Activation of Master Autophagy Regulator TFEB During Systemic LPS Administration in the Cornea

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Abstract: The involvement of autophagy in the cornea during the systemic inflammatory response elicited by intravenous administration of lipopolysaccharide (LPS) was investigated. Eight-week-old male Sprague-Dawley rats were injected i.v. with 15 mg/kg body weight LPS. RC4 rabbit corneal keratocytes were also used and treated with 100 ng/mL of tumor necrosis factor α (TNFα) and/or cycloheximide (CHX). The nuclear translocation of transcription factor EB (TFEB), the master transcriptional regulator for autophagy, was observed after LPS administration in the corneal epithelium. Induction of autophagy-related proteins was observed in the cornea after LPS administration, as well as in RC4 cells after treatment with TNFα. Administration of trehalose, an inducer of TFEB, mitigated RC4 cell death caused by TNFα/CHX. These results demonstrate the importance of TFEB activation in cellular defense against the systemic inflammatory response in the cornea. (DOI: 10.1293/tox.2014-0004; J Toxicol Pathol 2014; 27: 153–158)

Key words: cornea, LPS, TFEB, autophagy, lysosome

Ocular tissue homeostasis is maintained in a highly regulated manner so as to retain transparency. The cornea, which is composed of five layers of tissue, the epithelium, Bowman’s layer, stroma, Descemet’s membrane, and endothelium, functions as a vital barrier against the outside environment to protect the eye¹. Indeed, the corneal epithelium is separated from the environment only by tear fluids, suggesting that the corneal epithelium is always exposed to the risk of infection. Keratitis caused by viral, fungal and microbial infection can arise due to faulty use of contact lenses², contamination during corneal graft surgery³, laser-assisted in situ keratomileusis (LASIK) surgery or trauma and is also associated with systemic inflammatory diseases such as sepsis⁴. Keratitis due to focal as well as systemic infection can ultimately lead to multiple sight-threatening defects such as ulceration, opacification and perforation.

Proteases and cellular protein degradation systems play essential roles in the maintenance of cellular homeostasis, especially in ocular tissues from which aberrant proteins should be eliminated to maintain transparency⁵. Autophagy, a cellular protein degradation pathway implicated in periods of starvation⁶, is also known to play crucial roles in innate immune responses⁷ as well as cellular defense against xenobiotics⁷. Recently, we have shown that autophagy is induced in the liver⁸ and heart⁹ in a model of systemic inflammatory disease developed by administering lipopolysaccharide (LPS) to rats. We have also shown that transcription factor EB (TFEB), which was first identified as a renal carcinoma-responsible gene¹⁰, but later revealed to be a master regulator of lysosome biogenesis¹¹ and autophagy¹², is activated in the heart during LPS administration⁹. In this study, we examined whether the TFEB/autophagy pathway is also activated in the cornea of rats during the systemic inflammatory response.

The animal experiment protocols used in this study were approved by the Institutional Animal Care and Use Committee of the Tokyo Medical and Dental University. In brief, male Sprague-Dawley rats (eight weeks old) were intravenously injected with 15 mg/kg LPS (Sigma, St. Louis, MO, USA) (n = 3 or 4/group). Extraction of corneal tissues from the eyeball was performed under a stereomicroscope (Nikon, Tokyo, Japan), and the tissues were stored at –80°C until use. For immunohistochemical analysis, the tissues were fixed immediately with formalin.

Corneal tissues fixed with formalin were embedded in paraffin and subjected to immunohistochemical analysis as previously described⁹. In brief, tissue sections were incubated at 4 °C overnight with 1/100 diluted anti-TFEB (ab56330, Abcam, Cambridge, MA, USA) or 1/100 diluted anti-microtubule-associated protein light chain-3 (LC3) (#4445, Cell Signaling Technology, Beverly, MA, USA) antibodies and then incubated with peroxidase-conjugated secondary antibodies (Promega, Madison, WI, USA). Diaminobenzidine (DAB) was used as a substrate to visualize antigens. The
tissues were then analyzed under a light microscope (Olympus AX80).

Complementary DNA was synthesized from the corneal tissues using TRizol reagent (Invitrogen, Carlsbad, CA, USA) and SuperScript II reverse transcriptase (Invitrogen). Quantitative RT-PCR (qPCR) was performed with a Real-Time PCR System (StepOnePlus, Applied Biosystems, Foster City, CA, USA) using SYBR green as a fluorescent dye. The primers used were as follows: 5'-CGGGTTGAGGAGACACAA-3' and 5'-CTTTTGTTCCAAGCTCCGC-3' for LC3; 5'-CGGGTTGAGGAGACACAA-3' and 5'-CTTTGTTCGAAGCTCCGGC-3' for p62; 5'-GCAAGGCCGCTCGCCCTCAAT-3' and 5'-GCCCAGTGACTCTCTTCCC-3' for LAMP1; 5'-AGGCTTTCTTGGTTCG-3' and 5'-AGGGCT-GCTCCACCGCTAT-3' for LAMP2; and 5'-CACCCGGAGTACACCTTCTG-3' and 5'-CCCTCTTGCTCTGGGCCTCGT-3' for actin. The primers used were as follows: with a Real-Time PCR System (StepOnePlus, Applied Biosystems, Foster City, CA, USA) and SuperScript II reverse transcriptase (Invitrogen, Carlsbad, CA, USA) was used to visualize the antigens; signal intensities were quantified using an image analyzer (CS analyzer; Keyence, Osaka, Japan).

Reagent Plus Kit (Perkin Elmer Life Science, Boston, MA, USA), and anti-actin (Sigma-Aldrich, St. Louis, MO, USA). Peroxidase-conjugated secondary antibodies were obtained from Promega. A Western Lightning Chemiluminescence Reagent Plus Kit (Perkin Elmer Life Science, Boston, MA, USA) was used to visualize the antigens; signal intensities were quantified using an image analyzer (CS analyzer; ATTO, Tokyo, Japan).

RC4 rabbit corneal keratocyte-derived cells were obtained from RIKEN BioResource Center (Tsukuba, Japan), and cultured in DMEM supplemented with 10% FBS under a 5% CO₂ atmosphere at 37 °C. TNFα (mouse recombinant; T7539, Sigma) was added to the medium at a final concentration of 100 µg/mL. Trehalose (obtained from Sigma) was also used at a final concentration of 100 mM.

RC4 cells were transfected with vectors harboring fluorescence marker proteins using Lipofectamine2000 (Invitrogen). The following fluorescence marker proteins were used: TFEF fused with green fluorescence protein (GFP-TFEF, Addgene plasmid 38119)³, LC3 fused to GFP (GFP-LC3)³⁴, and LAMP1 fused to monomeric GFP (LAMP1-mGFP)³⁵. Fluorescence images were obtained under a BZ-8100 microscope (KEYENCE, Osaka, Japan).

Cell viabilities were measured using an LDH release assay kit (Wako, Osaka, Japan) according to the manufacturer’s instructions. In brief, LDH activity in living cells (attached to the dish) as well as in the medium (including dead cells) was measured after lysing the cells with 0.2% Tween-20 in PBS. LDH activity in living cells was divided by that in total cells (living and dead cells) and expressed as cell viability (%).

First, we examined whether TFEF is activated in the cornea during systemic LPS administration to rats. Representative images of corneas stained with an anti-TFEF antibody are shown in Fig. 1. Without LPS administration, TFEF localizes to the punctate structure in the cytoplasm of epithelial base layer cells (Fig. 1), corresponding to the lysosomal and/or cytoplasmic localization of TFEF in unstimulated cells³. In contrast, TFEF localizes to the nuclei after LPS administration (Fig. 1), suggesting the activation of TFEF in the LPS-treated rat cornea. In correlation with the nuclear translocation of TFEF, an increased occurrence of autophagosomes in the LPS-treated cornea was demonstrated by staining the tissue with an anti-LC3 antibody (Fig. 1). These results indicate that in response to LPS administration, TFEF should be activated to induce autophagy in the cornea.

TFEB has been shown to transactivate the genes for proteins involved in autophagy to the lysosome pathway. To confirm TFEF activation during LPS administration in the cornea, immunoblot analysis was performed to evaluate the protein levels of LC3, p62, LAMP1, and LAMP2. Several hours (3–6 h) after LPS administration, LC3-II (activated form of LC3) and p62 increase in a time-dependent manner, whereas LAMP1 and LAMP2 levels increase transiently with a peak at 3 hours (Fig. 2A). We next performed qPCR analysis to determine whether or not LPS induces the expression of these genes. As shown in Fig. 2B, more than a 3-fold induction of the LC3 gene was observed 6 hours after LPS administration in the cornea. Although not statistically significant, the expression of p62 also showed a tendency to be induced by LPS (Fig. 2B). The LAMP1 and LAMP2 genes showed no induction after 6 hours of LPS administration (Fig. 2B), corresponding to the transient induction of these proteins during LPS administration (Fig. 2A).

To examine further the activation of TFEF and the induction of autophagy during the inflammatory response elicited by LPS in the cornea, we checked whether similar cellular responses could be observed in RC4 rabbit corneal keratocyte (fibroblast)-derived cells. As the LPS-stimulated inflammatory response in corneal tissues is associated with an elevation in pro-inflammatory cytokines such as IL-1, IL-6, and TNFα, we investigated cellular responses during TNFα treatment in RC4 cells. Cells were transfected with expression vectors harboring GFP-tagged TFEF, LC3 and LAMP1, treated with TNFα for 6 hours, and observed under a fluorescence microscope. As shown in Fig. 3A, TNFα causes the translocation of TFEF from the cytoplasm to the nucleus, as well as LC3 punctation, as observed in the LPS-treated rat cornea (Fig. 1). The structure and abundance of lysosomes do not seem to be affected by TNFα,
as estimated by GFP-LAMP1 staining (Fig. 3A). Immunoblot analysis also showed an increase in the LC3-II and p62 proteins, whereas LAMP1 and LAMP2 levels seemed to remain constant after TNFα treatment for 6 hours (Fig. 3B and C). These results correlate well with the results obtained in the LPS-treated rat cornea, further confirming activation of the TFEB/autophagy pathway during the inflammatory response in corneal cells.

Finally, we evaluated whether the activation of TFEB and subsequent induction of autophagy is involved in the homeostasis of corneal cells. Trehalose, an mTOR-independent but TFEB-dependent enhancer of autophagy to lysosome system\(^{18, 19}\), was used for this purpose. Administration of 100 mM trehalose for 24 hours resulted in the nuclear translocation of TFEB in RC4 cells, confirming its effect on TFEB activation (Fig. 4A). Although several reports have indicated that corneal cells undergo apoptosis in response to TNFα treatment, we could not observe RC4 cell death during treatment with 100 ng/mL TNFα for 24 hours (data not shown). We thus exposed the cells to TNFα plus CHX (TNFα/CHX), another apoptosis-inducing stimulant of corneal cells\(^{20, 21}\). An approximate 50% loss of cell viability was observed following treatment of the cells with TNFα/CHX for 24 hours (Fig. 4B). Pretreatment with trehalose for 24 hours resulted in the suppression of cell death caused by the subsequent 24 hours of treatment with TNFα/CHX (Fig. 4B). Taken together, TFEB activation might represent an essential cellular reaction to maintain corneal homeostasis during the inflammatory response in corneal cells.

In this study, we demonstrated the activation of the TFEB/autophagy cellular degradation pathway during the systemic inflammatory response in the rat cornea. The activation of this pathway seems to be involved in maintenance of corneal homeostasis, as activation of this pathway by trehalose significantly suppresses the death of corneal-derived cells.

Fig. 1. Sections of corneal tissue from rats sacrificed 6 hours after administration of LPS (15 mg/kg body weight) or untreated control rats were stained with anti-TFEB and anti-LC3 antibodies. Representative images (original magnification, ×200) are shown: TFEB in the control cornea (a), TFEB in the LPS-treated cornea (b), LC3 in the control cornea (c), LC3 in the LPS-treated cornea (d). Bars, 10 μm. White arrowheads indicate cells which intracellular structures (putative lysosomes) were stained by the anti-TFEB antibody. Black arrowheads indicate cells which nuclei were stained by the anti-TFEB antibody. Black arrows indicate cells which autophagosomes were stained by the anti-LC3 antibody.

Fig. 2. (A) Immunoblot analysis of the levels of LC3-II, p62 and glycosylated mature forms of LAMP1 and LAMP2 in the cornea of LPS-treated (at 3 and 6 hours after administration of 15 mg/kg LPS) and control rats. Representative results obtained from four animals are shown. (B) qPCR analysis of the levels of LC3, p62, LAMP1 and LAMP2 transcripts in the cornea of LPS-treated (at 6 hours after administration of 15 mg/kg LPS) (black columns) and control (white columns) rats. Actin transcripts were also analyzed as an internal control. Each bar represents the mean ± SE of three animals. *, P<0.05 versus control by Student’s t-test.
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cells during an apoptosis-inducing inflammatory insult.

Beneficial roles of TFEB in the pathogenesis of multiple diseases have been reported. Transfer of the TFEB gene improves autophagic flux and subsequently mitigates the progression of Pompe disease in skeletal muscle, α-synucleinopathy in the midbrain, and hepatic lesions due to the accumulation of a toxic mutant of alpha-1-antitrypsin. A gene transfer strategy to defend the corneal epithelium has been successful in several experimental animal models including for graft rejection during cornea transplantation. Hence, TFEB should represent a possible candidate gene for the protection of the cornea against focal as well as systemic inflammatory diseases.

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Fig. 4. (A) Trehalose activates TFEB in RC4 cells. The cells were transfected with GFP-TFEB and then treated with trehalose (100 mM) for 24 hours. (B) Trehalose suppresses RC4 cell death caused by TNFα/CHX. Cells were treated with 100 mM trehalose for 24 hours, followed by treatment with 100 ng/mL TNFα plus 10 µg/mL CHX (TNFα/CHX) for another 24 hours. Cell viabilities were determined by the LDH release assay. Each bar represents the mean ± S.E. of three samples. **, P < 0.05 by Tukey’s post hoc test.


