types of laboratory bioassays for testing the efficacy of permethrin-treated textiles against human biting ticks were reviewed previously (Eisen et al., 2017a). This topic will not be discussed further here; the following Sections will focus on use of permethrin-treated clothing to protect humans from tick bites and tick-borne infections in natural settings.

4.3.1. Experimental field or semi-field studies to evaluate the impact of permethrin-treated clothing on the frequency of human tick encounters or tick bites—A suite of experimental field studies in the United States have assessed the protective effect of permethrin-treated clothing against human biting tick species, including *A. americanum* (Schreck et al., 1980, 1982a, b; Mount and Snoddy, 1983; Evans et al., 1990; Vaughn and Meshnick, 2011; Jordan et al., 2012; Vaughn et al., 2014; Richards et al., 2015), *D. occidentalis* (Lane and Anderson, 1984), *D. variabilis* (Mount and Snoddy, 1983; Evans et al., 1990), *I. pacificus* (Lane, 1989), and *I. scapularis* (Schreck et al., 1986; Evans et al., 1990; Jordan et al., 2012; Mitchell et al., 2020b). The majority of these studies focused on use of permethrin-treated coveralls or military uniforms, thus covering a very large portion of the body, and were limited by small (n = 2–10) participant sample sizes and inclusion of experimental field activities rather than normal daily outdoor activities (Schreck et al., 1980, 1982a, b, 1986; Mount and Snoddy, 1983; Lane and Anderson, 1984; Lane, 1989; Evans et al., 1990; Jordan et al., 2012). One important finding in the early studies, from 1982 to 1990, was that ticks removed from permethrin-treated clothing at the conclusion of the field activity periods, as well as ticks purposefully placed on the clothing and forced to stay in contact with the permethrin-treated textile for a short period of time (<5 min), frequently were impacted by the permethrin to the point of being incapable of normal movement. As ticks start to become impacted by the permethrin and loose the capacity for coordinated movement, they may become trapped in the fibers of the textile rather than being able to actively disengage or passively fall off the textile. Simply counting the number of ticks present on permethrin-treated clothing without also assessing their vigor therefore is likely to underestimate the protective effect of the clothing. This also presents a challenge when comparing results across studies where some only recorded the numbers of ticks recovered from permethrin-treated clothing whereas others also account for the vigor of the collected ticks.

Considering only studies that accounted for both the number of ticks collected from clothing or skin and the vigor of the ticks, the protection against tick bites for subjects wearing permethrin-treated coveralls or military uniforms, compared to similar but untreated clothing, was estimated to be: 65–100% for *D. variabilis* adults (Mount and Snoddy, 1983; Evans et al., 1990); 85–100% for *A. americanum* adults (Schreck et al., 1982a, b; Mount and Snoddy, 1983; Evans et al., 1990); 95–100% for *A. americanum* nymphs (Schreck et al., 1982a, b; Mount and Snoddy, 1983; Evans et al., 1990); and to approach 100% for *I. scapularis* nymphs and adults (Schreck et al., 1986; Evans et al., 1990) and *I. pacificus* adults (Lane, 1989). A similar pattern with greater impact of brief (1–2 min) exposures to permethrin-treated textile for *I. scapularis* nymphs, *I. scapularis* adults, and *A. americanum* nymphs, compared to *D. variabilis* adults and *A. americanum* adults, was later observed in a laboratory bioassay (Prose et al., 2018). Moreover, a comparable level of protection to that seen for *I. pacificus* and *I. scapularis* (>95%) was recorded also for the closely related *I. ricinus* in field evaluations of the protective efficacy of permethrin-treated military uniforms in Germany (Faulde et al., 2008, 2014).

More recent prospective studies in the United States aimed to evaluate the protective effect against tick bites of permethrin-treated clothing worn by outdoor workers during their normal daily activities: these include two pilot studies with smaller numbers (n = 16–34) of total participants conducted in geographical areas where *A. americanum* is the dominant human biting tick (Vaughn and Meshnick, 2011; Richards et al., 2015), and two larger-scale randomized-controlled trials involving 80 to 160 total participants in areas where the dominant human biting tick is *A. americanum* (Vaughn et al., 2014) or *I. scapularis* (Mitchell et al., 2020b). In all four studies, articles of work clothing worn by the participants were sent to Insect Shield, LLC (Greensboro, NC, USA) for permethrin-impregnation (and sham-impregnation in those studies where treatment versus control was blinded to the participants). Of the two pilot studies, one showed a dramatic (93%) reduction in work-related tick bite incidence for subjects in the treatment group (Vaughn and Meshnick, 2011) whereas the other study found no protective effect of permethrin-treated clothing against tick bites (Richards et al., 2015). Factors potentially impacting the outcomes of these pilot studies include that the study demonstrating protection against tick bites: (i) focused on a study population with more homogenous work duties conducted within a more restricted geographical area; (ii) included permethrin-treatment not only for pants and shirts but also for boots and socks; and (iii) made a clear distinction between tick bites perceived to be associated with work versus non-work activities.

Both larger-scale studies demonstrated protective effects of wearing permethrin-treated work clothing, with reductions in perceived work-related tick bite incidence ranging from 50 to 65% across two study years in the area where *I. scapularis* is the dominant human biting tick (Mitchell et al., 2020b) to 34–82% across two study years in the area where *A. americanum* is the dominant human biting tick (Vaughn et al., 2014). The level of tick bite protection decreased from the first to the second year in both studies, possibly due to greater adherence in wearing the treated clothing during the first year. It is also worth noting here that a recent study from Korea (Han et al., 2021) focusing on members of the public in rural areas evaluated the protective effect against tick bites of wearing permethrin-treated socks. With the treated clothing limited to socks, overall tick bite rates were found to be similar for the treatment group and a control group wearing untreated socks, although there was a reduction in tick bite rates specifically for the lower extremities for the treatment group. As tick species was not determined in the study, it is not possible to relate this outcome to tick host-seeking behavior.

Another point worth considering is that using biting ticks (attached to human skin) as the outcome measure may underestimate the protective effect of permethrin-treated clothing. A semi-field trial where volunteers were experimentally exposed to *I. scapularis* nymphs (Miller et al., 2011) indicated that temporary exposure to summer-weight permethrin-treated clothing prior to a bite resulted in most nymphs dying within hours of their attachment. Moreover, wearing permethrin-treated versus untreated summer-weight clothing articles (sneakers, socks, shorts, and T-shirt) resulted in a 3-fold reduction in the number of laboratory-reared nymphs that attached after being introduced onto shoes or skin on the legs or arms of the human volunteers (Miller et al., 2011). Prospective experimental studies on tick bite protection for members of the public associated with wearing permethrin-treated summer-weight clothing articles during normal daily activities are still lacking.

4.3.2. Studies on associations between use of permethrin-treated clothing and TBDs—

A single LD case-control study conducted in Connecticut (Connally et al., 2009) has attempted to evaluate the association between use of permethrin-treated clothing and tick-borne infection. There was no difference in the proportions of cases (0.7%) and controls (0.7%) using permethrin-treated clothing, but it should be noted that very few study participants used this personal protection measure, and that use was defined as wearing permethrin-treated clothing at least on some occasion while in the yard in the month prior to onset of symptoms for case patients or during the same time period for their matched controls. A cross-sectional study in Indiana (Kianersi et al., 2020) also included permethrin-treated clothing but it is not clear from the publication if permethrin-treated clothing was grouped with clothing treated with skin/clothing repellents in the data presentation for associations with self-reported TBD. The strong results from studies with tick bites as the primary outcome measure (see Section 4.3.1) merit additional efforts to evaluate the protective effect of permethrin-treated clothing also for TBDs. It would be beneficial in such studies to: (i) better define the impact of frequency of use of permethrin-treated clothing on the level of protection against TBD; (ii) account for which pieces of worn clothing (including shoes, socks, long pants, shorts, long-sleeved shirts, and short-sleeved shirts) typically are treated with permethrin, which may be relevant to the questing behavior of different tick species and life stages; and (iii) determine whether individuals choosing not to use permethrin-treated clothing instead are using untreated protective clothing or repellents applied to clothing for tick bite prevention. These types of analyses could help to define the circumstances under which use of permethrin-treated clothing fail or succeed to protect against TBD.

4.4. Tick checks

No prospective experimental study in the United States has evaluated the protective effect against tick bites or tick-borne infections of conducting tick checks. However, data for use of this personal protection measure collected as part of 11 case-control or cross-sectional studies (Table 4) provide insights into the potential to prevent tick-borne infections, including LD. The context of survey questions has been variable across studies, ranging from general without qualifiers for circumstance or frequency of use (e.g., perform tick check; check body for ticks) to more specific by defining the circumstance of use (e.g., in the yard versus elsewhere) or other aspects of use (e.g., while outdoors versus after coming inside).

Of the 11 studies presenting data on associations between tick checks and TBD, eight found no significant beneficial effect of performing tick checks on the probability of acquiring LD or other TBDs for outdoor workers (Smith et al., 1988) or the public (Ley et al., 1995; Klein et al., 1996; Orloski et al., 1998; Armstrong et al., 2001; Phillips et al., 2001; Vázquez et al., 2008; Finch et al., 2014). Five of these studies (Ley et al., 1995; Orloski et al., 1998; Phillips et al., 2001; Vázquez et al., 2008; Finch et al., 2014) included analyses that took the frequency of performing tick checks into account. Four studies focusing on the public did show a protective (n = 3) or borderline protective (n = 1) effect. Smith et al. (2001) found tick checks (without defining the frequency of use) to be protective against physician-diagnosed LD in Pennsylvania when performed during outdoor activities (OR = 0.6; 90% CI = 0.5–0.7) but not when done after outdoor activities. Connally et al. (2009) found that performing tick checks within 36 h after spending time in the yard (at least on some occasion in the month prior to onset of symptoms for case patients, or during the same time period for their matched controls) was protective against physician-diagnosed LD in Connecticut (OR = 0.6; 95% CI = 0.4–0.9). Kianersi et al. (2020) found a thorough body/clothes tick check after being outdoors to be protective against self-reported TBD in Indiana (Doubly Robust Adjusted OR = 0.4; 95% CI = 0.2–0.7). Moreover, Orloski et al. (1998) reported borderline protective effects against physician-diagnosed LD for members of the public in New Jersey performing regular tick checks (OR = 0.5; 95% CI = 0.2–1.1).

The overall results for tick checks are contradictory, with some studies indicating a protective or borderline protective effect against TBD but other studies failing to find such an effect. The finding by Smith et al. (2001) that tick checks were protective against LD when performed during but not after outdoor activities underscores the importance of evaluating tick checks under each of these circumstances rather than focusing only on tick checks when coming indoors. This finding may be most relevant to *Ixodes* nymphs, which are small and notoriously diffi-cult to detect while biting, and it therefore is important to conduct regular tick checks while outside to maximize the likelihood of detecting them while still crawling. Moreover, a recent study from the Upper Midwest using tick specimens embedded in resin blocks showed that <60% of respondents recognized *I. scapularis* nymphs as ticks, whereas >75% recognized adults of *A. americanum, D. variabilis*, and *I. scapularis* as ticks (Bron et al., 2021). It would be useful to better understand how quick, cursory tick checks conducted while outside, versus more thorough tick checks conducted when coming back inside, perform against different tick species and life stages with variable size and movement speed while on clothing or skin. In future studies, it would be beneficial to: (i) explore the impact of frequency of conducting tick checks on the level of protection against TBD; (ii) include analysis for a composite of conducting tick checks while outside and when coming inside in addition to analyzing each of these actions separately; (iii) account for variable thoroughness of conducting tick checks when coming inside (e.g., portions of the body examined and whether clothing was removed to facilitate detection of ticks crawling on or attached to the skin); (iv) account for tick checks done separately from versus part of the process of showering/bathing; and (v) account for use of untreated protective clothing, repellents, and permethrin-treated clothing as taking these actions may modify the likelihood of doing a tick check or the thoroughness of the tick check. It also may be beneficial to address tick checks in a broader context including actions relating to handling of clothing worn outdoors when returning inside. These types of analyses could help to define the circumstances under which tick checks fail or succeed to protect against TBD.

4.5. Showering/bathing after coming indoors

Four studies have evaluated associations between showering or bathing after coming indoors and outcomes related to tick detection or occurrence of tick-borne infection. Mead et al. (2018) reported an increased probability (OR = 3.7; 95% CI = 1.3–10.3) for Connecticut residents to find a tick on them on days when they took a shower or bath, which should lead to fewer ticks attaching if they were discovered before biting or shortened feeding durations prior to tick removal if they had already attached. Moreover, Connally et al. (2009) reported a protective effect of bathing within 2 h after spending time in the yard (at least on some occasion in the month prior to onset of symptoms for case patients, or during the same time period for their matched controls) against physician-diagnosed LD in Connecticut (OR = 0.6; 95% CI = 0.4–0.96). However, Kianersi et al. (2020) found no similar beneficial effect of showering immediately after being outdoors on self-reported TBD in Indiana residents (Doubly Robust Adjusted OR = 1.2; 95% CI = 0.7–2.1). In an older LD case-control study of children, Klein et al. (1996) found no significant association between the frequency of children bathing and physician-diagnosed LD (no further details about the analysis were given). In future studies, it would be beneficial to: (i) explore the impact of the frequency of showering/bathing on the protective effect against TBD; and (ii) define a biologically justified time period after coming indoors for which showering/bathing is considered to be most effective to prevent tick bites. It also may be beneficial to address showering/bathing in a broader context including actions relating to handling of clothing worn outdoors when returning inside and tick checks done separately from those conducted as part of showering/bathing.

5. Knowledge gaps, challenges, and opportunities for personal protection measures to prevent human tick bites

Despite well-documented use by the public of commonly recommended personal protection measures to prevent tick bites (see Section 3), there are major knowledge gaps for the effectiveness of these measures to prevent tick bites and tick-borne infections when they are used by the public in their daily lives (see Section 4). This stems in part from lack of prospective experimental studies to evaluate the impact of these measures. There also has been a disconnect between the complexity of how personal protection measures may impact human tick encounters (see Section 2.2) and how these measures have been addressed in LD/TBD case-control or cross-sectional studies (Sections 4.1–4.5). To some extent, this results from personal protection measures to prevent tick bites being part of broader surveys rather than being the main focus in case-control or cross-sectional studies, which has limited the amount of information reasonable to pursue for this particular sub-topic in the broader survey. The mixed results for evaluations of the ability of different personal protection measures to protect against TBD outlined in Section 4 suggest (from an optimistic perspective) that they can be protective, but the information gathered to date has not been sufficient to clarify the circumstances under which protection is achieved. It is also worth noting that the effectiveness of the two most commonly used tick bite prevention measures – wearing untreated protective clothing and conducting tick checks – to prevent TBD were evaluated in 11 case-control or cross-sectional studies published from 1988 to 2009, but only in two studies from 2010 to present time (see Table 4).

Future studies need to generate more detailed information about how personal protection measures to prevent tick bites are used, especially for critically important information on the frequency of use and extent of the body included in the protective action, to better define the circumstances under which a given action, or combination of actions, are ineffective versus protective. Such analyses should be based on information from each study participant on the full range of personal protection measures to avoid the pitfall for assessments of single measures that individuals not taking a given protective action (such as wearing long pants tucked into socks and a long-sleeved shirt tucked into the pants) chose to do so because they took another action (in this case, applying repellent to exposed skin on the arms and legs) with the same purpose. Slunge and Boman (2018) found that while a large share of respondents in Sweden stated that they always or often used untreated protective clothing (64%) or checked their body for ticks after being outdoors in areas with ticks (63%), considerably fewer respondents (45%) reported using both of these complementary methods to prevent tick bites. A similar finding was reported for use of repellent or tick checks, versus both, from Tennessee (Jones et al., 2002). Moreover, Butler et al. (2016) found that while 82% of respondents in Connecticut consistently used one of four personal protection measures (wearing untreated protective clothing, using repellent, performing a tick check, or bathing/showering within two hours of coming indoors), this fell to 66% for use of at least two of these complementary actions.

The overview of information on the level of use of personal protection measures by the public, presented in Section 3, underscores the difficulty in interpreting results across studies conducted over a long time period and where data were generated for different types of human populations and based on variable context for circumstance and frequency of use. In particular, comparing results across studies that did not define the frequency of taking a given protective action and other studies using variable frequency classification schemes for doing so is problematic. Studies presenting data based on well-defined frequency classification schemes (e.g., Gupta et al., 2018; Kopsco and Mather, 2021) illustrate how the percentage of respondents reporting taking a given action may change based on how a survey question defined, or did not define, how commonly the personal protection measure is used. For example, conducting tick checks when returning from the outdoors was reported by 78% of respondents when classified as being done at least rarely, whereas this fell to 53% for conducting tick checks at least half of the time and 22% for more than half of the time (Gupta et al., 2018). To be most informative, future studies should present clear usage frequency classification schemes for actions to prevent tick bites, such as Always / Frequently (more than half the time) / Sometimes (half the time) / Rarely (less than half the time) / Never. However, always (100% of the time) is perhaps not the best classification term if it is interpreted strictly by the respondents, and the combination of always/more than half of the time does not provide a breakdown of frequency of use above 51%. Another alternative is a breakdown based on percentage of occasions presenting risk for tick bites when the action is taken, such as 0%, 1–25%, 26–50%, 51–75%, or >75%. At present, it is not clear which of these options are most likely to capture a frequency of use potentially translating into protection against tick-borne infection. Other areas for survey improvement could include to focus on the most relevant time periods of the year for protective actions based on the seasonality of human biting tick species/life stages present in the target area, clarify which parts of the body typically are protected when using repellents or permethrin-treated clothing, and elucidate details of how tick checks are conducted.

The no-cost, non-chemical personal protection measures represented by untreated protective clothing and tick checks (including when showering/bathing) are intended to facilitate detection of ticks crawling on clothing and skin before they have a chance to bite. Although not evaluated experimentally, it stands to reason that these measures will be most effective in facilitating detection of adults of large *Amblyomma* and *Dermacentor* species, less effective against the smaller adults of *Ixodes* species, and least effective against the even smaller nymphal and larval life stages for those tick species where the immatures quest in such a manner that they encounter humans. Field observations on how ticks of different species and life stages behave when coming into contact with persons wearing untreated summer-weight protective clothing are lacking from the published literature.

Skin/clothing repellents and permethrin-treated clothing provide additional protection against tick bites as these measures do not rely on detection of crawling ticks. With the exception of purchasing factory-impregnated permethrin-treated clothing, these personal protection measures also carry low cost which is an important factor determining the level of use by the public or outdoor workers (Gould et al., 2008; Schotthoefer et al., 2020; Niesobecki et al., 2022). However, field or semi-field observations on how ticks of different species and life stages behave when coming into contact with persons wearing skin repellents or summer-weight clothing treated with repellents or permethrin are very scarce (Miller et al., 2011). Efforts to detect and promptly remove biting ticks is the last resort for the suite of actions addressed in this paper to primarily prevent tick bites and secondarily reduce the risk of pathogen transmission from biting ticks. This is another no-cost action but there is no question that it can be very challenging to conduct a thorough check for attached ticks, and information is very scarce for the details of how such checks typically are conducted by members of the public (Shadick et al., 1997).

In addition to improving the knowledge of the details of how personal protection measures are used and to what extent they reduce tick bites and TBDs, achieving an increase in the public's use of personal protection measures proven to be effective is a main challenge going forward. An in-depth discussion of different models to promote behavioral change and elucidate drivers for use of personal protection measures to prevent tick bites is beyond the scope of this paper. These topics, together with the outcomes of education interventions to promote the practice of tick bite prevention, are addressed in a set of previous reviews (Corapi et al., 2007; Mowbray et al., 2012; Richardson et al., 2019; Coderre-Ball et al., 2021; Nesgos et al., 2021).

Factors associated with increased use of personal protection measures to prevent tick bites have been addressed in numerous studies from the United States (for example, Cartter et al., 1989; Herrington et al., 1997; Shadick et al., 1997; McKenna et al., 2004; Bayles et al., 2013; Valente et al., 2015; Niesobecki et al., 2019; Omodior et al., 2020, Omodior et al., 2021b). A few key findings are worth mentioning here. Not surprisingly, commonly reported predictors for taking action to prevent tick bites include previous tick bites, especially if they are numerous, and a history of TBD for the respondent or a family member. However, even for these seemingly obvious factors some studies failed to find significant positive associations with use of tick bite prevention measures. This may result from geographical variation in the level of familiarity with ticks and TBDs, whether or not risk for tick bites occur in the peridomestic environment in the study area, the specific respondent population (such as outdoor workers versus members of the public), and other unknown factors.

Education intervention studies in the United States aiming to improve knowledge of tick bite prevention measures and increase the use of such actions have focused on outdoor workers (Jones et al., 2015) and the public, including children (Lawless et al., 1997; Malouin et al., 2003; Daltroy et al., 2007; Gould et al., 2008; Shadick et al., 2016; Hornbostel et al., 2021). Similar studies have targeted the general public in Canada (Aenishaenslin et al., 2016) and children or adults in Europe (Beaujean et al., 2016a, b). These education interventions universally led to increased knowledge of personal protection measures against tick bites. For the studies in the United States, corresponding increases in the practice of tick bite prevention measures after education interventions were reported for adult subjects conducting tick checks when coming indoors and using repellents and permethrin-treated clothing (Malouin et al., 2003), and for adults and children ≥14 years of age conducting tick checks (Daltroy et al., 2007). Another education intervention study focusing on elementary school children (7 to 11 years of age) reported a small but significant improvement in the practice of checking for ticks but not for wearing untreated protective clothing (Shadick et al., 2016). However, three other studies focusing on outdoor workers or the public found no or only borderline significant improvement for subjects participating in educational interventions to take increased action to prevent tick bites (Lawless et al., 1997; Jones et al., 2015; Hornbostel et al., 2021). In the case with borderline significant improvement (Hornbostel et al., 2021), it was noted that a high proportion (88%) of respondents reported using personal protective measures before the education intervention, so there was little room for improvement. Other specific reasons for educational interventions failing to result in improved tick bite prevention practice by children or adults may include low confidence in the ability of the actions to prevent tick bites, unwillingness to take the same action (e.g., conducting a tick check) day after day, and hesitancy to use some prevention measures (i.e., using repellents or wearing permethrin-treated clothing). It also remains to be determined how long increased motivation for taking action to prevent tick bites will persist after an education intervention (Lawless et al., 1997). One final notable study (Gould et al., 2008) assessed the impact of a community-wide education intervention in Connecticut, rather than education focusing on individual subjects. Results were mixed, with significantly increased levels of use for always performing tick checks and always using repellents in one study community but not in another study community, whereas there was no increase in use of untreated protective clothing in either community.

6. Moving forward

Numerous studies have provided information on the level of use of personal protection measures to prevent tick bites and the impact of taking such measures on tick bites and tick-borne infections. In the majority of these studies, however, personal protection measures to prevent tick bites were part of a broader scope of topics rather than the main focus of the research. Consequently, the information gathered specifically for personal protection measures to prevent tick bites has not included the level of detail needed to understand why results are so variable across studies. To better understand how personal protection measures to prevent tick bites need to be used to have the greatest public health impact, there is a need for additional, more detailed studies that account for frequency of use, parts of the body being protected, and use of single protective actions versus combinations of two or more protective actions. Accomplishing this should be straightforward for case-control and cross-sectional studies, by generating more detailed information for use of personal protection measures in study surveys, but challenging for prospective experimental studies as this ideally would require the inclusion of control groups where the subjects refrain from taking actions widely recommended for protection against tick bites and with some evidence of being protective against TBDs. The current situation, where the effectiveness of widely recommended personal protection measures to reduce tick bites and TBD remains unclear, is not acceptable.

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References

Adenubi OT, McGaw LJ, Eloff JN, Naidoo V, 2018. *In vitro* bioassays used in evaluating plant extracts for tick repellent and acaricidal properties: a critical review. Vet. Parasitol 254, 160–171. [PubMed: 29657003]

Aenishaenslin C, Michel P, Ravel A, Gern L, Milord F, Waaub JP, Bélanger D, 2015. Factors associated with preventive behaviors regarding Lyme disease in Canada and Switzerland: a comparative study. BMC Publ. Health 15, 185.

Aenishaenslin C, Bouchard C, Koffi JK, Pelcat Y, Ogden NH, 2016. Evidence of rapid changes in Lyme disease awareness in Canada. Ticks Tick Borne Dis. 7, 1067–1074. [PubMed: 27665265]

Aenishaenslin C, Bouchard C, Koffi JK, Ogden NH, 2017. Exposure and preventive behaviours toward ticks and Lyme disease in Canada: results from a first national survey. Ticks Tick Borne Dis. 8, 112–118. [PubMed: 27771334]

Akin Belli A, Dervis E, Kar S, Ergonul O, Gargili A, 2016. Revisiting detachment techniques in human-biting ticks. J. Am. Acad. Dermatol 75, 393–397. [PubMed: 26944595]

Alekseev AN, Burenkova LA, Vasilieva IS, Dubinina HV, Chunikhin SP, 1996. Preliminary studies on virus and spirochete accumulation in the cement plug of Ixodid ticks. Exp. Appl. Acarol 20, 713–723. [PubMed: 9004495]

Antonise-Kamp L, Beaujean D, Crutzen R, van Steenbergen JE, Ruwaard D, 2017. Prevention of tick bites: an evaluation of a smartphone app. BMC Infect. Dis 17, 744. [PubMed: 29202704]

Armstrong PM, Brunet LR, Spielman A, Telford SR, 2001. Risk of Lyme disease: perceptions of residents of a lone star tick-infested community. Bull. W.H.O 79, 916–925. [PubMed: 11693973]

Bartosik K, Kubrak T, Olszewski T, Jung M, Buczek A, 2008. Prevention of tick bites and protection against tick-borne diseases in south-eastern Poland. Ann. Agric. Environ. Med 15, 181–185. [PubMed: 19061252]

Bayles BR, Evans G, Allan BF, 2013. Knowledge and prevention of tick-borne diseases vary across an urban-to-rural human land-use gradient. Ticks Tick Borne Dis. 4, 352–358. [PubMed: 23538110]

Beck A, Solomon J, Hinckley AF, Nelson CA, 2021. Tick bite frequency, prevention practices and Lyme disease diagnoses among U.S. Hispanic survey respondents. Zoonoses Publ. Health 68, 658–665.

Beaujean DJMA, Bults M, van Steenbergen JE, Voeten HACM, 2013a. Study on public perceptions and protective behaviors regarding Lyme disease among the general public in the Netherlands: implications for prevention programs. BMC Publ. Health 13, 225.

Beaujean DJMA, Gassner F, Wong A, van Steenbergen JE, Crutzen R, Ruwaard D, 2013b. Determinants and protective behaviours regarding tick bites among school children in the Netherlands: a cross-sectional study. BMC Publ. Health 13, 1148.

Beaujean DJMA, Crutzen R, Gassner F, Ameling C, Wong A, van Steenbergen JE, Ruwaard D, 2016a. Comparing the effect of a leaflet and a movie in preventing tick bites and Lyme disease in the Netherlands. BMC Publ. Health 16, 495.

Beaujean DJMA, Gassner F, Wong A, Steenbergen JE, Crutzen R, Ruwaard D, 2016b. Education on tick bite and Lyme borreliosis prevention, aimed at schoolchildren in the Netherlands: comparing the effects of an online educational video game versus a leaflet or no intervention. BMC Publ. Health 16, 1163.

Benelli G, Pavela R, Canale A, Mehlhorn H, 2016. Tick repellents and acaricides of botanical origin: a green roadmap to control tick-borne diseases? Parasitol. Res 115, 2545–2560. [PubMed: 27146901]

Berglund J, Eitrem R, Ornstein K, Lindberg A, Ringner A, Elmrud H, Carlsson M, Runehagen A, Svanborg C, Norrby R, 1995. An epidemiologic study of Lyme disease in southern Sweden. N. Engl. J. Med 333, 1319–1324. [PubMed: 7566023]

Bissinger BW, Apperson CS, Sonenshine DE, Watson DW, Roe RM, 2009. Efficacy of the new repellent BioUD® against three species of Ixodid ticks. Exp. Appl. Acarol 48, 239–250. [PubMed: 19140016]

Bissinger BW, Roe RM, 2010. Tick repellents: past, present, and future. Pestic. Biochem. Physiol 96, 63–79.

Bron GM, Fernandez MDP, Larson SR, Maus A, Gustafson D, Tsao JI, Diuk-Wasser MA, Bartholomay LC, Paskewitz SM, 2020. Context matters: contrasting behavioral and residential risk factors for Lyme disease between high-incidence states in the northeastern and midwestern United States. Ticks Tick Borne Dis. 11, 101515. [PubMed: 32993935]

Bron GM, Fenelon H, Paskewitz SM, 2021. Assessing recognition of the vector of Lyme disease using resin-embedded specimens in a Lyme endemic area. J. Med. Entomol 58, 866–872. [PubMed: 33128056]

Büchel K, Bendin J, Gharbi A, Rahlenbeck S, Dautel H, 2015. Repellent efficacy of DEET, Icaridin, and EBAAP against *Ixodes ricinus* and *Ixodes scapularis* nymphs (Acari, Ixodidae). Ticks Tick Borne Dis. 6, 494–498. [PubMed: 25936273]

Buczek A, Pilch J, Buczek W, 2020. Tick preventive behaviors and practices adopted by medical students from Poland, Germany, and Thailand in relation to socio-demographic conditions and their knowledge of ticks and tick-borne diseases. Insects 11, 863. [PubMed: 33287425]

Butler AD, Sedghi T, Petrini JR, Ahmadi R, 2016. Tick-borne disease preventive practices and perceptions in an endemic area. Ticks Tick Borne Dis. 7, 331–337. [PubMed: 26704290]

Carroll JF, 2003. A cautionary note: survival of nymphs of two species of ticks (Acari: Ixodidae) among clothes laundered in an automatic washer. J. Med. Entomol 40, 732–736. [PubMed: 14596290]

Carroll JF, Kramer M, 2001. Different activities and footwear influence exposure to host-seeking nymphs of *Ixodes scapularis* and *Amblyomma americanum* (Acari: Ixodidae). J. Med. Entomol 38, 596–600. [PubMed: 11476342]

Carroll JF, Maradufu A, Warthen JD, 1989. An extract of *Commiphora erythraea*: a repellent and toxicant against ticks. Entomol. Exp. Appl 53, 111–116.

Carroll JF, Solberg VB, Klun JA, Kramer M, Debboun M, 2004. Comparative activity of deet and AI3–37220 repellents against the ticks *Ixodes scapularis* and *Amblyomma americanum* (Acari: Ixodidae) in laboratory bioassays. J. Med. Entomol 41, 249–254. [PubMed: 15061285]

Carroll JF, Klun JA, Debboun M, 2005. Repellency of deet and SS220 applied to skin involves olfactory sensing by two species of ticks. Med. Vet. Entomol 19, 101–106. [PubMed: 15752184]

Carroll JF, Cantrell CL, Klun JA, Kramer M, 2007. Repellency of two terpenoid compounds isolated from *Callicarpa americana* (Lamiaceae) against *Ixodes scapularis* and *Amblyomma americanum* ticks. Exp. Appl. Acarol 41, 215–224. [PubMed: 17380408]

Carroll JF, Paluch G, Coats J, Kramer M, 2010. Elemol and amyris oil repel the ticks *Ixodes scapularis* and *Amblyomma americanum* (Acari: Ixodidae) in laboratory bioassays. Exp. Appl. Acarol 51, 383–392. [PubMed: 20016930]

Carroll JF, Zhang A, Kramer M, Paluch GE, Coats JR, 2011. Using lone star ticks, *Amblyomma americanum* (Acari: Ixodidae), in *in vitro* laboratory bioassays of repellents: dimensions, duration, and variability. Recent Developments in Invertebrate Repellents. American Chemical Society, Washington, D.C., USA, pp. 97–120.

Carroll JF, Babish JG, Pacioretty LM, Kramer M, 2016. Repellency to ticks (Acari: Ixodidae) of extracts of *Nigella sativa* (Ranunculaceae) and the anti-inflammatory DogsBestFriendTM. Exp. Appl. Acarol 70, 89–97. [PubMed: 27394440]

Carroll SP, 2008. Prolonged efficacy of IR3535 repellents against mosquitoes and blacklegged ticks in North America. J. Med. Entomol 45, 706–714. [PubMed: 18714871]

Cartter ML, Farley TA, Ardito HA, Hadler JL, 1989. Lyme disease prevention – knowledge, beliefs, and behaviors among high school students in an endemic area. Connecticut Med. 53, 354–356.

CDC (Centers for Disease Control and Prevention), 2021a. Preventing tick bites. Accessed 10 August 2021; https://www.cdc.gov/ticks/avoid/on_people.html!.

CDC (Centers for Disease Control and Prevention), 2021b. Tick removal and testing. Accessed 10 August 2021; https://www.cdc.gov/lyme/removal/index.html.

Coderre-Ball AM, Robertson M, Matzinger E, Durando P, Egan R, 2021. Training initiatives that enhance knowledge, attitudes, and practices regarding the prevention, diagnosis and treatment of Lyme disease: a systematic review. Int. J. Health Promot. Educ 10.1080/14635240.2021.1920045.

Coleman N, Coleman S, 2017. Methods of tick removal: a systematic review of the literature. Australas. Med. J 10, 53–62.

Connally NP, Durante AJ, Yousey-Hindes KM, Meek JI, Nelson RS, Heimer R, 2009. Peridomestic Lyme disease prevention - results of a population-based case-control study. Am. J. Prev. Med 37, 201–206. [PubMed: 19595558]

Connally NP, Rose DA, Breuner NE, Prose R, Fleshman AC, Thompson K, Wolfe L, Broeckling CD, Eisen L, 2019. Impact of wearing and washing/drying of permethrin-treated clothing on their contact irritancy and toxicity for nymphal *Ixodes scapularis* (Acari: Ixodidae) ticks. J. Med. Entomol 56, 199–214. [PubMed: 30165532]

Corapi KM, White MI, Phillips CB, Daltroy LH, Shadick NA, Liang MH, 2007. Strategies for primary and secondary prevention of Lyme disease. Nat. Clin. Pract. Rheumatol 3, 20–25. [PubMed: 17203005]

Cull B, Pietzsch ME, Gillingham EL, McGinley L, Medlock JM, Hansford KM, 2020. Seasonality and anatomical location of human tick bites in the United Kingdom. Zoonoses Publ. Health 67, 112–121.

Daltroy LH, Phillips C, Lew R, Wright E, Shadick NA, Liang, 2007. A controlled trial of a novel primary prevention program for Lyme disease and other tick-borne illnesses. Health Educ. Behav 34, 531–542. [PubMed: 17468463]

Dautel H, Kahl O, Siems K, Oppenrieder M, Müller-Kuhrt L, Hilker M, 1999. A novel test system for detection of tick repellents. Entomol. Exp. Appl 91, 431–441.

Dautel H, Dippel C, Werkhausen A, Diller R, 2013. Efficacy testing of several *Ixodes ricinus* tick repellents: different results with different assays. Ticks Tick Borne Dis. 4, 256–263. [PubMed: 23339971] de Boer R, van den Bogaard AEJM, 1993. Removal of attached nymphs and adults of *Ixodes ricinus* (Acari: Ixodidae). J. Med. Entomol 30, 748–752. [PubMed: 8360898]

de la Fuente J, Contreras M, Estrada-Peña A, Cabezas-Cruz A, 2017. Targeting a global health problem: vaccine design and challenges for the control of tick-borne diseases. Vaccine 35, 5089–5094 [PubMed: 28780117]

de Wet S, Rutz H, Hinckley AF, Hook SA, Campbell S, Feldman KA, 2020. Love the ones you're with: characteristics and behaviour of Maryland pets and their owners in relation to tick encounters. Zoonoses Publ. Health 67, 876–881.

Dolan MC, Panella NA, Paluch GE, Coats JR, 2011. A review of arthropod repellents. Recent Developments in Invertebrate Repellents. American Chemical Society, Washington, D.C., USA, pp. 1–19.

Donohoe H, Omodior O, Roe J, 2018. Tick-borne disease occupational risks and behaviors of Florida fish, wildlife, and parks service employees – a health belief model perspective. J. Outdoor Recreat. Tour 22, 9–17.

Ebel GD, Kramer LD, 2004. Duration of tick attachment required for transmission of Powassan virus by deer ticks. Am. J. Trop. Med. Hyg 71, 268–271.

Edlow JA, McGillicuddy DC, 2008. Tick paralysis. Infect. Dis. Clin. North Am 22, 397–413. [PubMed: 18755381]

Eisen L, 2018. Pathogen transmission in relation to duration of attachment by *Ixodes scapularis* ticks. Ticks Tick Borne Dis. 9, 535–542. [PubMed: 29398603]

Eisen L, 2021. Control of ixodid ticks and prevention of tick-borne diseases in the United States: the prospect of a new Lyme disease vaccine and the continuing problem with tick exposure on residential properties. Ticks Tick Borne Dis. 12, 101649. [PubMed: 33549976]

Eisen L, Dolan MC, 2016. Evidence for personal protective measures to reduce human contact with blacklegged ticks and for environmentally based control methods to suppress host-seeking blacklegged ticks and reduce infection with Lyme disease spirochetes in tick vectors and rodent reservoirs. J. Med. Entomol 53, 1063–1092. [PubMed: 27439616]

Eisen L, Eisen RJ, 2016. Critical evaluation of the linkage between tick-based risk measures and the occurrence of Lyme disease cases. J. Med. Entomol 53, 1050–1062. [PubMed: 27330093]

Eisen L, Gray JS, Braks MAH, Van Wierer SE, Takken W, Sprong H, 2016. Lyme borreliosis prevention strategies: united States versus Europe. Ecology and Prevention of Lyme Borreliosis. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 429–450.

Eisen L, Stafford KC, 2021. Barriers to effective tick management and tick-bite prevention in the United States (Acari: Ixodidae). J. Med. Entomol 58, 1588–1600. [PubMed: 32372075]

Eisen L, Rose D, Prose R, Breuner NE, Dolan MC, Thompson K, Connally N, 2017a. Bioassays to evaluate non-contact spatial repellency, contact irritancy, and acute toxicity of permethrin-treated clothing against nymphal *Ixodes scapularis* ticks. Ticks Tick Borne Dis. 8, 837–849. [PubMed: 28754599]

Eisen RJ, Eisen L, 2018. The blacklegged tick, *Ixodes scapularis*: an increasing health concern. Trends Parasitol. 34, 295–309. [PubMed: 29336985]

Eisen RJ, Mead PM, 2020. Prevention of Lyme disease. Up to date article. Accessed 10 August 2021; https://www.uptodate.com/contents/prevention-of-lyme-disease.

Eisen RJ, Paddock CD, 2021. Tick and tickborne pathogen surveillance as a public health tool in the United States. J. Med. Entomol 58, 1490–1502. [PubMed: 32440679]

Eisen RJ, Kugeler KJ, Eisen L, Beard CB, Paddock CD, 2017b. Tick-borne Zoonoses in the United States: persistent and emerging threats to human health. ILAR J. 58, 319–335. [PubMed: 28369515]

EPA (Environmental Protection Agency), 2021. Find the repellent that is right for you. Accessed 10 August 2021; https://www.epa.gov/insect-repellents/find-repellent-right-you.

Evans SR, Korch GW, Lawson MA, 1990. Comparative field evaluation of permethrin and deet-treated military uniforms for personal protection against ticks (Acari). J. Med. Entomol 27, 829–834. [PubMed: 2231620]

Evolva, 2021. NootkaShield. Accessed 10 August 2021; https://nootkashield.com.

Falco RC, Fish D, 1988. Ticks parasitizing humans in a Lyme disease endemic area of southern New York state. Am. J. Epidemiol 128, 1146–1152. [PubMed: 3189288]

Falco RC, Fish D, Piesman J, 1996. Duration of tick bites in a Lyme disease-endemic area. Am. J. Epidemiol 143, 187–192. [PubMed: 8546120]

Faulde M, Scharninghausen J, Tisch M, 2008. Preventive effect of permethrin-impregnated clothing to *Ixodes ricinus* ticks and associated *Borrelia burgdorferi* s.l. in Germany. Int. J. Med. Microbiol 298 (S1), 321–324.

Faulde MK, Rutenfranz M, Keth A, Hepke J, Rogge M, Görner A, 2014. Pilot study assessing the effectiveness of factory-treated, long-lasting permethrin-impregnated clothing for the prevention of tick bites during occupational tick exposure in highly infested military training areas, Germany. Parasitol. Res 114, 671–678. [PubMed: 25416331]

Felz MW, Durden LA, 1999. Attachment sites of four tick species (Acari: Ixodidae) parasitizing humans in Georgia and South Carolina. J. Med. Entomol 36, 361–364. [PubMed: 10337108]

Finch C, Al-Damluji MS, Krause PJ, Niccolai L, Steeves T, O'Keefe CF, Diuk-Wasser MA, 2014. Integrated assessment of behavioral and environmental risk factors for Lyme disease infection on Block island, Rhode island. PLoS One 9, e84758. [PubMed: 24416278]

Fleshman AC, Graham CB, Maes SE, Foster E, Eisen RJ, 2021. Reported county-level distribution of Lyme disease spirochetes, *Borrelia burgdorferi* sensu stricto and *Borrelia mayonii* (Spirochaetales: Spirochaetaceae), in host-seeking *Ixodes scapularis* and *Ixodes pacificus* ticks (Acari: Ixodidae) in the contiguous United States. J. Med. Entomol 58, 1219–1233. [PubMed: 33600574]

Foster E, Fleshman AC, Ford SL, Levin ML, Delorey MJ, Eisen RJ, Eisen L, 2020. Preliminary evaluation of human personal protective measures against the nymphal stage of the Asian longhorned tick, *Haemaphysalis longicornis* (Acari: Ixodidae). J. Med. Entomol 57, 1141–1148. [PubMed: 32073128]

Gardulf A, Wohlfart I, Gustafson R, 2004. A prospective cross-over field trial shows protection of lemon eucalyptus extract against tick bites. J. Med. Entomol 41, 1064–1067. [PubMed: 15605645]

Gleim ER, Garrison LE, Vello MS, Savage MY, Lopez G, Berghaus RD, Yabsley MJ, 2016. Factors associated with tick bites and pathogen prevalence in ticks parasitizing humans in Georgia, USA. Parasit. Vectors 9, 125. [PubMed: 26935205]

Goddard J, 1992. Ecological studies of adult *Ixodes scapularis* in Central Mississippi: questing activity in relation to time of year, vegetation type, and meteorologic conditions. J. Med. Entomol 29, 501–506. [PubMed: 1625300]

Goddard J, Varela-Stokes A, Schneider JC, 2011. Observations on questing activity of adult gulf coast ticks, *Amblyomma maculatum* Koch (Acari: Ixodidae), in Mississippi, U.S.A. Syst. Appl. Acarol 16, 195–200.

Goldstein MD, Schwartz BS, Friedmann C, Maccarillo B, Borbi M, Tuccillo R, 1990. Lyme disease in New Jersey outdoor workers: a statewide survey of seroprevalence and tick exposure. Am. J. Publ. Health 80, 1225–1229.

Gomes-Solecki M, Arnaboldi PM, Backenson PB, Benach JL, Cooper CL, Dattwyler RJ, Diuk-Wasser M, Fikrig E, Hovius JW, Laegreid W, Lundberg U, Marconi RT, Marques AR, Molloy P, Narasimhan S, Pal U, Pedra JHF, Plotkin S, Rock DL, Rosa P, Telford SR, Tsao J, Yang XF, Schutzer SE, 2020. Protective immunity and new vaccines for Lyme disease. Clin. Infect. Dis 70, 1768–1773. [PubMed: 31620776]

Gould LH, Nelson RS, Griffith KS, Hayes EB, Piesman J, Mead PS, Cartter ML, 2008. Knowledge, attitudes, and behaviors regarding Lyme disease prevention among Connecticut residents, 1999–2004. Vector Borne Zoonotic Dis 8, 769–776. [PubMed: 18637724]

Guglielmone AA, Robbins RG, 2018. Hard Ticks (Acari: Ixodida: Ixodidae) Parasitizing Humans: A Global Overview. Springer International Publishing AG, Cham, Switzerland.

Gupta S, Eggers P, Arana A, Kresse B, Rios K, Brown L, Sampson L, Kploanyi M, 2018. Knowledge and preventive behaviors towards tick-borne diseases in delaware. Ticks Tick Borne Dis. 9, 615–622. [PubMed: 29428491]

Hallman W, Weinstein N, Kadakia S, Chess C, 1995. Precautions taken against Lyme disease at three recreational parks in endemic areas of New Jersey. Environ. Behav 27, 437–453.

Han GS, Stromdahl EY, Wong D, Weltman AC, 2014. Exposure to *Borrelia burgdorferi* and other tick-borne pathogens in Gettysburg national military park, south-central Pennsylvania, 2009. Vector Borne Zoonotic Dis. 14, 227–233. [PubMed: 24689815]

Han MA, Kim CM, Yun NR, Kim DM, Park SM, Kim H, Shin HH, 2021. The effect of long-lasting permethrin impregnated socks on tick bite in Korea. J. Korean Med. Sci 36, e49. [PubMed: 33619917]

Heller JE, Benito-Garcia E, Maher NE, Chibnik LB, Maher CP, Shadick NA, 2010. Behavioral and attitudes survey about Lyme disease among a Brazilian population in the endemic area of Martha's Vineyard, Massachusetts. J. Immigr. Minor Health 12, 377–383. [PubMed: 18792780]

Herrington JE, 2004. Risk perceptions regarding ticks and Lyme disease - a national survey. Am. J. Prev. Med 26, 135–140. [PubMed: 14751325]

Herrington JE, Campbell GL, Bailey RE, Cartter ML, Adams M, Frazier EL, Damrow TA, Gensheimer KF, 1997. Predisposing factors for individuals' Lyme disease prevention practices: Connecticut, Maine, and Montana. Am. J. Publ. Health 87, 2035–2038.

Hook SA, Nelson CA, Mead PS, 2015. U.S. public's experience with ticks and tickborne diseases: results from national HealthSyles surveys. Ticks Tick Borne Dis. 6, 483–488. [PubMed: 25887156]

Hornbostel VL, Krall RK, Reid JJ, Schappach JL, Volpe S, Connally NP, 2021. *Spray safe, play safe:* story-based films increase homeowner confidence about backyard tick management. J. Med. Entomol 58, 857–865. [PubMed: 33225365]

Hu YS, Starr JA, Gharpure R, Mehta SP, Feldman KA, Nelson CA, 2019. Knowledge and prevention of tickborne diseases among Hispanic and non-Hispanic residents of Maryland and Virginia. Zoonoses Publ. Health 66, 805–812.

Hügli D, Moret J, Rais O, Moosmann Y, Erard P, Malinverni R, Gern L, 2009. Tick bites in a Lyme borreliosis highly endemic area in Switzerland. Int. J. Med. Microbiol 299, 155–160. [PubMed: 18722157]

Huygelen V, Borra V, de Buck E, Vandekerckhove P, 2017. Effective methods for tick removal: a systematic review. J. Evid. Based Med 10, 177–188. [PubMed: 28464468]

Jones EH, Chanlongbutra A, Wong D, Cunningham F, Feldman KA, 2015. Knowledge, attitudes, and practices regarding Lyme disease prevention among employees, day visitors, and campers at Greenbelt Park. Park Sci. 32, 46–53.

Jones EH, Hinckley AF, Hook SA, Meek JI, Backenson B, Kugeler KJ, Feldman KA, 2018. Pet ownership increases owner risk of encountering ticks. Zoonoses Publ. Health 65, 74–79.

Jones TF, Garman RL, LaFleur B, Stephan SJ, Schaffner W, 2002. Risk factors for tick exposure and suboptimal adherence to preventive recommendations. Am. J. Prev. Med 23, 47–50. [PubMed: 12093423]

Jordan RA, Egizi A, 2019. The growing importance of lone star ticks in a Lyme disease endemic county: passive tick surveillance in Monmouth County, NJ, 2006–2016. PLoS One 14, e0211778. [PubMed: 30753233]

Jordan RA, Schulze TL, Dolan MC, 2012. Efficacy of plant-derived and synthetic compounds on clothing as repellents against *Ixodes scapularis* and *Amblyomma americanum* (Acari: Ixodidae). J. Med. Entomol 49, 101–106. [PubMed: 22308777]

Journault AA, Richard L, Aenishaenslin C, 2020. Lyme disease prevention: a content analysis of Canadian patient group and government websites. Zoonoses Publ. Health 67, 177–185.

Kianersi S, Luetke M, Wolfe CG, Clark WA, Omodior O, 2020. Associations between personal protective measures and self-reported tick-borne disease diagnosis in Indiana residents. J. Community Health 45, 739–750. [PubMed: 31916179]

Klein JD, Eppes SC, Hunt P, 1996. Environmental and life-style risk factors for Lyme disease in children. Clin. Pediatr 35, 359–363.

Kopsco HL, Mather TN, 2021. Tick-borne disease prevention behaviors among participants in a tick surveillance system compared with a sample of master gardeners. J. Community Health 47, 246–256. [PubMed: 34727297]

Lane RS, 1989. Treatment of clothing with a permethrin spray for personal protection against the western black-legged tick, *Ixodes pacificus* (Acari: Ixodidae). Exp. Appl. Acarol 6, 343–352. [PubMed: 2743839]

Lane RS, Anderson JR, 1984. Efficacy of permethrin as a repellent and toxicant for personal protection against the Pacific coast tick and the pajaroello tick (Acari: Ixodidae and Argasidae). J. Med. Entomol 21, 692–702. [PubMed: 6502628]

Lane RS, Manweiler SA, Stubbs HA, Lennette ET, Madigan JE, Lavoie PE, 1992. Risk factors for Lyme disease in a small rural community in northern California. Am. J. Epidemiol 136, 1358–1368. [PubMed: 1488962]

Lane RS, Steinlein DB, Mun J, 2004. Human behaviors elevating exposure to *Ixodes pacificus* (Acari: Ixodidae) nymphs and their associated bacterial zoonotic agents in a hardwood forest. J. Med. Entomol 41, 239–248. [PubMed: 15061284]

Lantos PM, Rumbaugh J, Bockenstedt LK, Falck-Ytter YT, Aguero-Rosenfeld ME, Auwaerter PG, Baldwin K, Bannuru RR, Belani KK, Bowie WR, Branda JA, Clifford DB, DiMario FJ, Halperin JJ, Krause PJ, Lavergne V, Liang MH, Meissner HC, Nigrovic LE, Nocton JJJ, Osani MC, Pruitt AA, Rips J, Rosenfeld LE, Savoy ML, Sood SK, Steere AC, Strle F, Sundel R, Tsao J, Vaysbrot EE, Wormser GP, Zemel LS, 2021. Clinical practice guidelines by the infectious diseases society of America (IDSA), American academy of neurology (AAN), and American college of rheumatology (ACR): 2020 guidelines for the prevention, diagnosis and treatment of Lyme disease. Clin. Infect. Dis 72, e1–e48. [PubMed: 33417672]

Lawless KA, Brown SW, Cartter M, 1997. Applying educational psychology and instructional technology to health care issues: combating Lyme disease. Int. J. Instr. Media 24, 287–297.

Lehane A, Maes SE, Graham CB, Jones E, Delorey M, Eisen RJ, 2021. Prevalence of single and coinfections of human pathogens in *Ixodes* ticks from five geographical regions in the United States, 2013–2019. Ticks Tick Borne Dis. 12, 101637. [PubMed: 33360805]

Levin ML, Ford SL, Hartzer K, Krapiunaya L, Stanley H, Snellgrove AN, 2020. Minimal duration of tick attachment sufficient for transmission of infectious *Rickettsia rickettsii* (Rickettsiales: Rickettsiaceae) by its primary vector *Dermacentor variabilis* (Acari: Ixodidae): duration of rickettsial reactivation in the vector revisited. J. Med. Entomol 57, 585–594. [PubMed: 31687749]

Ley C, Olshen EM, Reingold AL, 1995. Case-control study of risk factors for incident Lyme disease in California. Am. J. Epidemiol 142, S39–S47. [PubMed: 7572986]

Little EAH, Anderson JF, Stafford KC, Eisen L, Eisen RJ, Molaei G, 2019. Predicting spatiotemporal patterns of Lyme disease incidence from passively collected surveillance data for *Borrelia burgdorferi* sensu lato-infected *Ixodes scapularis* ticks. Ticks Tick Borne Dis. 10, 970–980. [PubMed: 31101553]

Logar M, Ruzic-Sabljic E, Strle F, 2002. Comparison of self-assessment and scutal index for the duration of *Ixodes ricinus* tick attachment. Wiener Klin. Wochenschr 114, 489–492.

Malouin R, Winch P, Leontsini E, Glass G, Simon D, Hayes EB, Schwartz BS, 2003. Longitudinal evaluation of an educational intervention for preventing tick bites in an area with endemic Lyme disease in Baltimore County, Maryland. Am. J. Epidemiol 157, 1039–1051. [PubMed: 12777368]

McKenna D, Faustini Y, Nowakowski J, Wormser GP, 2004. Factors influencing the utilization of Lyme disease-prevention behaviors in a high-risk population. J. Am. Acad. Nurse Pract 16, 24–30. [PubMed: 15008035]

Mead P, 2011. Education, behavior change, and other non-pharmaceutical measures against Lyme and other tick-borne diseases. Institute of Medicine of the National Academies Workshop Report Critical Needs and Gaps in Understanding Prevention, Amelioration, and Resolution of Lyme and Other Tick-Borne Diseases. The National Academies Press, Washington, DC, United States, pp. 165–169. The Short-Term and Long-Term Outcomes. Institute of Medicine of the National Academies Workshop Report.

Mead P, Hook S, Niesobecki S, Ray J, Meek J, Delorey M, Prue C, Hinckley A, 2018. Risk factors for tick exposure in suburban settings in the northeastern United States. Ticks Tick Borne Dis. 9, 319–324. [PubMed: 29174449]

Mejlon HA, Jaenson TGT, 1997. Questing behaviour of *Ixodes ricinus* ticks (Acari: Ixodidae). Exp. Appl. Acarol 21, 747–754.

Merten HA, Durden LA, 2000. A state-by-state survey of ticks recorded from humans in the United States. J. Vector Ecol 25, 102–113. [PubMed: 10925803]

Miller NJ, Rainone EE, Dyer MC, González ML, Mather TN, 2011. Tick bite protection with permethrin-treated summer-weight clothing. J. Med. Entomol 48, 327–333. [PubMed: 21485369]

Mitchell CL, Lin FC, Vaughn M, Apperson CS, Meshnick SR, Commins SC, 2020a. Association between lone star tick bites and increased alpha-gal sensitization: evidence from a prospective cohort of outdoor workers. Parasit. Vectors 13, 470. [PubMed: 32928302]

Mitchell C, Dyer M, Lin FC, Bowman N, Mather T, Meshnick S, 2020b. Protective effectiveness of long-lasting permethrin impregnated clothing against tick bites in an endemic Lyme disease setting: a randomized control trial among outdoor workers. J. Med. Entomol 57, 1532–1538. [PubMed: 32277701]

Molaei G, Little EA, Williams SC, Stafford KC, 2019. Bracing for the worst – range expansion of the lone star tick in the northeastern United States. N. Engl. J. Med 381, 2189–2192. [PubMed: 31800982]

Mount GA, Snoddy EL, 1983. Pressurized sprays of permethrin and deet on clothing for personal protection against the lone star tick and the American dog tick (Acari: Ixodidae). J. Econ. Entomol 76, 529–531. [PubMed: 6875081]

Mowbray F, Amlôt R, Rubin GJ, 2012. Ticking all the boxes? A systematic review of education and communication interventions to prevent tick-borne disease. Vector Borne Zoonotic Dis. 12, 817–825. [PubMed: 22607072]

Mowbray F, Amlôt R, Rubin GJ, 2014. Predictors of protective behaviour against ticks in the UK: a mixed methods study. Ticks Tick Borne Dis. 5, 392–400. [PubMed: 24713278]

Narasimhan S, Kurokawa C, Diktas H, Strank NO, Černý J, Murfin K, Cao Y, Lynn G, Trentleman J, Wu MJ, DePonte K, Kantor F, Anguita J, Hovius J, Fikrig E, 2020. *Ixodes scapularis* saliva components that elicit responses associated with acquired tick-resistance. Ticks Tick Borne Dis. 11, 101369. [PubMed: 31924502]

Narasimhan S, Kurokawa C, DeBlasio M, Matias J, Sajid A, Pal U, Lynn G, Fikrig E, 2021. Acquired tick resistance: the trail is hot. Parasite Immunol. 43, e12808. [PubMed: 33187012]

Nawrocki CC, Hinckley AF, 2021. Experiences with tick exposure, Lyme disease, and use of personal prevention methods for tick bites among members of the U.S. population, 2013–2015. Ticks Tick Borne Dis 12, 101605. [PubMed: 33217712]

Needham GR, 1985. Evaluation of five popular methods for tick removal. Pediatrics 75, 997–1002. [PubMed: 4000801]

Nelson CA, Hayes CM, Markowitz MA, Flynn JJ, Graham AC, Delorey MJ, Mead PS, Dolan MC, 2016. The heat is on: killing blacklegged ticks in residential washers and dryers to prevent tickborne diseases. Ticks Tick Borne Dis. 7, 958–963. [PubMed: 27156138]

Nesgos AT, Harrington LC, Mader EM, 2021. Experience and knowledge of Lyme disease: a scoping review of patient-provider communication. Ticks Tick Borne Dis. 12, 101714. [PubMed: 33780825]

Niesobecki S, Hansen A, Rutz H, Mehta S, Feldman K, Meek J, Niccolai L, Hook S, Hinckley A, 2019. Knowledge, attitudes, and behaviors regarding tick-borne disease prevention measures in endemic areas. Ticks Tick Borne Dis. 10, 101264. [PubMed: 31431351]

Niesobecki S, Rutz H, Niccolai L, Hook S, Meek J, Hansen A, Feldman K, Hinckley A, 2022. Willingness to pay for select tickborne disease prevention measures in endemic areas. J. Publ. Health Manag. Pract 28, E37–E42.

Nieto NC, Porter WT, Wachara JC, Lowrey TJ, Martin L, Motyka PJ, Salkeld DJ, 2018. Using citizen science to describe the prevalence and distribution of tick bite and exposure to tick-borne diseases in the United States. PLoS One 13, e0199644. [PubMed: 30001350]

Noden BH, Garner KD, Lalman D, Talley JL, 2020. Knowledge, attitudes, and practices regarding ticks, tick-borne pathogens, and tick prevention among beef producers in Oklahoma. Southwest Entomol. 45, 341–349.

Nolan K, Mauer MP, 2006. An evaluation of a Lyme disease prevention program in a working population. Am. J. Health Promot 20, 379–382. [PubMed: 16871815]

Nwanade CF, Wang M, Wang T, Yu Z, Liu J, 2020. Botanical acaricides and repellents in tick control: current status and future directions. Exp. Appl. Acarol 81, 1–35. [PubMed: 32291551]

Omodior O, Anderson KR, Clark W, Eze P, Donohoe H, 2021b. Preventing tick-bites among children in Indiana, USA: an analysis of factors associated with parental protective behaviors. Ticks Tick Borne Dis 12, 101647. [PubMed: 33445070]

Omodior O, Kianersi S, Luetke M, 2021a. Prevalence of risk and protective factors for tick exposure and tick-borne disease among residents of Indiana. J. Publ. Health Manage. Pract 27, E210–E219.

Omodior O, Luetke M, Kianersi S, Cólon A, 2020. Predictors of tick exposure risk-reduction behavior in Indiana. J. Community Health 45, 862–870. [PubMed: 32157640]

Orloski KA, Campbell GL, Genese CA, Beckley JW, Schriefer ME, Spitalny KC, Dennis DT, 1998. Emergence of Lyme disease in Hunterdon County, New Jersey, 1993: a case-control study of risk factors and evaluation of reporting patterns. Am. J. Epidemiol 147, 391–397. [PubMed: 9508107]

Pages F, Dautel H, Duvallet G, Kahl O, de Gentile L, Boulanger N, 2014. Tick repellents for human use: prevention of tick bites and tick-borne diseases. Vector Borne Zoonotic Dis. 14, 85–93. [PubMed: 24410143]

Panella NA, Dolan MC, Karchesy JJ, Xiong Y, Peralta-Cruz J, Khasawneh M, Montenieri JA, Maupin GO, 2005. Use of novel compounds for pest control: insecticidal and acaricidal activity of essential oil components from heartwood of Alaska yellow cedar. J. Med. Entomol 42, 352–358. [PubMed: 15962787]

Parrott C, Johnson K, Strauss S, Greco M, Israel E, Schwartz BS, 1993. Lyme disease in outdoor workers on Assateague Island: high tick-exposure but low disease risk. Maryland Med. J 42, 165–168.

Phillips CB, Liang MH, Sangha O, Wright EA, Fossel AH, Lew RA, Fossel KK, Shadick NA, 2001. Lyme disease and preventive behaviors in residents of Nantucket Island, Massachusetts. Am. J. Prev. Med 20, 219–224. [PubMed: 11275450]

Piesman J, Dolan MC, 2002. Protection against Lyme disease spirochete transmission provided by prompt removal of nymphal *Ixodes scapularis* (Acari: Ixodidae). J. Med. Entomol 39, 509–512. [PubMed: 12061448]

Porter WT, Motyka PJ, Wachara J, Barrand ZA, Hmood Z, McLaughlin M, Pemberton K, Nieto NC, 2019. Citizen science informs human-tick exposure in the northeastern United States. Int. J. Health Geogr 18, 9. [PubMed: 31064416]

Prose R, Breuner NE, Johnson TL, Eisen RJ, Eisen L, 2018. Contact irritancy and toxicity of permethrin-treated clothing for *Ixodes scapularis, Amblyomma americanum* and *Dermacentor variabilis* ticks (Acari: Ixodidae). J. Med. Entomol 55, 1217–1224. [PubMed: 29800259]

Richards SL, Balanay JAG, Harris JW, 2015. Effectiveness of permethrin-treated clothing to prevent tick exposure in foresters in the central Appalachian region of the USA. Int. J. Environ. Health Res 25, 453–462. [PubMed: 25290464]

Richardson M, Khouja C, Sutcliffe K, 2019. Interventions to prevent Lyme disease in humans: a systematic review. Prev. Med. Rep 13, 16–22. [PubMed: 30456054]

Rego ROM, Trentelman JJA, Anguita J, Nijhof AM, Sprong H, Klempa B, Hajdusek O, Tomas-Cortazar J, Azagi T, Strnad M, Knorr S, Sima R, Jalovecka M, Fumačová Havlíková S, Ličková M, Sláviková, Kopacek P, Grubhoffer L, Hovius JW, 2019. Counterattacking the tick bite: towards a rational design of anti-tick vaccines targeting pathogen transmission. Parasit. Vectors 12, 229. [PubMed: 31088506]

Rosenberg R, Lindsey NP, Fischer M, Gregory CJ, Hinckley AF, Mead PS, Paz-Bailey G, Waterman SH, Drexler NA, Kersh GJ, Hooks H, Partridge SK, Visser SN, Beard CB, Petersen LR, 2018. Vital signs: trends in reported vectorborne disease cases — united states and territories, 2004–2016. Morb. Mortal. Wkly. Rep 67, 496–501.

Salkeld DJ, Porter WT, Loh SM, Nieto NC, 2019. Time of year and outdoor recreation affect human exposure to ticks in California, United States. Ticks Tick Borne Dis. 10, 1113–1117. [PubMed: 31201125]

Schotthoefer A, Stinebaugh K, Martin M, Munoz-Zanzi C, 2020. Tickborne disease awareness and protective practices among U.S. forest service employees from the upper Midwest, USA. BMC Publ. Health 20, 1575.

Schreck CE, Snoddy EL, Mount GA, 1980. Permethrin and repellents as clothing impregnants for protection from the lone star tick. J. Econ. Entomol 73, 436–439.

Schreck CE, Mount GA, Carlson DA, 1982a. Wear and wash persistence of permethrin used as a clothing treatment for personal protection against the lone star tick (Acari: Ixodidae). J. Med. Entomol 19, 143–146. [PubMed: 6123602]

Schreck CE, Mount GA, Carlson DA, 1982b. Pressurized sprays of permethrin on clothing for personal protection against the lone star tick (Acari: Ixodidae). J. Econ. Entomol 75, 1059–1061. [PubMed: 7161438]

Schreck CE, Snoddy EL, Spielman A, 1986. Pressurized sprays of permethrin or deet on military clothing for personal protection against *Ixodes dammini* (Acari: Ixodidae). J. Med. Entomol 23, 396–399. [PubMed: 3735345]

Schreck CE, Fish D, McGovern TP, 1995. Activity of repellents applied to skin for protection against *Amblyomma americanum* and *Ixodes scapularis* ticks (Acari: Ixodidae). J. Am. Mosq. Contr. Assoc 11, 136–140.

Schwartz BS, Goldstein MD, 1990. Lyme disease in outdoor workers: risk factors, preventive measures, and tick removal methods. Am. J. Epidemiol 131, 877–885. [PubMed: 2321630]

Shadick NA, Daltroy LH, Phillips CB, Liang US, Liang MH, 1997. Determinants of tick-avoidance behaviors in an endemic area for Lyme disease. Am. J. Prev. Med 13, 265–270. [PubMed: 9236962]

Shadick NA, Zibit MJ, Nardone E, Demaria A, Iannaccone CK, Cui J, 2016. A school-based intervention to increase Lyme disease preventive measures among elementary school-aged children. Vector Borne Zoonotic Dis. 16, 507–515. [PubMed: 27248436]

Slaff M, Newton NH, 1993. Location of tick (Acari: Ixodidae) attachment sites on humans in North Carolina. J. Med. Entomol 30, 485–488. [PubMed: 8459429]

Slunge D, Boman A, 2018. Learning to live with ticks? The role of exposure and risk perceptions in protective behaviour against tick-borne diseases. PLoS One 13, e0198286. [PubMed: 29924806]

Smith G, Wileyto EP, Hopkins RB, Cherry BR, Maher JP, 2001. Risk factors for Lyme disease in Chester County, Pennsylvania. Publ. Health Rep 116, 146–156.

Smith PF, Benach JL, White DJ, Stroup DF, Morse DL, 1988. Occupational risk of Lyme disease in endemic areas of New York state. Ann. N.Y. Acad. Sci 539, 289–301. [PubMed: 3190100]

Sonenshine DE, 2018. Range expansion of tick disease vectors in North America: implications for spread of tick-borne disease. Int. J. Environ. Res. Publ. Health 15, 478.

Sood SK, Salzman MB, Johnson BJB, Happ CM, Feig K, Carmody L, Rubin LG, Hilton E, Piesman J, 1997. Duration of tick attachment as a predictor of the risk of Lyme disease in an area in which Lyme disease is endemic. J. Infect. Dis 175, 996–999. [PubMed: 9086168]

Stafford KC, 2017. Prevention of ticks and tick-associated disease in companion animals. Connecticut Agricultural Experiment Station Fact Sheet, New Haven, CT, USA, 9 pp., https://portal.ct.gov/CAES/Publications.

Stafford KC, Williams SC, Molaei G, 2017. Integrated pest management in controlling ticks and tick-associated diseases. J. Integr. Pest Manag 8, 28.

Stjernberg L, Berglund J, 2005. Detecting ticks on light versus dark clothing. Scand. J. Infect. Dis 37, 361–364.

Stewart RL, Burgdorfer W, Needham GR, 1998. Evaluation of three commercial tick removal tools. Wilderness Environ. Med 9, 137–142. [PubMed: 11990185]

Tsunoda T, Mori K, 2000. No distributional association between the tick *Haemaphysalis longicornis* (Acari: Ixodidae) and plant surface area. Ecol. Res 15, 357–359.

USCB (United States Census Bureau), 2021. 2010 Census regions and divisions of the United States. Accessed 10 August 2021; https://www.census.gov/geographies/reference-maps/2010/geo/2010-census-regions-and-divisions-of-the-united-states.html.

Valente SL, Wemple D, Ramos S, Cashman SB, Savageau JA, 2015. Preventive behaviors and knowledge of tick-borne illnesses: results of a survey from an endemic area. J. Publ. Health Manag. Pract 21, E16–E23.

Vaughn MF, Meshnick SR, 2011. Pilot study assessing the effectiveness of long-lasting permethrin-impregnated clothing for the prevention of tick bites. Vector-Borne Zoonotic Dis. 11, 869–875. [PubMed: 21395420]

Vaughn MF, Funkhouser SW, Lin FC, Fine J, Juliano JJ, Apperson CS, Meshnick SR, 2014. Long-lasting permethrin impregnated uniforms. A randomized-controlled trial for tick bite prevention. Am. J. Prev. Med 46, 473–480. [PubMed: 24745637]

Vázquez M, Muehlenbein C, Cartter M, Hayes EB, Ertel S, Shapiro ED, 2008. Effectiveness of personal protective measures to prevent Lyme disease. Emerg. Infect. Dis 14, 210–216. [PubMed: 18258112]

Wierzbicka A, Raczka G, Skorupski M, Michalik J, Lane RS, 2016. Human behaviors elevating the risk of exposure to *Ixodes ricinus* larvae and nymphs in two types of lowland coniferous forests in west-central Poland. Ticks Tick Borne Dis. 7, 1180–1185. [PubMed: 27499188]

White A, Gaff H, 2018. Application of tick control technologies for blacklegged, lone star, and American dog ticks. J. Integr. Pest Manag 9, 12.

Wilhelmsson P, Lindblom P, Fryland L, Nyman D, Jaenson TGT, Forsberg P, Lindgren PE, 2013. *Ixodes ricinus* ticks removed from humans in Northern Europe: seasonal pattern of infestation, attachment sites and duration of feeding. Parasit. Vectors 6, 362. [PubMed: 24360096]

Xu G, Mather TN, Hollingsworth CS, Rich SM, 2016. Passive surveillance of *Ixodes scapularis* (Say), their biting activity, and associated pathogens in Massachusetts. Vector Borne Zoonotic Dis. 16, 520–527. [PubMed: 27248292]

Xu G, Pearson P, Dykstra E, Andrews ES, Rich SM, 2019. Human-biting *Ixodes* ticks and pathogen prevalence from California, Oregon, and Washington. Vector Borne Zoonotic Dis. 19, 106–114. [PubMed: 30207871]

Young I, Prematunge C, Pussegoda K, Corrin T, Waddell L, 2021. Tick exposures and alpha-gal syndrome: a systematic review of the evidence. Ticks Tick Borne Dis. 12, 101674. [PubMed: 33529984]

Zhang AJ, Klun JA, Wang SF, Carroll JF, Debboun M, 2009. Isolongifolenone: a novel sesquiterpene repellent of ticks and mosquitoes. J. Med. Entomol 46, 100–106. [PubMed: 19198523]

Zöldi V, Turunen T, Lyytikäinen O, Sane J, 2017. Knowledge, attitudes, and practices regarding ticks and tick-borne diseases, Finland. Ticks Tick Borne Dis. 8, 872–877. [PubMed: 28778675]

Table 1

Characteristics of personal protection measures to prevent human tick encounters from resulting in bites or to shorten the duration a biting tick stays attached.

Type of action	Personal protection measure	Rationale(s) for use
Action taken while outdoors in tick habitat	Wear light-colored clothing	Creates contrast with dark-colored ticks, to facilitate spotting them crawling on clothing during a quick, cursory tick check
	Wear untreated clothing covering skin on feet, legs, torso, and arms (physical barrier)	Forces ticks that make first contact with untreated clothing to move a longer distance before reaching skin, thereby increasing the chance of ticks falling off clothing or being detected while crawling prior to reaching skin
	Apply repellent to skin/clothing (synthetic or natural product)	Prevents ticks that make contact with treated skin from continuing to crawl and reach a bite site on untreated skin; Prevents ticks that make contact with treated clothing from continuing to crawl to reach skin
	Wear permethrin-treated clothing (pre-impregnated or sprayed with permethrin)	Prevents ticks that make contact with treated clothing from continuing to crawl to reach skin
	Perform regular cursory checks for crawling ticks	Improves the likelihood of spotting ticks crawling on clothing or skin before they can bite
Action taken soon after coming back indoors	Perform a thorough check for crawling and attached ticks	Improves the likelihood of spotting ticks crawling on clothing or skin before they can bite; Facilitates prompt removal of attached ticks
	Change clothes and run the clothes worn outdoors in dryer on high heat	Prevents bites by ticks still remaining on outdoor clothing by changing clothes; Kills ticks by drying outdoor clothing at high heat; Improves the likelihood of spotting ticks that were crawling on skin under clothing or are biting
	Take a shower/bath	Improves the likelihood of spotting ticks that were crawling on skin under clothing or are biting; Potential for crawling ticks to be dislodged while showering/bathing
Action to shorten the duration of time before detected attached ticks are removed	Promptly remove detected attached ticks	Overall risk of pathogen transmission by attached infected ticks increases with duration of attachment
Action to disrupt feeding by attached ticks that go undetected[a]	Receive anti-tick vaccine to disrupt tick feeding[a]	Overall risk of pathogen transmission by attached infected ticks increases with duration of attachment
	Apply acaricidal skin product to disrupt tick feeding[a]	Overall risk of pathogen transmission by attached infected ticks increases with duration of attachment
	Ingest oral acaricidal product to disrupt tick feeding[a]	Overall risk of pathogen transmission by attached infected ticks increases with duration of attachment

[a]Potential future approach.

Table 2

Studies presenting data for level of use of personal protection measures intended to prevent tick bites in the United States.

Study area	Predominance of tick-borne diseases associated with ***Ixodes*** versus ***Amblyomma*** or ***Dermacentor*** species in study area	Personal protection measure included in the study					Reference
		Untreated protective clothing	Repellents for skin and clothing	Permethrin-treated clothing	Tick checks	Showering/ bathing after coming indoors	
United States	*Ixodes; Amblyomma*/ *Dermacentor*	X	X				Herrington (2004)
United States	*Ixodes; Amblyomma*/ *Dermacentor*		X		X	X	Hook et al. (2015)
United States	*Ixodes; Amblyomma*/ *Dermacentor*		X	X	X	X	Beck et al. (2021)
United States	*Ixodes; Amblyomma*/ *Dermacentor*		X	X	X	X	Nawrocki and Hinckley (2021)
United States[a]	*Ixodes; Amblyomma*/ *Dermacentor*	X	X	X	X		Kopsco and Mather (2021)
Connecticut	*Ixodes*	X	X		X		Cartter et al. (1989)
Connecticut	*Ixodes*	X	X		X		Gould et al. (2008)
Connecticut	*Ixodes*	X	X		X		Vázquez et al. (2008)
Connecticut	*Ixodes*	X	X	X	X	X	Connally et al. (2009)
Connecticut	*Ixodes*	X	X		X	X	Butler et al. (2016)
Connecticut/Maryland	*Ixodes*		X		X	X	Niesobecki et al. (2019)
Delaware	*Ixodes*	X	X	X[c]	X	X	Gupta et al. (2018)
Maryland	*Ixodes*	X	X	X			Parrott et al. (1993)
Maryland	*Ixodes*		X	X	X		Malouin et al. (2003)
Maryland	*Ixodes*	X	X	X	X	X	Jones et al. (2015)
Maryland/Virginia	*Ixodes*		X	X	X	X	Hu et al. (2019)
Massachusetts	*Ixodes*	X	X		X		Shadick et al. (1997)
Massachusetts	*Ixodes*	X			X		Shadick et al. (2016)
Massachusetts	*Ixodes*	X	X		X		Phillips et al. (2001)
Massachusetts	*Ixodes*				X		Daltroy et al. (2007)
Massachusetts	*Ixodes*	X	X		X		Heller et al. (2010)
Massachusetts	*Ixodes*	X	X		X		Valente et al. (2015)
New Jersey	*Ixodes*	X	X		X		Goldstein et al. (1990)

Study area	Predominance of tick-borne diseases associated with *Ixodes* versus *Amblyomma* or *Dermacentor* species in study area	Personal protection measure included in the study					Reference
		Untreated protective clothing	Repellents for skin and clothing	Permethrin-treated clothing	Tick checks	Showering/ bathing after coming indoors	
New Jersey	*Ixodes*	X	X		X		Hallman et al. (1995)
New Jersey	*Ixodes*	X	X		X		Orloski et al. (1998)
New Jersey/New York/ Wisconsin	*Ixodes*	X	X	X	X	X	Bron et al. (2020)
New York	*Ixodes*	X	X		X		Smith et al. (1988)
New York	*Ixodes*	X			X		Nolan and Mauer (2006)
Pennsylvania	*Ixodes*	X	X		X		Smith et al. (2001)
Pennsylvania	*Ixodes*	X	X		X		Han et al. (2014)
Rhode Island	*Ixodes*	X	X		X		Finch et al. (2014)
Wisconsin	*Ixodes*	X			X		Schotthoefer et al. (2020)
Florida	*Amblyomma*/*Dermacentor*	X	X		X		Donohoe et al. (2018)
Indiana[b]	*Amblyomma*/*Dermacentor*	X	X	X[c]	X	X	Omodior et al., 2021a
Missouri	*Amblyomma*/*Dermacentor*	X	X	X	X		Bayles et al. (2013)
Oklahoma	*Amblyomma*/*Dermacentor*	X			X		Noden et al. (2020)
Tennessee	*Amblyomma*/*Dermacentor*		X		X		Jones et al. (2002)

[a]The survey included participants across the United States but the majority of responses came from northeastern and Mid-Atlantic states, and the results are therefore most representative of areas where *Ixodes*-associated diseases predominate.

[b]Arguments could be made for placing Indiana in either the *Ixodes* or *Amblyomma*/*Dermacentor* grouping but the latter was chosen because cases of *Ixodes*-associated disease occur primarily in northernmost Indiana, whereas cases of disease associated with *Amblyomma*/*Dermacentor* occur more broadly throughout the state.

[c]The survey included permethrin treatment of clothing but the questions were phrased so that answers also may have included treatment of clothing with skin/clothing repellents.

Table 3

Breakdown of states included as high incidence states for Lyme disease, or states neighboring high incidence states, for national surveys on level of use of personal protection measures intended to prevent tick bites in the United States.

Surveys	High incidence states for Lyme disease	Neighboring states	Low incidence states for Lyme disease
Herrington et al. (2004)[a]	Connecticut, Delaware, New Jersey, New York, Pennsylvania, Rhode Island	Not included	The remaining 42 contiguous states and the District of Columbia
Beck et al. (2021)[b]Nawrocki and Hinckley (2021)[b]	Connecticut, Delaware, Maine, Maryland, Massachusetts, Minnesota, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, Virginia, Wisconsin	Illinois, Indiana, Iowa, Kentucky, Michigan, North Carolina, North Dakota, Ohio, South Dakota, Tennessee, West Virginia, District of Columbia	The remaining 23 contiguous states

[a]High Lyme disease incidence states defined as having ≥10 reported cases per 100,000 persons per year from 1992 to 1998. Low Lyme disease incidence states defined as having <10 reported cases per 100,000 persons per year from 1992 to 1998.

[b]High Lyme disease incidence states defined as having ≥10 reported confirmed cases per 100,000 persons per year from 2008 to 2015. Neighboring states defined as having <10 reported confirmed cases per 100,000 persons per year from 2008 to 2015 but sharing a border with a high Lyme disease incidence state. Low incidence states defined as having <10 reported confirmed cases per 100,000 persons per year from 2008 to 2015 and not sharing any border with a high Lyme disease incidence state.

Table 4

Studies presenting data for the effectiveness of personal protection measures to prevent tick-borne disease in the United States.

Study area	Predominance of tick-borne diseases associated with *Ixodes* versus *Amblyomma* or *Dermacentor* species in study area	Personal protection measure included in the study					Reference
		Untreated protective clothing	Repellents for skin and clothing	Permethrin-treated clothing	Tick checks	Showering/ bathing after coming indoors	
Northeastern U.S.	*Ixodes*	X	X		X	X	Klein et al. (1996)
California	*Ixodes*	X					Lane et al. (1992)
California	*Ixodes*	X	X		X		Ley et al. (1995)
New Jersey	*Ixodes*		X				Schwartz and Goldstein (1990)
Connecticut	*Ixodes*	X	X		X		Vázquez et al. (2008)
Connecticut	*Ixodes*	X	X	X	X	X	Connally et al. (2009)
Maryland	*Ixodes*	X	X		X		Armstrong et al. (2001)
Massachusetts	*Ixodes*	X	X		X		Phillips et al. (2001)
New Jersey	*Ixodes*	X	X		X		Orloski et al. (1998)
New York	*Ixodes*	X	X		X		Smith et al. (1988)
Pennsylvania	*Ixodes*	X	X		X		Smith et al. (2001)
Rhode Island	*Ixodes*	X	X		X		Finch et al. (2014)
Indiana[a]	*Amblyomma*/*Dermacentor*	X	X	X[b]	X	X	Kianersi et al. (2020)

[a]Arguments could be made for placing Indiana in either the *Ixodes* or *Amblyomma*/*Dermacentor* grouping but the latter was chosen because cases of *Ixodes*-associated disease occur primarily in northernmost Indiana, whereas cases of disease associated with *Amblyomma*/*Dermacentor* occur more broadly throughout the state.

[b]The study included permethrin treatment of clothing but the questions were phrased so that answers also may have included treatment of clothing with skin/clothing repellents.