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Title

Identification and Analysis of Host Proteins that Interact with the 3'-Untranslated Region of Tick-Borne Encephalitis Virus Genomic RNA

Running title: Identification of the host proteins interact with the variable region of 3'-UTR of TBEV

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Abstract

Tick-borne encephalitis virus (TBEV) causes severe neurological disease, but the pathogenetic mechanism is unclear. The conformational structure of the 3'-untranslated region (UTR) of TBEV is associated with its virulence. We tried to identify host proteins interacting with the 3'-UTR of TBEV. Cellular proteins of HEK293T cells were co-precipitated with biotinylated RNAs of the 3'-UTR of low- and high-virulence TBEV strains and subjected to mass spectrometry analysis. Fifteen host proteins were found to bind to the 3'-UTR of TBEV, four of which—cold shock domain containing-E1 (CSDE1), spermatid perinuclear RNA binding protein (STRBP), fragile X mental retardation protein (FMRP), and interleukin enhancer binding factor 3 (ILF3)—bound specifically to that of the low-virulence strain. An RNA immunoprecipitation and pull-down assay confirmed the interactions of the complete 3'-UTRs of TBEV genomic RNA with CSDE1, FMRP, and ILF3. Partial deletion of the stem loop (SL) 3 to SL 5 structure of the variable region of the 3'-UTR did not affect interactions with the host proteins, but the interactions were markedly suppressed by deletion of the complete SL 3, 4, and 5 structures, as in the high-virulence TBEV strain. Further analysis of the roles of host proteins in the neurologic pathogenicity of TBEV is warranted.

Key words

Tick-borne encephalitis virus, 3'-untranslated region, host factor, pathogenicity

Text

Tick-borne encephalitis (TBE) virus (TBEV), a member of the genus *Flavivirus* in the family *Flaviviridae*, is a major arbovirus that causes thousands of cases of severe

neurological illness annually (WHO Publication, 2011). Humans are accidental hosts, and become infected via a tick bite, and unpasteurized goat-milk also can be a source of infection. TBE is a huge public health problem in endemic areas in European and Asian countries (Carletti et al., 2017; Lindquist and Vapalahti, 2008; Mansfield et al., 2009; Yoshii et al., 2017). Mortality rates vary from about 0.5 to 30%, and neurological sequelae occur in 30 to 60% of survivors (Grard et al., 2007; Gritsun et al., 2003; Heinz and Kunz, 2004).

TBEV has a single-stranded RNA genome of positive polarity that encodes a long polyprotein in a single open reading frame, flanked by 5'- and 3'-untranslated regions (UTRs). The 5'- and 3'-UTRs are believed to be associated with viral genome replication (Khromykh et al., 2001; Kofler et al., 2006). The 3'-UTR of TBEV is divided into two domains: the 5'-terminal variable region and the 3'-terminal core element. The core element is highly conserved among TBEV strains and contains a sequence that is essential for viral genome replication (Kofler et al., 2006). In recent studies, it was shown that subgenomic flavivirus RNA (sfRNA) is produced by the 3'-UTR of viral genomic RNA, and it was suggested that sfRNA is involved in innate immunity response in mosquito-borne flavivirus infection (Chang et al., 2013; Pijlman et al., 2008; Rouha et al., 2010; Sakai et al., 2015; Schnettler et al., 2014).

The variable region of the 3'-UTR is considered to be essential for the natural transmission cycle of TBEV, but was previously considered not to be involved in viral replication and virulence in mammals (Mandl et al., 1998). The sequence and length of the variable region vary among TBEV strains (Wallner et al., 1995). Notably, few strains contain polyA sequences in the variable region isolated from ticks (Mandl et al., 1998; Růžek et al., 2008), and deletions of sequences in the variable region were identified in strains passaged in mammalian cell culture and in clinical isolates (Formanova et al., 2015; Leonova et al., 2013; Mandl et al., 1998). Those reports suggested that the viral

quasispecies with deletions or polyA insertions in the variable region are selected during adaptation from the tick vector to mammalian host environment (Asghar et al., 2014). Our previous studies reported that the deletion in the variable region of the 3'-UTR was involved in the pathogenicity of the strains from the Far-Eastern subtype of TBEV. In a mouse model, Sofjin-HO (accession no. AB062064) showed higher virulence than Oshima 5-10 strain (accession no. AB062064) (Chiba et al., 1999). The Oshima strain putatively forms seven Stem Loop (SL) structures in the variable region (Fig. 1A), while the SL 3 to 5 structures were deleted in the Sofjin strain. By reverse genetics analysis, introduction of the deletion into the Oshima strain drastically increased the virulence (Sakai et al., 2015). However, the role of this region in virus pathogenicity remains unclear.

Host factors that bind to the viral 3'-UTR RNA including sfRNA play important roles in infections by mosquito-borne flaviviruses, such as Dengue virus (DENV), Japanese encephalitis virus (JEV), and West Nile virus (WNV) (Bidet et al., 2014; Manokaran et al., 2015). However, few study has focused on TBEV, and prion-like T-cell-restricted intracellular antigen 1 (TIA-1) and TIA-1-related protein (TIAR) were the only identified proteins interacting the TBEV RNA (Albornoz et al., 2014). In this study, we hypothesized that differences in the variable region of the 3'-UTR of TBEV affect the interaction of this virus with host factors. We thus identified and characterized host proteins that bind to the 3'-UTR of TBEV.

To identify host proteins that bind to the variable region of the 3'-UTR of TBEV, biotinylated RNAs for 100 nt of the 3' end of the coding sequence and the 3'-UTR of the Oshima (Full) or Sofjin (Δ _SL3-5) strain, and the coding sequence for EGFP as a control, were synthesized *in vitro* using a Biotin RNA Labeling Kit (Roche, Basel, Switzerland). One μ g of the RNAs were mixed with 200 μ g of proteins in lysate of HEK293T cells and precipitated using streptavidin magnetic beads (GE Healthcare, Buckinghamshire, UK) (Fig.

1A). The co-precipitated proteins were subjected to sodium dodecyl sulfate-polyacrylamide gel electrophoresis and silver stained using a SilverQuest Staining Kit (Invitrogen, Carlsbad, CA, USA) (Fig. 1B). Proteins bound to the viral RNA were detected at 72–90 kDa. The bands were excised from the gels, and each was trypsinized and subjected to liquid chromatography-electrospray tandem mass spectrometry (LC-ESI-MS/MS) (LTQ Orbitrap Velos + ETD, Thermo Fisher Scientific) to identify co-precipitated proteins. All of the proteins were analyzed with Mascot Server2.5 (MATRIX SCIENCE, Tokyo, Japan), and those from cells containing the 3'-UTR RNA of TBEV but not in those containing EGFP RNA were regarded as candidate binding partners of the 3'-UTR of TBEV. The proteins with a spectral and ion score of > 200 are listed in Table 2. Cold shock domain containing-E1 (CSDE1), interleukin enhancer binding factor 3 (ILF3), spermatid perinuclear RNA binding protein (STRBP) which is a paralogue of ILF3 (Schumacher et al., 1995), and fragile X mental retardation protein (FMRP) bound specifically to the 3'-UTR of the Oshima strain. Neither of these 4 proteins interacted with the 3'-UTR of the Sofjin strain. CSDE1, FMRP, and ILF3 were confirmed to co-precipitate with the 3'-UTR of the Oshima strain, but not that of the Sofjin strain or the EGFP coding sequence, by western blot analysis using rabbit anti-CSDE1 (AB176584, Abcam, Cambridge, UK), mouse monoclonal anti-FMRP (MAB2160, Merck KGaA, Darmstadt, Germany), and mouse anti-ILF3 antibodies (H00003609-B01P, Abnova, Taipei) (Fig. 1C). Similar results were obtained for CSDE1 and ILF3 in human neuroblastoma SHSY5Y cells while the binding of FMRP could not be confirmed due to the low expression of endogenous FMRP in the cell line (Data not shown).

To examine their specific interactions with viral 3'-UTR RNA, total RNA was extracted from HEK293T cells and subjected to RT-PCR using gene specific primer sets (Table 1). The Flag-tagged candidate proteins were overexpressed in HEK293T cells and

lysates were mixed with *in vitro*-synthesized RNA and subjected to immunoprecipitation (IP) using an anti-Flag antibody (F3165; Sigma, St. Louis, MO, USA). Co-precipitated RNA was amplified by reverse transcription-polymerase chain reaction (RT-PCR). The full-length 3'-UTR RNA of the Oshima strain (Full) co-precipitated with all of the RNA-binding proteins, but that of the Sofjin strain (Δ _SL3-5) did not (Fig. 2). Therefore, several host proteins interact specifically with the 3'-UTR RNA of the Oshima strain but not the Sofjin strain.

Next, we examined the effects of deletions in the 3'-UTR on the differential binding to host proteins of the Oshima and Sofjin strains. Biotinylated Δ _SL3-4, Δ _SL5, and Δ _SL3-5 RNAs were prepared by deleting the SL 3 and 4 (nt 10,443–10,567), SL 5 (nt 10,568–10,649) and SL 3 to 5 (nt 10,443–10,649) regions in the Oshima RNA, respectively. A pull-down assay using streptavidin beads showed that all three proteins interacted with the Full, Δ _SL3-4, and Δ _SL5 RNA, but not with the Δ _SL3-5 RNA (Fig. 3). These results indicate that complete deletion of SL3, SL4, and SL5, but not their partial deletion, affects the interactions of the 3'-UTR with RNA-binding proteins.

To investigate the role of the host proteins in viral replication, gene silencing was performed in SH-SY5Y cells (Fig. 4). For knockdown of the CSDE1 and ILF3 gene, siRNA for CSDE1 (HSS111760, Thermo Fisher Scientific) and for ILF3 (HSS105413, Thermo Fisher Scientific) were transfected using Lipofectamine RNAiMax (Invitrogen). For knockdown of the FMRP gene, a lentiviral vector that expresses a short hairpin RNA (shRNA) for FMRP (5'-CCGGGCGTTTGGAGAGATTACAAATCTCGAGATTTGTAATCTCTCCAAACGCTTTTGTG-3') was generated by using pFU6-pGK puro vector. Pseudotyped lentivirus was infected to SH-SY5Y cells and selected with 6 μ g/ml of Puromycin. The treatment of siRNA for ILF3 did not reduced the ILF3 expression significantly. The CSDE1

knock-down cells showed no significant differences in the viral titers as compared to mock cells (Fig. 4A). In contrast, knockdown of FMRP reduced the viral titer of all virus strains, but the viral titer of Oshima-IC was slightly recovered by the deletion of SL3-5 (Δ _SL3-5) to the same extent as that of the Sofjin ($p < 0.01$) (Fig. 4B).

CSDE1, FMRP, and ILF3 bound specifically to the 3'-UTR RNA of the low-virulence Oshima strain, and higher MS scores of ILF3 were observed in the host proteins co-precipitated with the 3'-UTR RNA of the Oshima strain than that of the highly virulent Sofjin strain. The SL 3–5 structures, which are recognized by host proteins, are deleted in the Sofjin strain (Fig. 3). As described previously, the interaction of host factors with the viral RNA via the SL structures of the 3'-UTR might affect the pathogenicity of TBEV, possibly by enabling escape from host antiviral responses. The variable region may act as a spacer separating the folded 3'-UTR from the rest of the genome, which could facilitate binding of the viral RNA polymerase and cellular factors involved in transcription. Alternatively, binding of the host proteins identified in this study may compete with that of viral or host proteins involved in transcription.

CSDE1 is mostly localized in cytoplasm and is involved in the regulation of mRNA stability and translation (Mihailovich et al., 2010). CSDE1 reportedly binds the 3'-UTR of DENV, and knockdown of CSDE1 suppresses DENV replication (Phillips et al., 2016). Moreover, CSDE1 is involved in neural differentiation (Ju Lee et al., 2017). TBEV infection affects neuronal functions, such as neurite development (Hirano et al., 2017; Yoshii et al., 2014), in a manner possibly involving the interaction with CSDE1.

The transcript variants of ILF3 form a complex involved in neural transport (Larcher et al., 2004). ILF3 and interleukin enhancer-binding factor 2 (ILF2), also known as nuclear factor 90 (NF90) and nuclear factor 45 (NF45), respectively, form a protein complex that is involved in the post-transcriptional control of gene expression in vertebrates (Barber, 2009).

Within cytoplasmic viral replication foci, the ILF3/ILF2 complex associates with the genomic RNA of HCV and DENV through regulatory structures in the 5'- and 3'-UTR (Gomila et al., 2011; Isken et al., 2007). Thus, protein complexes consisting of ILF3 and ILF2 may affect viral replication and neuropathogenicity.

FMRP is highly expressed in neurons, forms part of a complex responsible for intracellular mRNA transport, and plays an important role in neuronal diseases in humans. FMRP binds the 5'-UTR of TBEV genomic RNA, which results in the development of neurological disease (Hirano et al., 2017). FMRP and ILF3 are involved in the formation of RNA granules (El Fatimy et al., 2012; Shiina and Nakayama, 2014), which are large messenger ribonucleoprotein complexes that control translation and mRNA translocation (Anderson and Kedersha, 2006). Neuronal RNA granule also plays important roles in transport and local translation of mRNA in dendrites (Bramham and Wells, 2007). RNA granules recognized viral RNAs, which induces translation of interferon-stimulated mRNAs, and antiviral responses are affected by RNAs derived from 3'-UTR of DENV (Bidet et al., 2014). It was also reported that TIA-1 and TIAR are components of stress granules, and bound to the RNA of TBEV (Albornoz et al., 2014).

In this study, silencing of FMRP significantly reduced viral replication (Fig. 4B), indicating that the FMRP played important roles in TBEV replication. On the other hand, the reduction of viral replication by FMRP-knockdown was relatively lower in Sofjin-IC infection, and the deletion of the complete SL 3-5 structure increased the viral replication of Oshima-IC in the FMRP-knockdown cells. These results suggested that the deletion of the complete SL 3-5 structures compensated the TBEV replication without the binding of FMRP. However, the role of FMRP during viral infection *in vivo* was not investigate in this study, therefore, further research is warranted.

In summary, we identified host proteins that bind to the 3'-UTR of TBEV genomic

RNA. Some of the proteins interacted specifically with the RNA of the low-virulence strain, and the SL structures in the 3'-UTR were involved in these interactions. Further analysis of the mechanism of interaction between the host proteins and viral RNA will contribute to our understanding of the pathogenicity of TBEV, and facilitate development of therapies for TBE.

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Figure Legends

Fig. 1. (A) Schematic of the 3'-untranslated region (UTR) of tick-borne encephalitis virus (TBEV) genomic RNA. The SL 3, 4, and 5 (nt 10,443–10,649) were deleted in the Sofjin-HO strain and Δ _SL3-5. The SL 3 and 4 (nt 10,443–10,567) were deleted in Δ _SL3-4. The SL 5 (nt 10,568–10,649) was deleted in Δ _SL5. (B) Cellular proteins that interact with the 3'-UTR of TBEV. HEK293T cell lysates were mixed with the biotinylated 3'-UTR of TBEV, and precipitated using streptavidin beads. The proteins were resolved by sodium dodecyl sulfate polyacrylamide gel electrophoresis and silver stained. Black square indicates the range of proteins subjected to mass spectrometry analysis. The bottom panel shows input biotinylated RNA for the pull down assay. (C) Proteins that co-precipitated with the 3'-UTR of TBEV were analyzed by western blotting.

Fig. 2. Interaction of host proteins with *in vitro*-synthesized RNA. The lysates of cells overexpressing Flag-tagged proteins were mixed with *in vitro*-synthesized RNA for the 3'-UTR of TBEV, and were precipitated using an anti-Flag antibody. The RNA was extracted from immunocomplexes and TBEV RNA was detected by reverse transcription-polymerase chain reaction (RT-PCR). Upper panel, RT-PCR analysis of

co-precipitated RNA; lower panel, western blot analysis of proteins immunoprecipitated with the anti-Flag antibody.

Fig. 3. Effect of deletions in the variable region on the interactions of TBEV RNA with cold shock domain containing-E1 (CSDE1), fragile X mental retardation protein (FMRP), and interleukin enhancer binding factor 3 (ILF3). Biotinylated 3'-UTR RNA of TBEV with or without deletion of stem loop 3–5 was incubated with HEK293T cell lysates and pulled down using streptavidin beads. The co-precipitated proteins were detected using an anti-CSDE1, -FMRP, or -ILF3 antibody. The synthesized RNAs were subjected to RT-PCR and agarose gel electrophoresis.

Fig. 4. Analysis of the function of the host proteins in TBEV replication.

CSDE1 (A) or FMRP (B) was knocked down by siRNA or shRNA in SHSY5Y cells, respectively. The expression levels of CSDE1 or FMRP were analyzed by Western blotting. β -actin was used as a loading control. The knockdown cells were infected at an MOI of 0.05 with Oshima-IC, Δ _SL3-5, or Sofjin-IC, respectively. The supernatant from each cells was harvested at 18 h.p.i. and the viral titer was measured by plaque assay. Each viral titer was normalized as the ratio of viral titer in mock cells. Data represent mean $\pm$ S.D. of three independent experiments. Statistical significance was assessed using the Steel test, and is indicated by asterisks (*, $p < 0.01$).

Fig. 1

A

B

C

Fig. 2

Fig. 3

Fig. 4

A CSDE1-knockdown

B FMRP knockdown

Table 1. Primers for the construction of plasmid expressing each host

Primer	Primer sequence (5' to 3')
CSDE1_Fw	TGACGATAAACTCGAATGGAGAACGTTTTTACT
CSDE1_Rv	TGGATCCCCGCGGCCTTAGTCAATGACACCAGC
FMRP_Fw	TGACGATAAACTCGAATGGAGGAGCTGGTGGTG
FMRP_Rv	TGGATCCCCGCGGCCTTAGGGTACTCCATTAC
ILF3_Fw	TGACGATAAACTCGAATGCGTCCAATGCGAATT
ILF3_Rv	TGGATCCCCGCGGCCTTATCTGTACTGGTAGTTC

Table 2. Identified proteins interacting with the 3'-UTR of TBEV by MS analysis

Accession No.	Score*			Protein Description	Gene
	Oshim	Sofjin	EGFP		
1 CSDE1_HUMAN	1957		14	Cold shock domain-containing protein E1	CSDE1
2 ILF3_HUMAN	1922	958	261	Interleukin enhancer-binding factor 3	ILF3
3 NUCL_HUMAN	1547	1049	827	Nucleolin	NCL
4 STRBP_HUMAN	988			Spermatid perinuclear RNA-binding protein	STRBP
5 HNRPQ_HUMAN	733	611		Heterogeneous nuclear ribonucleoprotein Q	SYNCRIP
6 HNRPR_HUMAN	771	930		Heterogeneous nuclear ribonucleoprotein R	HNRNPR
7 FMR1_HUMAN	341			Fragile X mental retardation protein 1	FMR1
8 HS90B_HUMAN	589	650	313	Heat shock protein HSP 90-beta	HSP90AB1
9 DDX21_HUMAN	440	558	53	Nucleolar RNA helicase 2	DDX21
10 HS71A_HUMAN	373	187		Heat shock 70 kDa protein 1A	HSPA1A
11 HS90A_HUMAN	431	528	208	Heat shock protein HSP 90-alpha	HSP90AA1
12 HSP7C_HUMAN	434	192		Heat shock cognate 71 kDa protein	HSPA8
13 IF2B1_HUMAN	324	404	20	insulin-like growth factor 2 mRNA-binding protein 1	IGF2BP1
14 PABP1_HUMAN	218	229		Polyadenylate-binding protein 1	PABPC1
15 ZFR_HUMAN	205	408		Zinc finger RNA-binding protein	ZFR

* Blank indicated the score under detection limit.