Anaplasma phagocytophilum-Borrelia burgdorferi Coinfection Enhances Chemokine, Cytokine, and Matrix Metalloprotease Expression by Human Brain Microvascular Endothelial Cells

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Borrelia burgdorferi and Anaplasma phagocytophilum coinfect and are transmitted by Ixodes species ticks. Clinical indicators suggest that A. phagocytophilum coinfection contributes to the severity, dissemination, and, possibly, sequelae of Lyme disease. Previous in vitro studies showed that spirochete penetration through human brain microvascular endothelial cells of the blood-brain barrier is facilitated by endothelial cell-derived matrix metalloproteases (MMPs). A. phagocytophilum-infected neutrophils continuously release MMPs and other vasoactive mediators. We examined B. burgdorferi infection of brain microvascular barriers during A. phagocytophilum coinfection and showed that coinfection enhanced reductions in transendothelial electrical resistance and enhanced or synergistically increased production of MMPs (MMP-1, -3, -7, -8, and -9), cytokines (interleukin 6 [IL-6], IL-10, and tumor necrosis factor alpha), and chemokines (IL-8 and macrophage inflammatory protein 1α) known to affect vascular permeability and inflammatory responses.

Lyme disease is the most frequently reported arthropod-borne infection in North America and Europe (12, 35). The bacteria which are transmitted to humans by the bites of infected Ixodes persulcatus complex ticks can spread to the skin, heart, joints, eyes, and, in addition, the peripheral and central nervous systems (CNS) (40, 51). As the diversity of clinical presentations for Lyme disease has been recognized, some have suggested that concurrent infections by other tick-borne pathogens could influence the natural course of disease, leading to more severe infection, persistence, and even refractoriness to effective therapies (3). A prime candidate as a potential influence on the clinical manifestations of Lyme disease is Anaplasma phagocytophilum, the causative agent of human granulocytic anaplasmosis (HGA). Like Borrelia burgdorferi, A. phagocytophilum is transmitted by I. persulcatus complex tick bites, and increasing amounts of data show that coinfection is not infrequent (16, 48). Coinfection that results in simultaneous clinical manifestations is well documented (31). At least five clinical studies provide evidence that coinfections contribute to enhanced morbidity and clinical manifestations lengthier than those observed with Lyme disease or HGA alone (4–6, 28, 36, 41).

Experimental coinfections in the mouse model reveal modified immunological responses to both pathogens associated with higher bacterial burdens, longer persistence, and worsened disease (23, 47, 52). As penetration into and out of the bloodstream are obligatory events for the dissemination of B. burgdorferi and A. phagocytophilum, their interactions at the level of the blood-endothelial cell interface are likely to be critical (20). We recently showed that, for the human cerebrospinal fluid isolate B. burgdorferi 297 (30), penetration through endothelial cells is facilitated by the actions of endothelial cell-derived matrix metalloproteases (MMPs) (20, 22). Moreover, we showed that A. phagocytophilum-infected neutrophils protractedly produce biologically active molecules, including chemokines, cytokines, and MMPs (14, 15). With the concept that A. phagocytophilum-infected neutrophil-derived products would increase spirochete spread, we found that A. phagocytophilum-infected neutrophils augment the trans-endothelial cell migration of B. burgdorferi, suggesting that increased blood and tissue spirochete loads also occur by a mechanism not dependent on adaptive immune response (32).

Since the major candidates as biological mediators for enhanced B. burgdorferi penetration of human brain microvascular endothelial cell (BMEC) barriers include MMPs, cytokines, and chemokines, we examined whether in vitro coinfection with B. burgdorferi and A. phagocytophilum-infected human neutrophils would (i) induce MMPs and cytokines known to affect endothelial barrier integrity or (ii) enhance in vitro vascular permeability, measured by transendothelial electrical resistance (TEER) since permeability in human BMECs (and epithelial cells) is inversely proportional to TEER (1, 24, 34, 50).

MATERIALS AND METHODS

The spirochetes. Low-passage (less than five in vitro passages) B. burgdorferi was cultured at 34°C in Barbour-Stoenner-Kelly II medium containing 10% rabbit serum as described by Barbour (2). In our study, we used B. burgdorferi 297, a strain originally isolated from human cerebrospinal fluid (30). The bacteria were examined for motility with a dark-field microscope to verify their viability and that the organisms were thoroughly dispersed at the start of all the assays. Borrelia burgdorferi quantification was performed by using quantitative real-time PCR targeting the single-copy chromosomal flgB (29). Amplifications were performed using a Bio-Rad iCycler iQ5 multicolor real-time PCR detector (20).
Anaplasma phagocytophilum-infected neutrophils. Neutrophils, obtained from the peripheral blood of healthy donors under a protocol approved by the Johns Hopkins School of Medicine institutional review board, were isolated and infected with A. phagocytophilum Webster strain (13). Romanowsky staining (Hema-3; Fisher, Middletown, VA) was used to confirm that >90% of the neutrophils were infected (13).

The human BMECs. A human BMEC cell line whose phenotypic expression was stabilized by immortalizing the cells with pSVT, a pBR322-based plasmid containing the DNA sequence encoding the simian virus 40 large-T antigen (44), was stabilized by immortalizing the cells with pSVT, a pBR322-based plasmid

**RESULTS**

MMP, cytokine, and chemokine expression during coinfection. Cultures were sampled after a 5- to 6-h incubation period determined in previous experiments to correspond to a time of significant spirochete transmigration (20, 32). At this point, little production of cytokines and chemokines was stimulated by infection of human BMECs by B. burgdorferi alone (Fig. 1). Nor did spirochetes alone cause induction of or increased expression of MMP-2, MMP-9, or MMP-1. Compared to the results with B. burgdorferi and neutrophils alone, coinfection with both A. phagocytophilum-infected neutrophils and B. burgdorferi resulted in increased, sometimes synergistic release of...
MMP-1 (1.064 ± 23 [mean ± standard deviation] versus 1.917 ± 112 pg/ml), MMP-3 (244 ± 11 versus 1,000 ± 51 pg/ml), MMP-7 (247 ± 18 versus 1,458 ± 93 pg/ml), MMP-8 (14.670 ± 1,128 versus 16.712 ± 610 pg/ml), and MMP-9 (14.393 ± 2,490 versus 26.706 ± 4,608 pg/ml), as well as of IL-10 (76 ± 10 versus 225 ± 7 pg/ml), MMP-1α (236 ± 85 versus 8,330 ± 2,892 pg/ml), and TNF-α (34 ± 8 versus 700 ± 39 pg/ml) (all P values were < 0.002) (Fig. 1). The secretion of cytokines IL-6 and IL-8 with coinfection was also greater than that with B. burgdorferi and neutrophils alone, but the results were additive (P < 0.02). The remaining cytokines/chemokines and MMPs were unaffected or minimally affected by coinfection (data not shown). Our finding is in accord with the results of a recent study showing that mouse brain endothelial cells can secrete granulocyte-macrophage colony-stimulating factor, IL-1α, IL-6, IL-10, and IL-12 but that, in the absence of lipopolysaccharide or amyloid-β, only IL-6 was spontaneously secreted in high levels (49). In addition, no IL-2, IL-4, or IFN-γ secretion was found. While synergistic release of MMP-8 and MMP-9 was also observed with uninfected neutrophils and B. burgdorferi, the quantities were statistically less than under conditions of coinfection (Fig. 1).

Assessment of human BMEC monolayer barrier function. When human BMECs were incubated with B. burgdorferi 297 alone, the BMEC monolayer integrity initially became compromised approximately 5 h after spirochete addition, reached a nadir by 11 h, and then recovered to control levels by 17 h (Fig. 2A). That human BMECs remained viable throughout the process was also shown by transient changes in human BMEC TEER that occurred in the presence of continuous spirochete infection. Interestingly, while the drop in TEER with coinfection also reached a nadir at 11 h, it was more dramatic with coinfection than with B. burgdorferi (Fig. 2A). That human BMECs remained viable throughout the overall TEER changes relative to TEER for human BMEC baseline controls (Fig. 2A).

DISCUSSION

It is reasonable to speculate that these data imply that MMPs and/or cytokines and chemokines induced during coinfection could promote the enhanced transmission and perhaps greater dissemination of B. burgdorferi across the blood-brain barrier (BBB) and other vascular barriers. MMPs induced by TNF-α subsequent to systemic or local inflammatory responses are known to play a role in BBB integrity by compromising or reorganizing tight junctions (18, 21, 33, 38). Occludin, a tight junction protein that contains a putative MMP cleavage site (8), serves as substrate for both MMP-3 and MMP-9 (18, 21). Furthermore, MMP-3 can also degrade tight junction claudins and most extracellular matrix proteins (21, 33). Aside from proteolytic effects on endothelial cell tight junctions, MMPs also modulate inflammation by either activating or inactivating cytokines and other inflammatory factors. These results reveal clear evidence that the presence of both bacteria enhances inflammatory cytokine/chemokine production and strengthens the hypothesis that A. phagocytophilum enhances the degradation of MMPs from neutrophils.

A critical question that remains is whether these MMPs enhance B. burgdorferi, A. phagocytophilum, or coinfection pathogenesis. MMPs (except membrane-type MMPs) are secreted in proenzyme forms and require proteolytic cleavage at the N terminus for activation. The activation cascade for MMPs in the healthy host is closely tied to the fibrinolytic pathway, and activated MMP-3 is believed to be the major physiological activator of most MMPs, including MMP-9 (27, 33). While regulation of MMP production in normal cells is tightly controlled and occurs at many levels, the dysregulation of MMPs often associated with disease (27) could be an important consequence of coinfection. This hypothesis could also explain the worsening of arthritis in the mouse model of coinfection with A. phagocytophilum and B. burgdorferi (47).

Although the most direct explanation for the observation that BMEC monolayer integrity is compromised not only in B. burgdorferi infection but also, to a greater degree, with A. phagocytophilum coinfection is that the compromised integrity is due to the actions of MMPs on tight junction proteins, another possibility is that A. phagocytophilum-infected neutro-
phils are markedly activated for the production of chemokines (IL-8) and cytokines (IL-6) (15, 26), biologically active compounds with multiple effects, including enhanced changes in vascular permeability related to alterations in the endothelial cell cytoskeleton. For example, IL-8 and TNF-α induce permeability changes in cerebral vascular endothelial cells (9) and nonbrain microvascular cells (7, 9) by altering actin rearrangements (F-actin polymerization/stress fiber formation) through Rho and Rac GTPase-mediated signaling (7, 39, 45). IL-6 can also influence the physiologic function of the BBB and contributes to parenchymal CNS injury (10), whereas both IL-6 and IL-10 could act as compensatory neuroprotective factors (42, 49). In keeping with this hypothesis, we showed enhanced secretion of chemokines (IL-8 and MIP-1α) and cytokines (IL-6, IL-10, and TNF-α) during coinfection that could directly contribute to the transient breakdown in human BMEC monolayer integrity, allowing more spirochete transmission with coinfection than with B. burgdorferi alone. Furthermore, the biological consequences of enhanced chemokine/cytokine secretion might be further amplified by the direct action of an MMP whose expression was also enhanced. That such effects might occur was recently suggested by Tester et al., who show that MMP-8 cleavage at Arg5-Ser6 can activate IL-8 (46).

Additionally, A. phagocytophilum infection of neutrophils impairs phagocytosis, and this could result in an increased availability of B. burgdorferi to transmigrate (17). Regardless, the combined effects of enhanced MMP, cytokine, and chemokine release and impaired neutrophil phagocytosis with coinfection could collectively lead to enhanced entry of B. burgdorferi into the CNS and other tissues, potentially worsening clinical manifestations of Lyme disease. A precedent for A. phagocytophilum-enhanced clinical disease in the CNS exists in sheep coinfected with looping ill virus, a tick-transmitted flavivirus of the tick-borne encephalitis group (11, 37), although the mechanism is not understood.

In summary, these data show that B. burgdorferi-A. phagocytophilum coinfection results in higher levels of MMP, cytokine, and/or chemokine production, as well as more-extensively compromised endothelial barrier function, than B. burgdorferi or A. phagocytophilum infection alone. Together, these factors could play a role in the observed enhancement of B. burgdorferi transmigration across the BBB in the human model. Further investigation will be required to prove the hypothesis that increased transmigration results from MMP/cytokine/chemokine-enhanced tight junction degradation and/or signal-mediated alterations of the host cell cytoskeleton. Importantly, these data provide a plausible alternate explanation for the enhanced tissue dissemination of Lyme disease spirochetes with A. phagocytophilum coinfection in animal models and set the stage for further work if concurrent HGA proves to exacerbate and facilitate spirochete dissemination in human Lyme disease.

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