The RNA-binding protein HuR contributes to neuroinflammation by promoting C-C chemokine receptor 6 (CCR6) expression on Th17 cells *

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ABSTRACT

In both multiple sclerosis and experimental autoimmune encephalomyelitis (EAE), the C-C chemokine receptor 6 (CCR6) is critical for pathogenic T helper 17 (Th17) cell migration to the central nervous system (CNS). While many cytokines and their receptors are potently regulated via post-transcriptional mechanisms in response to various stimuli, how CCR6 expression is post-transcriptionally regulated in Th17 cells is unknown. Here, using RNA-binding protein HuR conditional knockout (KO) and wild-type (WT) mice, we present evidence that HuR post-transcriptionally regulates CCR6 expression by binding to and stabilizing Ccr6 mRNA and by promoting CCR6 translation. We also found that HuR downregulates several microRNA biogenesis which could target the 3'UTR of Ccr6 mRNA for decay. Accordingly, knockout of HuR reduced CCR6 expression on Th17 cells and impaired their migration to CNS compared with the response of WT Th17 cells and thereby ameliorated EAE. Together, these findings highlight how HuR contributes to Th17 cell-mediated autoimmune neuroinflammation and support the notion that targeting HuR might be a potential therapeutic intervention for managing autoimmune disorders of the CNS.

T helper 17 (Th17) cells play critical roles in the inflammatory disorders including multiple sclerosis (MS) and experimental autoimmune encephalomyelitis (EAE) (1-5). The signature cytokine produced by Th17 cells, interleukin 17 (IL-17) (2,6), has been previously found to be involved in host defense against bacterial infection (7,8). Expression of the C-C chemokine receptor 6 (CCR6) on Th17 cells is required for migration of pathogenic Th17 cells to sites of inflammation (9-12). In the central nervous system (CNS) of mice with EAE, Th17 cells expressing CCR6 are attracted by the chemokine ligand 20 (CCL20), which is constitutively secreted by choroid-plexus epithelial cells(12-14); accordingly, anti-CCL20 antibody treatment in vivo significantly suppressed pathogenic CD4+ T cell accumulation and the development of EAE (15,16). Signaling by CCL20 through CCR6 allows Th17 cells to cross the epithelial barrier of the choroid plexus, and enter the cerebrospinal fluid.
Thus, the initial trigger of inflammation is induced by CCR6-dependent autoreactive Th17 cell infiltration of the uninflamed CNS (12-14). In agreement with this notion, CCR6−/− mice are resistant to development of EAE (12). Moreover, CCR6-expressing Th17 cells are enriched in the cerebrospinal fluid of patients with early clinical symptoms of MS (12,17,18). Therefore, further understanding the mechanisms that underlie CCR6 expression in Th17 cells may uncover novel therapeutic targets for treatment of Th17 cell-mediated autoimmune diseases.

Differentiation of Th17 cells is induced by activation of naïve CD4+ T cells in the presence of a milieu of inflammatory cytokines. TGF-β and IL-6 potently induce naïve CD4+ T cells to differentiate into Th17 cells, which are reinforced by IL-23 (6,19,20). During cytokine-mediated Th17 cell differentiation, the transcription factor STAT3 and two orphan nuclear receptors, RORγt and RORα, function to regulate Th17 cell differentiation (21,22). The transcriptional regulation of CCR6 gene expression in Th17 cells is known to be regulated by TGF-β and to require RORγt and RORα (11).

Despite recent progress in understanding the regulation and function of CCR6 on Th17 cells, it is still unclear how CCR6 expression is post-transcriptionally regulated. Given the importance of post-transcriptional gene regulation in eliciting quick responses to stimuli, defining the mechanisms mediating post-transcriptional regulation is a very active area of research (23,24). Mammalian HuR is the homolog of the ELAV (embryonic lethal abnormal vision) like protein in D. melanogaster (25), and is ubiquitously expressed in all tissues. HuR binds to target mRNAs bearing specific sequence elements, often U- and AU-rich and generally found in the mRNA 3′-untranslated regions (3′UTR), and plays a critical role in their post-transcriptional regulation (26). HuR stabilizes many target mRNAs encoding proteins with roles in cell proliferation, survival, immune responses, and differentiation (27). Although HuR is known to stabilize many of these mRNAs and/or modulate their translation, the molecular mechanisms by which HuR affects the fate of target mRNA remains unknown. In addition, recent studies indicate that HuR may mediate some of its effects through interplay with microRNAs (miRNAs) associated with the same target mRNAs (27).

In this study, we focused on investigating the role of HuR in mediating expression of CCR6 on pathogenic Th17 cells in EAE. HuR binds to Ccr6 mRNA to prolong its half-life and moderately increases its translation, leading to increased CCR6 expression. In addition, our data indicate that HuR negatively regulates the expression of some miRNAs, and thus HuR may prevent these miRNAs from binding to and degrading Ccr6 mRNA, further enhancing CCR6 expression. Knockout of HuR decreases CCR6 expression on Th17 cells and impairs their migration in response to its ligand, CCL20, thereby ameliorating EAE. These results further support the notion that targeting HuR might be a novel therapeutic intervention for autoimmune encephalomyelitis (28).

RESULTS

Th17 cells express high levels of HuR and CCR6-In previous studies, we demonstrated that in comparison with WT Th17 cells, HuR conditional knockout (HuR KO) Th17 cells induced less severe EAE after transfer into naïve C57BL/6 mice (28), which indicated that HuR plays a role in the initiation of EAE. When using Rag1−/− mice as recipients, the difference in induction of EAE between WT and HuR KO Th17 cells was much more significant and the difference in EAE severity between the two groups lasted for three weeks, at which time the experiment was ended (data not shown). Since recipients that received HuR KO Th17 cells had fewer CD4+ T cell infiltrations in the CNS (28), we speculated that HuR KO Th17 cells may exhibit impaired migration into the inflamed CNS. As CCR6 is crucial for the pathogenic Th17 cell migration in rheumatoid arthritis and EAE (10,12,29), we sought to investigate whether HuR regulates expression of CCR6 on Th17 cells.

Our previous studies showed that naïve CD4+ T cells expressed low levels of HuR protein, and activation of CD4+ T cells by anti-CD3 plus anti-CD28 increased expression of HuR (28). Further analysis showed that anti-CD3 alone induced intermediate level of HuR protein expression, and anti-CD28 or IL-2 synergized with anti-CD3 to induce high level of HuR protein expression (data not shown). These findings supported the idea that HuR may play an important role in T cell activation, in agreement with our previous studies (30). In order to determine if there is a relationship between expression of CCR6 and HuR protein in T helper
cells, naive CD4+ T cells from WT mice were isolated and cultured under different T helper cell or T regulatory (Treg) cell polarization conditions. The expression levels of CCR6 and HuR on Th1, Th2, Th17, and Treg cells were measured by qRT-PCR, flow cytometry and western blot analysis, respectively. As shown, CCR6 was highly expressed on Th17 cells, modestly expressed on Treg cells, and expressed at low levels on Th1 and Th2 cells, and the level of Ccr6 mRNA expression correlates well with level of CCR6 protein expression in these different Th subsets (Fig. 1A, B). Western blot analysis demonstrated a similar pattern of HuR expression in these T subset cells, with highest expression of HuR in Th17 cells, moderate HuR levels in Tregs and lowest expression in Th1 cells (Fig. 1C). Furthermore, differentiation of Th17 cells resulted in an average two fold increase in HuR protein expression levels in comparison with CD4+ T cells activated with anti-CD3 plus anti-CD28 and without Th17 cell polarization cytokines (Fig. 1C, D). Together, these findings suggest that the expression of CCR6 correlates with the level of HuR protein in Th17 cells, supporting our hypothesis that HuR positively promotes expression of CCR6 on Th17 cells.

HuR deficiency reduces the expression of Ccr6 mRNA and protein levels in Th17 cells—We utilized HuR conditional knockout mice to more definitively evaluate the relationship between HuR and CCR6 expression on Th17 cells. We isolated naive CD4+ T cells from spleen of WT and HuR KO mice, and cultured the cells under Th17 cell polarization conditions (28). Reverse transcription followed by qRT-PCR revealed that expression of Ccr6 mRNA, but not il22 mRNA, was significantly reduced in HuR KO Th17 cells in comparison with WT Th17 cells (Fig. 2A). Consistent with the qRT-PCR data, western blot and flow cytometric analyses revealed that the level of CCR6 protein was also decreased in HuR KO Th17 cells compared to WT Th17 cells (Fig. 2B-F). These results further supported the notion that HuR positively regulates CCR6 expression in Th17 cells.

Computational analysis showed that mouse Ccr6 mRNA with short 3'UTR contains one potential HuR binding site. However, the human CCR6 mRNA contains several HuR potential binding sites in the open reading frame (ORF) and the 3'UTR (data not shown). Thus, we hypothesized that HuR may also regulate CCR6 expression in human CD4+ T cells, which might have clinically relevant consequences given the identification of CCR6-positive Th17 cells in multiple sclerosis (17). To test this possibility, naive CD4+ T cells were isolated from human peripheral blood and HuR expression was reduced by transfection with small interfering (si)RNA directed at the HuR mRNA. The cells were differentiated using Th17 cell culture conditions (28). The results revealed that CCR6 expression was reduced following knockdown of HuR in human CD4+ T cells compared to cells treated with scrambled control siRNA (Fig. 2G, H, I), suggesting that HuR may play a similar role in controlling CCR6 expression in human CD4+ T cells.

Since macrophages treated with LPS express high levels of CCR6 (31,32), we evaluated whether knockdown of HuR altered CCR6 expression in macrophages. The results shows that silencing HuR significantly reduced the expression of HuR in RAW 264.7 macrophages (data not shown). Flow cytometric analysis revealed that HuR silencing also selectively decreased CCR6 expression in macrophages (data not shown). These data further support the notion that HuR positively regulates CCR6 expression.

HuR modulates CCR6 expression by binding to and stabilizing Ccr6 mRNA—HuR has three RNA recognition motifs (RRMs) through which it interacts with target mRNAs (26). To explore the mechanism underlying the regulation of CCR6 expression by HuR, we performed a RNA immunoprecipitation (RIP) assay to examine whether HuR proteins physically associate with Ccr6 mRNA. Following RIP using anti-HuR antibody (3A2) beads in Th17 cell lysates, the RNA was isolated from the IP material, reverse transcribed, and quantitated by qRT-PCR analysis. Control IP reactions were carried out in parallel using an IgG. As shown in Figure 3A, Ccr6 mRNA was significantly enriched in anti-HuR immunoprecipitation (IP) samples compared to isotype-matched IgG controls, after normalization of RNA levels in all IP samples by amplifying a Gapdh mRNA, which encodes a housekeeping protein and is not a target of HuR. These findings indicate that HuR forms a complex with Ccr6 mRNA.

HuR regulates many target mRNAs by modulating their stability and/or translation rate (27). In order to determine if HuR functions to protect Ccr6 mRNA from degradation, we isolated
Naive CD4+ T cells from WT and KO mice and cultured them under Th17 polarization conditions. The polarized Th17 cells were treated with the RNA polymerase II inhibitor actinomycin D to inhibit de novo transcription, and the Ccr6 mRNA decay rates were measured by qRT-PCR analysis. As indicated in Figure 3B, the half-life of Ccr6 mRNA in HuR KO Th17 cells was much shorter than that in WT Th17 cells (1.91 h vs 3.41 h), suggesting that HuR binds to and stabilizes Ccr6 mRNA to prolong its half-life.

We then asked whether HuR functions to modulate Ccr6 mRNA translation. Polysome fractionation analysis is useful to analyze the RNA-binding protein regulation of target mRNA translation (33). We compared the relative sizes of Ccr6 mRNA associated with polyribosomes in WT and HuR KO Th17 polarized cells. Following fractionation through sucrose gradients, Ccr6 mRNA polyribosomes in HuR KO Th17 cells showed moderately smaller size (shifted towards polysomes of lower molecular weight) compared with those in WT Th17 cells (Fig. 3C). By contrast, Actin mRNA, encoding a housekeeping protein, did not show this shift in distribution towards smaller molecular weight (Fig. 3D). These findings suggested that in addition to promoting the stability of Ccr6 mRNA, HuR also moderately promoted Ccr6 mRNA translation. Indeed, overexpression of HuR by HuR plasmid transfection increases the luciferase activity of vector containing Ccr6 mRNA ORF and 3’UTR in Hela cells compared with control group (Fig. 3E).

miRNA-mediated Ccr6 mRNA decay—Besides RNA-binding proteins, microRNAs also regulate gene expression in a sequence-specific manner, often through interplay with RNA-binding proteins that associate with the same mRNAs (34). The physical and functional interaction of HuR with miRNAs has been documented (27). To investigate the possibility that HuR affects the fate of Ccr6 mRNA via miRNAs, computational analyses were performed using the TargetScan and miRanda algorithms to identify potential miRNA binding sites in the Ccr6 3’UTR. Three sites were identified: miR-409, miR-197, and miR-335 (Fig. 4A). To determine whether there was any functional link between HuR and miRNAs predicted to bind the Ccr6 3’UTR, qRT-PCR analysis was performed to detect these miRNAs in WT and HuR KO Th17 cells. Interestingly, while miR-155 levels were unchanged in the two Th17 populations, miR-409 and miR-335 levels were increased 2- to 3-fold (Fig. 4B) and miR-197 level increased 1.5-fold (data not shown) in HuR KO Th17 cells compared to WT Th17 cells, suggesting that HuR may negatively impact on the levels of certain miRNAs.

Since miRNAs robustly regulate gene expression by degrading and/or repressing the translation of target mRNAs (34), we investigated whether miR-409 and miR-335 bind to their predicted sites of Ccr6 mRNA 3’UTR, and regulate its expression. A reporter vector expressing firefly luciferase (FL) from a transcript that contained the Ccr6 3’UTR (Fig. 4D) was cotransfected with miRNA mimics into HeLa cells. Analysis of luciferase activity in HeLa cells revealed that overexpression of miR-335 reduced the luciferase activity of the reporter construct while overexpression of control scrambled miRNAs did not (Fig. 4C), suggesting that miR-335 was capable of selectively degrading Ccr6 mRNA. Similarly, overexpression of miR-409 in HeLa cells elicited a similar reduction in reporter luciferase activity (data not shown).

Genetic ablation of HuR impairs Th17 cells migration in response to CCL20 in vitro and in vivo—CCR6 is critical for Th17 cell migration to sites of inflammation (10,12,29,35,36). The lack of CCR6 in Th17 cells in mice decreases their susceptibility to autoimmune diseases including EAE (12,29,35,36). To evaluate the function of HuR in Th17 cell migration, we used a 24-well plate carrying a transwell-permeable membrane to compare the ability of WT and HuR KO Th17 cells to migrate towards the chamber containing CCL20, as previously described (11). WT and HuR KO Th17 cells were cultured in the upper well in transmembrane plates and CCL20 was added to the lower chamber. As shown in Fig. 5A, a large number of WT Th17 cells migrated into the lower chamber in response to CCL20. In contrast, HuR KO Th17 cells were cultured in the upper well in transmembrane plates and CCL20 was added to the lower chamber. As shown in Fig. 5A, a large number of WT Th17 cells migrated into the lower chamber in response to CCL20. In contrast, HuR KO Th17 cell migration was significantly decreased, indicating that knockout of HuR in Th17 cells, where CCR6 expression was impaired, resulted in decreased Th17 cell migration, which is consistent with the in vivo findings that fewer CD4+ T cells were present in the CNS of recipients of HuR KO Th17 cells (28).

Consistent with this experiment in cultured cells, ex vivo experiments revealed that expression of Ccr6 mRNA in splenic CD4+ T cells was significantly reduced in HuR KO mice compared
with that of WT mice with EAE (Fig. 5B), suggesting that HuR may also promote expression of CCR6 by inflammatory cells in vivo. Indeed, flow cytometric analysis revealed that the number of inflammatory CD4+CCR6+ cells was significantly reduced in the CNS of HuR KO mice relative to WT mice with EAE (Fig. 5C). Furthermore, Ccr6 mRNA was much lower in CNS monocytes from mice that received HuR KO Th17 cells than mice receiving WT Th17 cells (Fig. 5D).

**HuR regulates CCR6 expression in Th17 cells for promoting the initiation of EAE**—We previously demonstrated that transfer of HuR−/− Th17 cells induced less severe EAE in naïve C57BL/6 recipients compared with that of WT Th17 cells (28). However, in active EAE, the clinical score in HuR KO mice is only slightly less severe than that of WT mice at early stages of immunization (d5-d10), and the disease severity in both groups is similar at the late stages of induction (Fig. 6A). It is well known that T regulatory cells (Treg) play an important role in the resolution of EAE (37-39). Since CCR6 is also expressed in Treg cells, we hypothesized that knockout of HuR reduces the expression of CCR6 in Treg resulting in fewer Treg migrating into the CNS and less suppression of EAE pathogenesis. To test this hypothesis, WT and HuR KO Treg cells were generated from naive CD4+ T cells under Treg cell culture conditions. The levels of Ccr6 mRNA (Fig. 6B) and protein (Fig. 6C, D) in HuR KO Treg were drastically lower than those in WT Treg. To exclude the effect of HuR on Treg cells and to better understand the function of HuR in Th17 cells, we depleted Tregs by injection of anti-CD25 (PC61) 10 days before induction of EAE in WT and HuR KO mice. This treatment regimen was chosen given our previous findings that one injection of anti-CD25 was able to transiently deplete most Tregs in the spleen and lymph nodes (40,41). In addition, anti-CD25 antibody was degraded 10 to 14 days later which would not deplete the effector T cells when mice are immunized for induction of EAE. The results showed that when Treg cells were transiently depleted, HuR KO mice developed significantly less severe EAE than did WT mice (Fig. 6E), which further demonstrated that knockout of HuR reduces CCR6 expression on Th17 cells leading to impaired initiation of EAE.

**DISCUSSION**

In this study, we have demonstrated that HuR post-transcriptionally regulates CCR6 expression in Th17 cells. Mechanistically, HuR binds to Ccr6 mRNA to promote its stability and prolong its half-life. HuR deficiency reduces Ccr6 mRNA and protein levels leading to reduced Th17 cell migration, in turn impairing the initiation of EAE.

Animal model studies showed that CCR6 is essential for development of autoimmune diseases, and Ccr6−/− mice are resistant to EAE, rheumatoid arthritis, and atherosclerosis (10,12,29,35,36). Clinical studies showed that CCR6 is expressed at significantly higher levels in lesions of psoriatic skin than in normal skin (42). CCR6 was identified as a risk factor for rheumatoid arthritis. Moreover, a nucleotide polymorphism within the CCR6 locus was shown to be associated with susceptibility to rheumatoid arthritis, Graves' disease, and Crohn's disease (43,44). Mechanistic studies further demonstrated that CCR6 is required for pathogenic Th17 cell migration to inflamed tissues (9,10,29). More specifically, CCR6-positive Th17 cells cross the blood-brain barrier through the interaction between CCR6 and its ligand CCL20 in choroid plexus to induce EAE and multiple sclerosis (12). Therefore, further understanding the regulation of CCR6 expression may provide a novel venue for drug design to treat autoimmune inflammation.

Previous studies indicated that TGF-β promotes CCR6 expression in Th17 cells through transcription factors RORγt and RORα (11). Further studies identified a noncoding region of the human CCR6 gene with methylation-sensitive transcriptional activity in CCR6+ T cells that controls stable CCR6 expression via epigenetic mechanisms (43). However, the post-transcriptional modulation of CCR6 expression is unknown. Understanding this process is important because post-transcriptional gene regulation permits 1) synthesis of protein by translation from mRNA stored in cytoplasmic granules more rapidly than from newly synthesized transcripts, 2) metabolic economy, as translational repression allows the rapid turning off of protein production while preserving the mRNA, which allows reinitiation at a later time if conditions warrant it, and 3) sensitivity to environmental stimuli via receptors on the cell surface linked to signaling pathways that regulate the translation and decay of mRNA (24). Thus, we studied how CCR6 expression is post-transcriptionally regulated by RNA-binding protein HuR. Interestingly, compared
to Th1 and Th2 cells, Th17 cells express the highest level of HuR, and Treg cells express moderate levels of HuR (Fig. 1), consistent with previous reports that SMAD transcriptionally activates HuR expression (45), and that TGF-β required for Th17 and Treg cell differentiation is able to activate SMAD (6,46,47).

We previously showed that knockout of HuR in Th17 cells reduces IL-17 mRNA stability (28). We now provide evidence that Ccr6 mRNA is enriched in anti-HuR IP complexes, indicating that HuR protein interacts with Ccr6 mRNA. In addition, we demonstrate that HuR+ CD4+ T cells display reduced Ccr6 mRNA half-life when cells are polarized under Th17 cell conditions (Fig. 3). Although HuR binds to and stabilizes Ccr6 mRNA to promote its expression, we could not exclude the possibility of HuR modulating transcription factors to modulate CCR6 expression in Th17 cells. Work is in progress to address this possibility.

RNA-binding proteins can coordinate with miRNAs to regulate target gene expression post-transcriptionally (34). Several miRNAs like miR-335 and miR-409 are expressed in Th17 cells. Reporter analyses revealed that miR-335 and miR-409 reduced the activity of vectors containing the Ccr6 3'UTR. Interestingly, knockout of HuR in CD4+ T cells increased the expression of these miRNAs, indicating that HuR may negatively regulate their expression. Additional studies are needed to define the underlying mechanism by which HuR inhibits the expression of certain miRNAs. One possible explanation is that HuR cooperates with the miRNA let-7 in downregulating the expression of c-Myc (48,49), a transcription factor that promotes microRNA biogenesis (50), and thus knockout of HuR may increase c-Myc expression, which, in turn, promotes expression of microRNAs. This possibility remains to be tested experimentally.

Our previous work showed that HuR KO Th17 cells are less pathogenic than WT Th17 cells for inducing EAE (28). Our current study revealed that HuR deficiency reduces CCR6 expression in Th17 cells and impairs their migration in response to its ligand CCL20. This finding is consistent with our previous report that fewer CD4+ T cells migrated into the CNS in mice receiving HuR KO Th17 cells compared to those transferred with WT Th17 cells (28). In addition, early reports showed that CCR6-deficient autoreactive Th17 cells failed to migrate to the CNS, which resulted in development of less severe EAE (12).

Because CCR6 is also expressed on Treg (11), knockout of HuR also reduced CCR6 expression in Treg (Fig. 6) resulting in reduced Treg migration to the CNS, which might account for the moderate difference in severity at early stages between WT and HuR KO mice in actively induced EAE. To test this possibility, we depleted Treg by anti-CD25 in WT and HuR KO mice before the induction of the disease. As expected, Treg-depleted HuR KO mice develop significantly less severe EAE than WT mice do (Fig. 6E), supporting the idea that knockout of HuR dampens the pathogenicity of Th17 cells for induction of EAE. Taken together, our results suggest that HuR modulates CCR6 expression on Th17 cells to contribute to autoimmune neuroinflammation.

**EXPERIMENTAL PROCEDURES**

**Animals**-HuR<sup>lox/lox</sup> mice were generated as previously described (28,51). Eight- to ten-week-old control (HuR<sup>lox/lox</sup>) mice and HuR conditional knockout mice (OX40-<i>cre</i> HuR<sup>lox/lox</sup>) (HuR KO) were used. All mice are on the C57BL/6 background and were bred at the animal facility of Arkansas Bioscience Institute at Arkansas State University and/or the Thomas Jefferson University. Animal experiments were approved by the Institutional Animal Care and Use Committee (IACUC) and done according to federal and institutional guidelines.

**Isolation and differentiation of CD4<sup>+</sup> T cells in vitro**-Naive CD4<sup>+</sup> T cells were purified from splenocytes using CD4 negative selection kits (#19852A, StemCell Tech., Vancouver, Canada) following the manufacturer’s protocol. Single splenocytes were prepared by using 70µm nylon mesh cell strainer (#22363548, Fisher Scientific) and incubated with mouse CD4<sup>+</sup> T cell isolation cocktail (#19852c.1, StemCell Tech) following with Straptavidin RapidSpereres (#50001, StemCell Tech) following with plate-bound anti-CD3 (10 µg/ml) (14-0032, eBioscience) and anti-CD28 (3 µg/ml) (14-0281, eBioscience). For Th1 polarization, IL-12 (10
ng/ml) (419-ML-010, R&D system Inc.) and anti-IL-4 (10 μg/ml) (16-7041, eBioscience) were additionally used. For Th17 polarization, TGF-β (3 ng/ml) (rH100-21, Peprotech), IL-6 (20 ng/ml) 9216-6, PeproTech), IL-23 (20 ng/ml) (14-8231, eBioscience), anti-IFN-γ (10 μg/ml) (16-7312, eBioscience) and anti-IL-4 (10 μg/ml) were additionally used. For Th2 cell polarization, IL-4 (10 μg/ml), IL-2 (10 ng/ml) (212-12, PeproTech) and anti-IFN-γ (10 μg/ml) were added. For T regulatory cell (Treg) polarization, TGF-β (5 ng/ml), IL-2 (10 ng/ml), anti-IFN-γ (10 μg/ml) and anti-IL-4 (10 μg/ml) were additionally used. All cytokines were purchased from R&D Systems (Minneapolis, MN) and Peprotech (Rocky Hill, NJ), and antibodies were purchased from eBiosciences (San Diego, CA).

RNA isolation and Quantitative real time-PCR(qRT-PCR)-Cells were collected and total RNA was extracted using TRizol (Invitrogen, Life Technologies Corp., Thermo Fisher Scientific). Five hundred ng of RNA was reverse transcribed into cDNA using SuperScript III Kit (Invitrogen) and cDNA was subjected to quantitative real-time PCR analysis using the CFX96 Real-Time PCR Detection system (Bio-Rad, Hercules, CA) with SYBR Green reagent Kit (Invitrogen) according to the manufacturer’s protocols. The Cq data of test mRNAs were normalized to that of Gapdh mRNA for each sample, and the gene expression of WT was designed as 1. The gene expression in KO group was relative to those of WT (28). Forward and reverse primers for specific murine target genes are listed in Table 3. Sequences of HuR siRNA and scrambled siRNA are listed in Table 2. Forward and reverse primers for human target genes are listed in Table 1.

In vitro migration assay-The migration assay was performed in 24-well plates (Costar, Corning, NY) carrying Transwell-permeable supports with a 5-μm polycarbonate membrane for T cells. Briefly, 5x10^5 polarized Th17 cells were added to the upper wells in 200 μl culture medium, and the recombinant CCL20 (250-27, Peprotech) was added to the lower chambers in 600 μl culture medium. Cells were cultured for 3 hrs and cell migration was determined by counting the number of T cells in the lower chambers.

Transient depletion of Treg and EAE induction-To deplete Tregs, anti-CD25 antibody (0.5 mg per mouse) (PC61, BioXcell) was injected i.p. 10 days before EAE induction. For induction of active EAE, 8- to 10-wk-old female WT mice and HuR conditional KO mice were immunized with MOG35-55 and CFA followed by injection of PTX. EAE was clinically assessed by daily assignment of scores on a scale of 0-5 as previously described (28).

Isolation of mononuclear cells from CNS-Mononuclear cells were extracted from inflamed CNS tissue of EAE mice as previously described (28,52). Briefly, mice were perfused with cold PBS to remove blood from internal organs. The spinal cord was flushed out by hydrostatic pressure. Brain and spinal cords were digested in a solution with 0.2 U/ml Liberase DL (Roche, Nutley, NJ) and 1 mg/ml DNase I (Roche) in DMEM at 37°C for 45 min. A single cell suspension was prepared by passing through a 70-μm cell strainer, followed by centrifugation through a percoll gradient (37%/70%). Mononuclear cells in the interphase layer were transferred into a fresh tube and used in subsequent experiments for RNA isolation and for flow cytometry analysis.

Western blotting-Whole-cell lysates were prepared in RIP buffer (#89900, Thermo Scientific) and western blot analysis was performed as previously described (28,52). The concentration of protein was determined with BCA protein assay reagent (Thermo Scientific Pierce, Rockford, IL). Protein samples were separated by 10% sodium dodecyl sulphate-polyacrylamide gel electrophoresis (SDS-PAGE) and transferred to a nitrocellulose membrane (Bi-Rad, Hercules, CA). The membranes were incubated with primary antibodies recognizing HuR (Sc-5261, Santa Cruz Biotech, Santa Cruz, CA), β-Actin (Sc-130657, Santa Cruz Biotech), or CCR6 (NBP2-25220, Novus Biologicals) followed by incubation with goat anti-mouse or goat anti-rat secondary Ig conjugated with HRP (Jackson ImmunoResearch Lab. Inc., West Grove, PA). Membranes were developed by SuperSignal West Pico Chemiluminescent Substrate (Thermo Scientific Pierce, Rockford, IL).

Flow cytometry-Cells obtained from in vitro and ex vivo culture were stained for surface markers with allophycocyanin-conjugated anti-CD4 and PE-conjugated anti-CCR6 (129804, Biolegend, San Diego, CA). Acquisitions were made with a BD FACSCalibur (BD Biosciences, San Diego, CA). Cell Quest software was used for data analysis.

Immunoprecipitation of endogenous messenger RNP complexes-RNA immunoprecipitation (RIP) was performed according to the...
established protocols (28,53). Briefly, Th17 polarized cells were lysed using polysome lysis buffer (28). The lysates were pre-cleared for 30 min at 4°C by adding 30 µg of IgG1 (BD Bioscience) and 50 µl of Protein-A Sepharose beads (P3391, Sigma-Aldrich) swollen in NT2 buffer with 5% BSA (27, 30). Beads (100 µl) were coated by adding 30 µg of either IgG1 (BD Biosciences, San Diego, CA) as control or anti-HuR antibody 3A2, and incubated overnight at 4°C. After extensive washes of pre-coated Protein-A sepharose beads, 100 µl of pre-cleared lysate was added and incubated for 4 h at 4°C, and then 30 µg of proteinase K was added and incubated for 30 min at 55°C to digest protein. RNA was extracted, reverse transcribed, and the presence of specific target mRNAs was quantified by qPCR analysis.

Transfection and luciferase assay-HeLa cells (CCL-2, ATCC) were cultured in DMEM containing 10% FBS, penicillin (100U/ml), streptomycin (100 µg/ml), 2 mM L-glutamine and non-essential amino acids (Invitrogen). A total of 2x10^5 cells in 1 ml cell culture medium was seeded into each well of 24-well plates and incubated overnight. Transient transfections were performed using Lipofectamine 2000 (Invitrogen) with 0.3 µg firefly-luciferase plasmid DNA (GeneCopoeia, Rockville, MD) and 0.15 µg of pRL-CMV-renilla-luciferase plasmid. Cells were co-transfected with 40-80 nmol miRNA (Life Sciences). Twenty-four hours later, cells were collected and luciferase activities were measured using a Dual-Luciferase Reporter Assay System according to the manufacturer’s instructions (Promega, Madison, WI). Firefly luciferase activity was normalized to renilla luciferase in the same transfection groups.

Statistical analysis-Student t-test was used to analyze the differences between two groups for the experiments. The data are expressed as the mean ± SEM. A p value < 0.05 was considered statistically significant.

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Author contributions: JC and SY designed and performed most of the experiments; JM did the polysome assay; CC, MG, UA, PDD and SY analyzed the data; JC, PDD, MG and SY wrote the manuscript. All authors reviewed the results and approved the final version of manuscript.
REFERENCE


16. Tracey, K. J. (2012) Immune cells exploit a neural circuit to enter the CNS. Cell 148, 392-394


inflammatory protein-3alpha/CCL20 in mucosal epithelial cells through NF-kappaB [correction of NK-kappaB]. International Immunology 13, 1255-1263


Footnotes:

2. Abbreviation used are: EAE, experimental autoimmune encephalomyelitis; HuR KO, HuR conditional knockout; CCR6, C-C chemokine receptor 6; CNS, central nervous system; RIP, RNA immunoprecipitation; 3’UTR, 3’-untranslated regions
FIGURE LEGENDS

Figure 1. Expression of CCR6 and HuR in T helper cells and T regulatory (Treg) cells. Naïve CD4+ T cells were isolated from spleen of WT mice and activated or polarized as described in Methods. Activation (Act), Th1, Th2, Th17, and Treg cells were analyzed after 5 days of cell culture. Expressions of CCR6 on T helper cells and Treg cells were analyzed by flow cytometry (A) and qRT-PCR (B). (C) HuR protein levels in CD4+ T cells were assessed by western blot analysis. (D) The summary of HuR protein level in Th17 cells compared to that of activated CD4+ T cells. One of three independent experiments is shown in (A) and (C). Data in (B) and (C) are derived from at least three independent experiments, and presented as mean ± s.e.m. *p<0.05, **p<0.01.

Figure 2. Knockout of HuR reduces CCR6 expression on Th17 cells. Naïve CD4+ T cells were isolated from spleen of WT and HuR KO mice, and cultured under Th17 cell polarizing condition for 5 days. (A) Ccr6 mRNA levels were measured by qRT-PCR analysis. (B) Western blot analysis of CCR6 expression in WT and HuR KO Th17 cells. (C, D) Flow cytometric analysis of CCR6 expression on Th17 cells. (E) Summary of flow cytometric analysis of three independent experiments. (F) The percentage of CCR6+IL-17+ cells was reduced in HuR KO Th17 cells compared to that of WT Th17 cells. (G) Human peripheral blood CD4+ T cells were isolated and transfected with scrambled and HuR siRNA, and cultured in the presence (Act) or absence (Act) of Th17 cell polarizing cytokines. HuR protein expression levels were then assessed by western blot analysis. (H) qRT-PCR analysis of Ccr6 mRNA levels in following transfection of human Th17 cells with Scramble and HuR siRNAs (SiHuR). (I) The level of CCR6 protein was also reduced in HuR siRNA transfected human Th17 cells compared to that with scramble siRNA by Western blots. Data in (B-D, F, I) represent one of three independent experiments. Data in (G) represent one of three independent experiments.

Figure 3. HuR binds to and stabilizes Ccr6 mRNA. Naïve CD4+ T cells were isolated from spleen of WT mice and stimulated under Th17 cell-polarizing condition. (A) RIP analysis was performed to detect Ccr6 mRNA enrichment after IP using anti-HuR (3A2) or isotype–matched antibody (IgG1) from Th17 cell cytoplasmic extracts. Il23r mRNA was assayed as negative control. (B) WT and HuR KO Th17-polarized cells were either left untreated or treated with actinomycin D (Act D; 3 µg/ml) and harvested 1, 3 and 5 h later. Ccr6 mRNA levels were determined by qRT-PCR analysis. (C) WT and HuR KO Th17 cell lysates were size-fractionated through sucrose gradients, and RNA was isolated from each of 12 fractions, reverse-transcribed, and measured by qRT-PCR analysis. The relative distribution of Ccr6 mRNA along the gradient was calculated and plotted as a percent of the total Ccr6 mRNA in the gradient. (D) The distribution of Actin mRNA, encoding a housekeeping protein, was included as a negative control. (E) Overexpression of HuR by HuR plasmid (0.2µg) transfection increased the luciferase activity of vector containing Ccr6 mRNA ORF and 3’UTR (0.2µg) in Hela cells in comparison with empty vector control groups. One of three independent experiments is shown in (A-D). Data in E represent one of two individual experiments. **p<0.01, ***p<0.001.

Figure 4. MiR-335 negatively regulates Ccr6 mRNA. (A) Targetscan analysis prediction that miR-335, miR-197, and miR-409 have potential binding sites on the CCR6 3’UTR. (B) qRT-PCR analysis shows that knockout of HuR increased the level of miR-335 and miR-409 in Th17 cells. (C) Overexpression of miR-335 reduced the activity of luciferase reporter containing the CCR6 3’UTR. HeLa cells were transfected with a luciferase reporter construct containing CCR6 3’UTR, in which overexpression of miR-335 decreased the luciferase activity. Data in (B) and (C) were derived from at least three independent experiments. (D) Sketch diagram of a luciferase reporter construct containing CCR6 3’UTR. *p<0.05 and **p<0.01.

Figure 5. Knockout of HuR impairs Th17 cell migration in vitro and in vivo. (A) Transwell chemotaxis assay of WT and HuR KO Th17 cells was performed in the presence of CCL20 (CCR6 ligand). The migrated cells were analyzed at 3h of culture. HuR deficiency significantly reduced Th17 cells migration to CCL20. (B) CCR6 mRNA level in splenic CD4+ T cells from WT and HuR KO and mice with EAE. (C) Number of CD4+CCR6+ cells in the CNS of WT and HuR KO mice with EAE measured by flow cytometric analysis. (D)
HuR and CCR6

CCR6 expression in CNS monocytes from recipients of WT and HuR KO Th17 cells. The results shown in (A-D) are summary of at least three independent experiments. All data are expressed as the mean ± s.e.m. *p<0.05 and **p<0.01.

Figure 6. After Treg depletion, the severity of EAE is lower in HuR KO than in WT mice. (A) EAE in WT and HuR KO mice without Treg depletion. Each group contains 6 mice. CCR6 levels in WT and HuR KO Tregs were analyzed by qRT-PCR (B), Western blots (C) and flow cytometry (D). (E) EAE in WT and HuR KO mice in which Tregs were depleted by anti-CD25 10 day earlier. Each group contains 11 mice. One of two representative experiments is shown in (A), (C), (D) and (E). Data in (B) are derived from at least three independent experiments and presented as mean ± s.e.m. *p<0.05 and **p<0.01.
Table 1. Sequences of quantitative RT-PCR primers

<table>
<thead>
<tr>
<th>Sequences of mouse qRT-PCR primers</th>
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<tbody>
<tr>
<td>CCR6 forward 5’-CCTCACATTCTTGGACTGGAGC-3’</td>
</tr>
<tr>
<td>CCR6 reverse 5’-GGCAAATCAGAGCTCTCGGA-3’</td>
</tr>
<tr>
<td>HuR forward 5’-ACTGCAGGGATGACATTGGGAGA-3’</td>
</tr>
<tr>
<td>HuR reverse 5’-AAGCTTTGCAATTCAACCTCGCC-3’</td>
</tr>
<tr>
<td>IL-23R forward 5’-TTCAGATGGGGAATGTTTTCT-3’</td>
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<tr>
<td>IL-23R reverse 5’-CCAAATCCGAGCTGTTCTAT-3’</td>
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<tr>
<td>IL-17A forward 5’-TGTGTCTCTGATGCTTGCTGCT-3’</td>
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<td>IL-17A reverse 5’-AGGAAGTCTCTGGCCTCAGTGGTTT-3’</td>
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<td>GAPDH forward 5’-TCAACAGCAACTCCACTCTCCCA-3’</td>
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<tr>
<td>GAPDH reverse 5’-ACCCCTGGCTGTAGCCGTATTC-3’</td>
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<tr>
<td>IL-22 forward 5’-TGGAGATTCCAAGTCCAGCA-3’</td>
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<tr>
<td>Sequences of siRNA for human T cell transfection</td>
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<td>-----------------------------------------------</td>
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<tr>
<td><strong>HuR siRNA</strong></td>
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<td><strong>Scramble siRNA</strong></td>
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### Table 3. Sequences of quantitative RT-PCR primers

<table>
<thead>
<tr>
<th>Sequences of human qRT-PCR primers</th>
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<tbody>
<tr>
<td>CCR6 forward</td>
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<tr>
<td>CCR6 reverse</td>
<td>5'-TCCTGCAAGGAGACAGTAACA-3'</td>
</tr>
<tr>
<td>HuR forward</td>
<td>5'- AACTACGTGACCGGAG-3'</td>
</tr>
<tr>
<td>HuR reverse</td>
<td>5'- CGCCCAAACCGAGAGAACA-3'</td>
</tr>
<tr>
<td>IL-23R forward</td>
<td>5'-ACATGCTTCTATGTACTGCACTG-3'</td>
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<tr>
<td>IL-23R reverse</td>
<td>5'-TGTGTCTATGTAGGTGAGCGTTCC-3'</td>
</tr>
<tr>
<td>GAPDH forward</td>
<td>5'- GGAGCGGATCCCTCCAAAT-3'</td>
</tr>
<tr>
<td>GAPDH reverse</td>
<td>5'- GGCTGTGTTCATCTTCATGG-3'</td>
</tr>
</tbody>
</table>
Figure 1

A

Activation  Th1  Th2  Th17  Treg

CCR6

CD4

B

CCR6 mRNA fold

Activation  Th1  Th2  Th17  Treg

C

Act  Th1  Th2  Th17  Treg

HuR Fold

1  2.06  2.07  2.89  2.45

β-Actin

D

HuR expression

Activation  Th17 polarization

fold

1  2  3

*
Figure 4

A

| Position 16-22 of CCR6 3' UTR | 5'   | ... C A CAAAGCA ACA UUG... |
|                               | 3'   | UCCCCAAGUGGCUCGUUGUA AG   |
| miR-409                       |      |

| Position 36-41 of CCR6 3' UTR | 5'   | ... UUGCCCCAAAAGCCUUGGUG AAA... |
|                               | 3'   | CGACCCACCUCUCUCCACC A CUU    |
| miR-197                       |      |

| Position 57-63 of CCR6 3' UTR | 5'   | ... AACUUGCUAUUUACAUAUGA AAAA... |
|                               | 3'   | CCAGUCCUCGUUAUUA CUUUUU       |
| miR-335                       |      |

B

![Bar graph showing miRNA fold change with significance markers](image)

C

![Bar graph showing luciferase activity with significance markers](image)

D

![Diagram of SV40 Enhancer and CCR6 3'UTR with hLuc and hRLuc](image)
The RNA-binding protein HuR contributes to neuroinflammation by promoting C-C chemokine receptor 6 (CCR6) expression on Th17 cells
Jing Chen, Jennifer L Martindale, Carole Cramer, Myriam Gorospe, Ulus Atasoy, Paul D Drew and Shiguang Yu

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