Impaired Autophagic Degradation of Transforming Growth Factor-β-Induced Protein by Macrophages in Lattice Corneal Dystrophy

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PURPOSE. Lattice corneal dystrophy (LCD) is related to the denaturation of transforming growth factor-β-induced protein (TGFBIp). Autophagic degradation of the denatured proteins by macrophages is one pathway to remove the denatured proteins. Thus, we investigated the role of autophagy in the degradation of mutant (MU) TGFBIp in macrophages.

METHODS. Corneas from participants were observed by slit-lamp photography and subjected to histopathologic and genetic analysis. Wild-type (WT) and MU TGFBIp were recombinated and expressed. Macrophages from MU participants were isolated and cocultured with the recombinant TGFBIp. Colocalization of the two molecules was observed by immunofluorescent microscopy. Enzyme-linked immunosorbent assay, Western blotting, and flow cytometry were used to detect changes in molecule expression related to the phenotype and autophagy process.

RESULTS. Fourteen members from a family of 25 were identified as LCD sufferers. Significant TGFBIp aggregates and macrophage infiltration were found only in the corneas of LCD sufferers. Marker accumulation of TGFBIp was found in macrophages exposed to MU TGFBIp even at 5 hours after MU TGFBIp was withdrawn. High expressions of CD68 and CD36 were found in macropahages exposed to WT TGFBIp, but not to MU TGFBIp. Impaired autophagic flux due to defective autophagosome fusion to lysosomes was found in macrophages exposed to MU TGFBIp. Blockage of the autophagic process suppressed the expression of CD68 and CD36 in macrophages exposed to WT TGFBIp to levels similar to those found in macrophages exposed to MU TGFBIp.

CONCLUSIONS. Our results suggested that reversion of the defective autophagic process in macrophages may be a therapeutic strategy for patients with LCD.

Keywords: autophagy, transforming growth factor-β-induced protein, lattice corneal dystrophy, macrophages, phagocytosis, protein degradation

Normal vision depends on the transparency of the cornea, and multiple cellular and molecular processes are involved in the maintenance of corneal transparency.1-4 Corneal dystrophies are a group progressive genetic disorders that cause loss of corneal transparency and eventually lead to loss of vision.4,6 Deposition of mutant (MU) protein aggregates is a major hallmark of these diseases.7-10 Mutations in transforming growth factor β-induced protein (TGFBIp) are associated with the majority of corneal dystrophies in the corneal stroma.10-14 The TGFBI gene contains a secretory signal peptide, a domain rich in cysteine residues, a cell attachment arginine-glycine-aspartic acid (RGD) signal residue, and four fasciclin 1 (FAS-1) domains.10-14 To date, more than 66 mutations have been reported in the TGFBI gene related to corneal dystrophies, including lattice corneal dystrophy (LCD) and granular corneal dystrophy (GCD) types I and II.15-17 In LCD corneas, the MU protein aggregates appear as amylod fibrils or long lattice lines, whereas in GCD type I, they appear as amorphous protein aggregates, and GCD type II exhibits amylod fibrils and amorphous aggregates.10-17 However, the exact molecular mechanisms, including the clearance mechanism, are not fully understood.

Macrophages are present universally in all vertebrate tissues and occupy a unique niche in the immune system that exerts a vital role as a bridge between innate and adaptive immunity.16-18 The major functions of macrophages in innate and adaptive immunity include phagocytosis; and subsequent destruction and elimination of debris of apoptotic or neoplastic cells; denaturing proteins and microbes; secretion of cytokines, chemokines and other soluble mediators; and the presentation of foreign antigens on their surface to T lymphocytes.19 Corneal macrophages are major immune cell types that account for approximately 50% of the resident corneal leukocytes and mainly distribute the central and peripheral corneal stroma.20-22 Recent studies indicated that corneal macrophages are critical for corneal wound repair and inflammation.23-25 However, the roles of the corneal macrophages of LCD patients in elimination of the amyloid TGFBIp remain unknown.

At present, Alzheimer’s disease (AD) is the most deeply investigated disease among various amyloidosis disorders. AD is...
characterized by accumulation of amyloid-β plaques that are directly toxic to neurons, resulting from inadequate amyloid-β clearance in relation to amyloid-β production.26–28 Although the role of macrophages (microglia) in the clearance of amyloid-β is controversial,29–31 a few lines of evidence have indicated that microglia are responsible for the clearance of amyloid-β plaques by phagocytosis in AD brains.31–35 Therefore, recent studies have sought new approaches to increase the macrophage-mediated clearance of amyloid-β plaques, indicating a possible alternative strategy for AD treatment in the future.36–40 To remove amyloid aggregates in extracellular stroma, macrophages must infiltrate into the stroma and clear the amyloid aggregates by phagocytosis. The phagocytized amyloid aggregates then are mainly degraded by the ubiquitin proteasome or autophagy pathways.41 The ubiquitin proteasome pathway selectively degrades phagocytized (substrate) proteins through ubiquitin modifiers in 26S proteasomes, whereas autophagy degrades denatured proteins or organelles via lysosomes. Any alterations in the processes of these proteolytic pathways may result in the extracellular or intracellular accumulation of denatured proteins, causing pathologic processes and disease.42 Recently, a study found alterations of autophagic clearance of TGFBIp in corneal fibroblasts from patients with LCD type II.43

MATERIALS AND METHODS

Subjects and Clinical Evaluation

We strictly followed the Declaration of Helsinki in the treatment of the participants. This study was approved by the ethics committee of Hainan Medical College, China. A three-generation LCD pedigree was collected in Hainan Province, China, from June 2012 to July 2013 (Fig. 1A). Written informed consent was obtained from all 25 participants (14 affected and 11 unaffected). The family members ranged from 10 to 89 years old. After informed consent was obtained, a detailed ophthalmologic examination was performed to determine the status of the corneas of all participants. Corneal phenotypes were detected by slit-lamp photography. The clinical history, including age at onset, initial presenting signs, clinical symptoms, and treatment history, also were obtained in detail.

Histopathologic and Genetic Analyses

Corneal tissue from the left eye of the proband excised at penetrating keratoplasty was fixed and analyzed using light microscopy following staining with hematoxylin and eosin (H&E), Congo red, and periodic acid-Schiff (PAS). In addition, peripheral blood was collected from all study subjects.
Impaired Autophagy to LCD TGFBIp in Macrophages

Genomic DNA was extracted from the peripheral blood using the QiAamp DNA blood Mini Kit (Qiagen, Hilden, Germany). All 17 coding exons of the TGFBI gene were amplified by polymerase chain reaction (PCR) using the previously reported primers and conditions. Gene sequencing for each PCR product was entrusted to a commercial company (Takara, Dalian, China). The sequencing results were compared to the TGFBI gene in GenBank (MIM 601692).

Corneal Immunohistochemistry

Immunohistochemical detection was performed using the ABC kit (Vector Labs, Inc., Burlingame, CA, USA). In brief, 5-μm sections of cornea from the proband and an age-matched victim of an eye accident were dewaxed with xylene and hydrated with graded ethanol. Thereafter, the sections were blocked in 2% BSA in PBS and stained overnight with unconjugated anti-TGFBIp (Abcam, Cambridge, UK) or anti-CD11b (Abcam). On the next day, a Cy2 or Cy3-conjugated secondary antibody (Abcam) was used to detect anti-TGFBIp and anti-CD11b, respectively. 4,6-Diamidino-2-phenylendole (DAPI) was used for nuclear counterstaining. Images were taken with a fluorescence microscope (80i; Nikon, Tokyo, Japan).

Preparation of Recombinant TGFBIp

Recombinant wild type (WT) and MU TGFBIp proteins were prepared as previously reported. Briefly, Spodoptera frugiperda (SF9) insect cells were propagated in 30 mL 28°C BacVector insect cell medium (Darmstadt, Germany) in 250 mL flasks with 140-rev/minute shaking. SF9 cells were transfected with a plasmid encoding a 6-His-tagged TGFBI cDNA amplified from WT and MU participants, respectively. Two days after transfection, the conditioned medium was exchanged to 10 mM imidazole in 0.3 M NaCl, 50 mM sodium phosphate buffer, pH 8 (Buffer B) using a 30-kDa cutoff Centricon concentrator. TGFBIp proteins were quantified from 10 to 250 mM in Buffer B eluted TGFBIp. Western blots (WB) identified the fractions containing TGFBIp, which were subsequently was washed with Buffer B. Increasing imidazole from 10 to 250 mM in Buffer B eluted TGFBIp. Western blots (WB) identified the fractions containing TGFBIp, which were pooled, and Buffer B was exchanged for PBS using a 30-kDa cutoff Centricon concentrator. TGFBIp proteins were quantified using SDS-PAGE gels, WB blots, and bicinchoninic acid protein assays.

TGFBIp Phagocytosis by Macrophages

Isolation of mononuclear cells and preparation of mature monocyte-derived macrophages from the WT and MU participants were performed as described previously. In brief, peripheral blood mononuclear cells (PBMCs) were isolated using the Ficoll-Hypaque technique; 50,000 PBMCs were placed into each well of an 8-well plate in Iscove’s medium with 10% autologous serum and penicillin/streptomycin/fungizone and were incubated for 7 to 10 days until adherent macrophages were differentiated. Macrophages then were treated with recombinant TGFBIp (2 μg/mL dissolved in dimethyl sulfoxide [DMSO]) at appropriate dilutions. After overnight incubation, the cells were washed, fixed using 4% paraformaldehyde, stained with first antibodies (anti-TGFBIp or anti-CD11b), and subsequently with second immunofluorescent-conjugated antibody (all antibodies were from Abcam). At the same time, DAPI was used to stain the cell nuclei. Thereafter, the fluorescent images were captured by confocal laser scanning microscopy (Olympus, FV3000).

Immunofluorescent Detection of Colocalization

Cells were fixed with 4% paraformaldehyde for 30 minutes, washed with PBS, and then incubated with 0.1% Triton X-100 for permeabilization. Cells were stained with anti-LC3B polyclonal antibody, TGFBIp, or anti-LAMP1 at 4°C overnight, and subsequently stained with Alexa Fluor 488-conjugated goat anti-rabbit IgG (Abcam, ab150077) or Cy3-conjugated second antibody (Abcam) at 37°C for 1 hour. Nuclei were stained with DAPI for 5 minutes. Images were captured using confocal laser scanning microscopy (Olympus, FV3000).

Enzyme-Linked Immunosorbent Assay (ELISA)

The concentrations of TGFBIp in cell culture medium at different time points were measured by ELISA using kits (BD Biosciences, San Jose, CA, USA) and antibody against TGFBIp (Abcam) according to the manufacturer’s protocol. Enzyme activity was measured with an ELISA reader (Bio-Tek, Winooski, VT, USA) as described previously.

WB Analysis

Cells were treated with or without chemical agents, such as 3-methyladenine (3-MA), MG132, and leupeptin, as reported previously. Cells were lysed with RIPA buffer (50 mM Tris, 1.0 mM EDTA, 150 mM NaCl, 0.1% Triton X-100, 1% sodium deoxycholate, and 1 mM PMSF). Protein was measured using a BCA protein assay kit (Pierce, 23225, Rockford, IL, USA) and resolved by 12% SDS-PAGE, and then transferred to polyvinylidene fluoride (PVDF; BioRad Laboratories, Hercules, CA, USA) membranes. After blocking, the membranes were incubated with primary antibodies at 4°C overnight, and then incubated with secondary antibodies at room temperature for 1 hour. Target proteins were examined using ECL reagents (WBKLS0100; Millipore, Billerica, MA, USA). Semiquantitative analysis was performed by measuring band density using Image software (V6, NIH).

Flow Cytometry

Cell surface proteins CD68 and CD36 were detected with a BD FACS caliber Flow cytometer, and the resultant data were analyzed by FlowJo software (BD Biosciences). Briefly, anti-CD68 or CD36 antibodies (Abcam) were used to stain the cells followed by a secondary antibody conjugated with either FITC or PE. For intracellular staining, the cells first were fixed, permeabilized, and stained with corresponding first antibodies and FITC- or PE-conjugated secondary antibodies. Thereafter, the stained cells were analyzed by cytometric analysis.

Statistical Analysis

Statistical analysis was performed using Prism 6 (GraphPad Software, Inc., San Diego, CA, USA). Statistical differences were determined by a nonparametric 2-tailed Student’s t-test in experiments comparing two samples and 1- or 2-way ANOVA with Bonferroni’s test for multiple comparisons when more than two samples were analyzed. Data are expressed as means ± SD and *P < 0.05 was deemed statistically significant. Error bars indicate SD unless otherwise indicated.

RESULTS

Clinical Characteristics

The pedigree of the participant family is shown in Figure 1A. Age at onset was 25 to 43 years in the affected family members.
The main complaints and initial symptoms were photophobia, visual acuity decrease, and foreign body sensation. The progress of corneal opacities in all affected members was bilateral symmetry. The proband (Fig. 1A, II-3) was a 51-year-old man with a 7-year history of photophobia and loss of visual acuity in each eye, but without any history of recurrent corneal erosions. Ultimately, penetrating keratoplasty was performed on his right eye. Slit-lamp biomicroscopic examination of a 27-year-old daughter of the proband (Fig. 1A, III-5) showed linear mid and deep stromal opacities that also were found in most affected members’ corneas (Fig. 1B).

Histopathologic analysis was performed on the proband’s corneal button that underwent penetrating keratoplasty. Variably sized, irregularly shaped deposits were situated mainly in the anterior and middle corneal stroma. The deposits were stained positively with Congo red, indicating that they were amyloid in nature (Fig. 1C). In addition, direct sequencing of TGFBI exons 1–17 in all affected members demonstrated a previously described heterozygous missense mutation. Exon 12 exhibited a T > C heterozygous substitution at nucleotide position 1673 that causes a leucine-to-proline amino acid substitution in the protein (Leu558Pro; Fig. 1D).

Macrophage Infiltration in LCD Corneal Stroma

To confirm the presence of resident macrophages in LCD corneas and the relationship between infiltrated macrophages and amyloid aggregates, corneal sections from the proband and control patient were double-stained with anti-TGFBIp and anti-CD11b (a monocyte/macrophage marker), which show as green and red colors, respectively. As shown in Figure 2, TGFBIp and CD11b (a monocyte/macrophage marker), which show as green and CD11b (red), respectively, and nuclei were stained by DAPI. Images are representative of three independent experiments.

Normal Initial Phagocytosis but Impaired Degradation of TGFBIp in Macrophages

Macrophages were isolated from the TGFBI MU sufferers. These macrophages had the obvious expression of CD11b and CD14 (Supplementary Fig. S1A), and did not markedly express endogenous TGFBIp (Supplementary Fig. S1B) by RT-PCR and WB. In addition, we also observed the morphology of recombinant MU and WT TGFBIp by transmission electron microscopy, respectively. We found their morphology to be different, with the recombinant MU TGFBIp in a form of long and straight fibrils (Supplementary Fig. S1C). To study whether macrophages normally phagocytose and degrade MU TGFBIp, we treated the macrophages from LCD sufferers with recombinant MU TGFBIp or its normal counterpart (WT) first for 5 hours and then removed the TGFBIp for the second 5 hours according to the protocol shown in Figure 3A. Representative images showed that uptake of MU and WT TGFBIp was almost the same at 2.5 and 5 hours (Fig. 3B). In contrast, intracellular MU TGFBIp was unchanged at 7.5 and 10 hours, but the intracellular WT TGFBIp significantly decreased at 7.5 hours and almost disappeared at 10 hours (Fig. 3B), indicating the accumulation of MU TGFBIp in macrophages exposed to MU TGFBIp. Quantification of the green signals in the cells also showed similar results in MU and WT TGFBIp by macrophages as shown in representative images (Fig. 3C). These phenomena were confirmed further by WB analysis. The WB results showed that the level of the intracellular MU TGFBIp was unchanged at each time point, but the level of WT TGFBIp significantly decreased at 7.5 hours and almost disappeared at 10 hours (Figs. 3D, E). We also found the same results in the macrophages from the non-LCD–affected family members (Supplementary Fig. S1D). To observe whether the intracellular TGFBIp was colocalized with LAMP1, we double stained the macrophages with antibodies against TGFBIp and LAMP1 (a lysosome marker), and found that there was obvious colocalization of GFBIp and LAMP1 in the macrophages exposed to WT TGFBIp, but not in those exposed to WU TGFBIp (Supplementary Fig. S1E). In addition, we also detected the concentration of TGFBIp in the culture medium by ELISA and WB using antibody against TGFBIp and 6-His tag, respectively. The results showed that the concentration of MU TGFBIp in the culture medium keep almost no change at 2.5 and 5 hours compared to the concentration of WT TGFBIp (Fig. 3F, Supplementary Fig. S1F). Taken together, these results suggested that MU TGFBIp, and not MU types of macrophages, cause initial normal phagocytosis but impaired degradation or accumulation of TGFBIp in macrophages.

Impaired Phagocytic Activation of Macrophages With MU TGFBIp

The expressions of phagocytic macrophage marker CD68 and surface scavenger receptor CD36 were detected to evaluate whether the macrophages had activated phagocytosis. The macrophages from the TGFBI MU sufferers were exposed to MU and WT TGFBIp as above. CD68 or CD36 expression was first detected by WB analysis. Compared to the unexposed
cells (time 0 hours), macrophages exposed to MU and WT TGFBIp had high expression of CD68 and CD36, with more significant expression in cells exposed to WT TGFBIp (Figs. 4A–C). In addition, the expressions of CD68 and CD36 were decreased in a time-dependent manner, especially in the macrophages after the WT TGFBIp was withdrawn, but almost unchanged in macrophages after MU TGFBIp was withdrawn (Figs. 4A–C). These results were strongly confirmed by flow cytometry analysis, which was similar to WB analysis (Figs. 4D–F). Together, these results indicated that phagocytic activation in macrophages exposed to MU TGFBIp was impaired compared to that in macrophages exposed to WT TGFBIp.

**Figure 3.** Normal initial phagocytosis, but impaired degradation of TGFBIp in macrophages. (A) Schematic representation of the protocol in which macrophages were exposed to TGFBIp and detected time points. (B) Cells were treated with MU or WT TGFBIp shown in (A). TGFBIp, CD11b, and nuclei (DAPI) were observed by confocal microscopy and merged to observe the colocalization (yellow) of TGFBIp (green) and CD11b (red). (C) Quantification of the fluorescence intensity of three independent experiments as in (B). (D) TGFBIp uptake into macrophages was detected by WB. (E) Quantification of band intensity of three independent WB experiments. (F) The concentration of the TGFBIp in the cell culture compared to the 0 time point was detected by ELISA. NS, not significant; *P < 0.05, **P < 0.01, ***P < 0.001.
Incomplete Autophagic Flux in Macrophages Exposed to MU TGFBIp

As autophagy is a common pathway to degrade unnatural or aggregate proteins, we investigated whether complete autophagic flux may be induced in macrophages after exposure to MU TGFBIp. We first detected the conversion of LC3-I to lipidated LC3-II, a classical marker of autophagosome formation. After macrophages were exposed to MU or WT TGFBIp, increased LC3-II conversion was found at 2.5 and 5 hours (Figs. 5A, 5B). However, the high LC3-II conversion persisted in macrophages at 7.5 and 10 hours even though the MU TGFBIp was withdrawn, but this phenomenon did not occur in macrophages exposed to WT TGFBIp (Figs. 5A, 5B).

To verify the formation of autophagosomes in macrophages exposed to MU and WT TGFBIp, we analyzed the distribution of endogenous LC3 puncta, another classical marker of autophagosome formation. Markedly increased endogenous LC3 puncta were found in macrophages exposed to MU and WT TGFBIp at 2.5 and 5 hours, which persisted in the macrophages exposed to MU TGFBIp, but not in those exposed to WT TGFBIp at 7.5 and 10 hours (Figs. 5D, 5E).

Since the inhibition of autophagosome turnover at the late stage also leads to LC3-II conversion and the accumulation of LC3 puncta, the above phenomena do not mean that the autophagy progress was complete. Sequestosome-1 (SQSTM1) protein is involved in the targeting of polyubiquitinated proteins to autophagosomes and is selectively degraded via autophagy. Thus, we observed SQSTM1 expression in macrophages exposed to MU and WT TGFBIp as above. As shown in Figures 5A and 5E, the expression of SQSTM1 was unchanged in macrophages not exposed to any TGFBIp (0 hours) and in those after MU and WT TGFBIp were withdrawn (7.5 and 10 hours). However, the expression of SQSTM1 significantly decreased in macrophages exposed to WT TGFBIp at 2.5 and 5 hours (Figs. 5A, 5C). These results strongly indicated that the autophagic flux (progress) in macrophages exposed to MU TGFBIp was not completed.

TGFBIp Accumulation in Macrophages due to Impaired Autophagosome Fusion to Lysosomes

To further verify whether the incomplete autophagic flux was related to impaired autophagosome fusion with lysosomes, we first blocked the autophagic process with 3-MA (an autophagy inhibitor) and the ubiquitin proteasome pathway by MG132, respectively. Figure 6A shows that neither 3-MA nor MG132 treatment influenced MU TGFBIp uptake by macrophages, and
MU TGFBIp accumulated in the macrophages at 7.5 and 10 hours after MU TGFBIp was withdrawn. However, WT TGFBIp had markedly accumulated in macrophages after WT TGFBIp was removed when the autophagic process was blocked by 3-MA, a result similar to MU TGFBIp exposure (Fig. 6A). Blockage of the ubiquitin proteasome pathway by MG132 did not influence WT TGFBIp uptake and caused WT TGFBIp accumulation in macrophages (Fig. 6A). Next, leupeptin, a moderate cell-permeable inhibitor of lysosomal cysteine proteases, was used to treat macrophages to block lysosome fusion with autophagosomes (Fig. 6A). LC3, TGFBIp, and nuclei (DAPI) were observed by confocal microscopy and merged to observe the colocalization (yellow) of LC3 (green) and TGFBIp (red). (D) Quantification of colocalized cells in three independent experiments. ***P < 0.001.

**Figure 5.** Incomplete autophagic flux in macrophages exposed to MU TGFBIp. Macrophages were exposed to MU or WT TGFBIp as shown in Figure 3A. (A) LC3 and STSQM1 at indicated time points were detected by WB. Quantification of band intensity of LC3 II/LC3 I (B) and STSQM1 (C) in three WB experiments. (D) LC3, TGFBIp, and nuclei (DAPI) were observed by confocal microscopy and merged to observe the colocalization (yellow) of LC3 (green) and TGFBIp (red). (E) Quantification of colocalized cells in three independent experiments. ***P < 0.001.

Impaired Autophagy to LCD TGFBIp in Macrophages

MU TGFBIp accumulated in the macrophages at 7.5 and 10 hours after MU TGFBIp was withdrawn. However, WT TGFBIp had markedly accumulated in macrophages after WT TGFBIp was removed when the autophagic process was blocked by 3-MA, a result similar to MU TGFBIp exposure (Fig. 6A). Blockage of the ubiquitin proteasome pathway by MG132 did not influence WT TGFBIp uptake and caused WT TGFBIp accumulation in macrophages (Fig. 6A). Next, leupeptin, a moderate cell-permeable inhibitor of lysosomal cysteine proteases, was used to treat macrophages to block lysosome fusion with autophagosomes. LC3, TGFBIp, and nuclei (DAPI) were observed by confocal microscopy and merged to observe the colocalization (yellow) of LC3 (green) and TGFBIp (red). Figure 6B shows that leupeptin treatment did not affect MU TGFBIp uptake by macrophages, and MU TGFBIp accumulated in macrophages at 5 and 10 hours after MU TGFBIp was removed. In macrophages exposed to WT TGFBIp, leupeptin treatment did not affect WT TGFBIp uptake, but remarkably influenced the degradation of WT TGFBIp after WT TGFBIp was removed (Fig. 6B). Moreover, obvious colocalization of endogenous LC3 puncta with LAMP1 (a lysosome marker) was found in macrophages exposed to WT TGFBIp, but not in those exposed to MU TGFBIp (Figs. 6C, 6D). Taken together, these results strongly indicated that autophagy is the major pathway by which uptake of TGFBIp in macrophages is degraded, and that the impaired autophagosome fusion to lysosomes causes the accumulation of MU TGFBIp in macrophages.

**Suppression of Phagocytic Activation in Macrophages Exposed to WT TGFBIp by Blocking Autophagy**

To investigate whether blockage of autophagy suppresses the phagocytic activation of macrophages exposed to WT TGFBIp,
we blocked the autophagic process with 3-MA and detected the expressions of CD68 and CD36 in the macrophages. Blockage of autophagy by 3-MA suppressed the expressions of CD68 and CD36 in macrophages exposed to WT TGFBIp, which were active in the macrophages exposed to WT TGFBIp only (Fig. 7, Supplementary Fig. S2). This was evidenced by almost the same expression levels of CD68 and CD36 in macrophages exposed to MU TGFBIp only and WT TGFBIp with 3-MA by WB analysis (Figs. 7A–C). Similar results were found by flow cytometry analysis (Figs. 7D–F). In addition, we also blocked the autophagic process with RNA interfering (siRNA) against Beclin 1 (siBeclin 1) and then detected the expression of CD68 and CD36 by WB. Similar results of CD68 and CD36 expression as blockage of the autophagic process by 3-MA were found (Supplementary Fig. S2A). Moreover, the expression of CD68 and CD36 in the macrophages not exposed to any MU or WT TGFBIp was not affected by 3-MA or siBeclin 1 (Supplementary Fig. S2B). These results are completely different from those shown in Figure 4. They indicated that phagocytic activation in macrophages exposed to WT TGFBIp is reversed to a similar level as that in macrophages exposed to MU TGFBIp only.

**DISCUSSION**

We reported the clinical, histopathologic, and molecular genetic features and possible molecular mechanism of a variant of LCD (p.[Leu558Pro] mutation) in a Chinese family, which has been previously reported in a Spanish family. TGFBI-associated corneal dystrophies are caused by extracellular depositions of insoluble protein aggregates, which can be amyloid and/or granular. The protein encoded by the TGFBI gene is 683 amino acids long and contains four tandemly repeated FAS-1 domains. Previous reports have indicated that most TGFBI mutations associated with corneal dystrophies are located in the fourth FAS-1 domain, except for those affecting amino acid residues 113 and 123–126 in the first FAS-1 domain and amino acid 501 in the third FAS-1 domain. Several lines of evidence show that mutations in the fourth FAS-1 domain cause MU protein deposition by altering TGFBIp...
structure, stability, and subsequent protein processing, or even by affecting TGFBIp fibrillation rates and protein turnover. A proteolytic cleavage site between the wild-type Arg557 and Leu558 residues in the fourth FAS-1 domain has been found by Underhaug et al. Therefore, the p.(Leu558Pro) mutation in our current study may encode a mutant TGFBIp that is significantly less susceptible to proteolysis. The resultant mutant TGFBIp may further disrupt the normal degradation and turnover of corneal TGFBIp, as demonstrated for the p.(Arg555Trp) mutation, leading to dystrophic corneal deposition. In addition, the phenotypic characteristics in our study do not present with those in the missense mutation involving Val113, suggesting that the disruption of the proteolytic cleavage site is of primary importance in terms of its effect on TGFBI function.

LCD is a degenerative disorder that causes loss of corneal transparency and eventually leads to loss of vision. Degenerative disorders are characterized mainly by the accumulation of extracellular or intracellular denatured protein aggregates that cause disease states, such as LCD in the eye or AD in the brain. At present, macrophages are thought to be the major cell components that clear extracellular denatured protein aggregates (such as amyloid deposits) so as to avoid disease states. Two important proteolytic systems, the ubiquitin/proteasome and the autophagy pathways, are involved in the degradation of denatured protein aggregates after they have been taken up into macrophages. Several studies have reported that autophagy is involved in the clearance of TGFBIp, and impaired autophagic degradation of TGFBIp is found in the fibroblasts of granular corneal dystrophy type 2 (GCD2). We reported on a family suffering from LCD due to a Leu558Pro mutation in exon 12 with a T>C heterozygous substitution. We then used the corneas from the proband and a normal subject to investigate the role of macrophages in the pathogenesis of LCD by directly observing macrophage infiltration in the proband’s cornea. Our results showed that there was obvious TGFBIp accumulation surrounded by CD11b+ macrophages in the TGFBI MU proband’s cornea, but not in the control normal subject. Although normal phagocytosis of MU and WT TGFBIp was found in macrophages from MU patients and normal family members, the degradation of MU TGFBIp, but not WT TGFBIp, was impaired in macrophages from MU and normal subjects, indicating that the MU TGFBIp itself, and not the MU macrophages, causes the accumulation and impaired degradation of MU TGFBIp.

Macrophages have an important role in phagocytosis and the removal of amyloid aggregates in the extracellular stroma. As autophagy is a pathway that degrades the phagocytic components in macrophages, we, thus, investigated the role of autophagy in the degradation of MU compared to WT TGFBIp by measuring the extent of autophagosome formation and the status of autophagy in macrophages from LCD sufferers. Our data demonstrated that autophagy was the main intracellular degradation mechanism for WT TGFBIp, but impaired autophagy was found for MU TGFBIp because MU TGFBIp, but not WT TGFBIp, accumulated in macrophages from MU and normal subjects. The impaired intracellular degradation in macrophages was due to incomplete autophagic flux that resulted from impaired autophagosome fusion to

**Figure 7.** Suppression of phagocytic activation in macrophages exposed to WT TGFBIp by blocking autophagy. Macrophages were exposed to MU or WT TGFBIp as shown in Figure 3A. (A) CD68 and CD36 at indicated time points were detected by WB. Quantification of band intensity of CD68 (B) and CD36 (C) in three independent WB experiments. (D) CD68 expression at indicated time points detected by flow cytometry in macrophages exposed to MU or WT TGFBIp. (E) Quantification of CD68 in three independent flow cytometry experiments. (F) CD36 expression at indicated time points detected by flow cytometry in macrophages exposed to MU or WT TGFBIp. (G) Quantification of CD68 in three independent flow cytometry experiments. NS, not significant, *P < 0.01.
lysosomes. The incomplete autophagic flux was evidenced by increased LC3-II conversion and endogenous LC3 puncta in macrophages exposed to WT or MU TGFβP, but SQSTM1, a protein involved in the targeting of polyubiquitinated proteins to autophagosomes and selectively degraded via autophagy, did not significantly change in macrophages exposed to MU TGFβP. However, the expression of SQSTM1 significantly decreased in macrophages exposed to WT TGFβP. In addition, blockage of the autophagic process with 3-MA, an autophagy inhibitor, did not influence MU TGFβP uptake and accumulation in macrophages. However, marked accumulation of WT TGFβP, similar to that of MU TGFβP, was observed when the autophagic process was blocked by 3-MA in macrophages. Blockage of the ubiquitin proteasome pathway by MG132 did not influence WT TGFβP uptake, but caused WT TGFβP accumulation in macrophages. Moreover, blockage of lysosome fusion with autophagosomes by leupeptin, a moderate cell-permeable inhibitor of lysosomal cysteine proteases, did not affect MU TGFβP uptake and accumulation in macrophages, but remarkably influenced the degradation of WT TGFβP.

Taken together, these results strongly indicated that autophagy is the major pathway by which the uptake of TGFβP in the macrophages is degraded, and that it is the impaired autophagosome fusion to lysosomes that results in the accumulation of MU TGFβP in macrophages.

In our study, we found significant uptake of MU and WT TGFβP in macrophages after exposure to MU or WT TGFβP. However, when MU or WT TGFβP exposure was removed, significant accumulation of TGFβP was found only in macrophages exposed to MU TGFβP and not to WT TGFβP. These results indicate that WT and MU TGFβP can be taken up by macrophages after initial exposure to WT and MU TGFβP, and that the uptake and degradation of WT TGFβP is a continuous process, but the process almost stops in the macrophages exposed to MU TGFβP, meaning that there is impaired degradation of MU TGFβP in macrophages. To investigate the possible mechanism, we analyzed the phenotypes of macrophages exposed to MU or WT TGFβP by detecting the expression of CD68 (a phagocytic marker) and CD36 (a surface scavenger receptor), respectively. WB and flow cytometry analysis showed that high expression of CD68 and CD36 was found mainly in macrophages exposed to WT TGFβP, and the levels of CD68 and CD36 in these macrophages were similar to those in normal macrophages not exposed to any TGFβP. In addition, the expressions of CD68 and CD36 were decreased in a time-dependent manner, especially in macrophages after WT TGFβP was withdrawn, but almost unchanged in macrophages after the MU TGFβP was withdrawn. Moreover, the high expressions of CD68 and CD36 in macrophages exposed to WT TGFβP ceased when the autophagic process was blocked by 3-MA. Taken together, these results indicated that the defective autophagic activation by MU TGFβP results in impaired phagocytic activation. Although the relationship between impaired degradation of MU TGFβP, impaired phagocytic activation of macrophages, and incomplete autophagic flux have been illuminated, the detailed molecular mechanisms still need further investigation.

In summary, we found impaired autophagic degradation of MU TGFβP due to incomplete autophagy flux in macrophages. Moreover, the incomplete autophagy flux prevents the further phagocytic activation of macrophages, which results in defective further uptake of MU TGFβP. Our results revealed the relationship among impaired degradation of MU TGFβP, impaired phagocytic activation of macrophages, and incomplete autophagic flux in macrophages exposed to MU TGFβP. Although the detailed molecular mechanisms leading to the defective autophagy remain unknown, our results suggested that reversion of the defective autophagic process in macrophages may be a therapeutic strategy for patients with LCD.

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References

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