Autophagy Regulates Formation of Primary Cilia in Mefloquine-Treated Cells

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Abstract
Primary cilia have critical roles in coordinating multiple cellular signaling pathways. Dysregulation of primary cilia is implicated in various ciliopathies. To identify specific regulators of autophagy, we screened chemical libraries and identified mefloquine, an anti-malaria medicine, as a potent regulator of primary cilia in human retinal pigmented epithelial (RPE) cells. Not only ciliated cells but also primary cilium length was increased in mefloquine-treated RPE cells. Treatment with mefloquine strongly induced the elongation of primary cilia by blocking disassembly of primary cilium. In addition, we found that autophagy was increased in mefloquine-treated cells by enhancing autophagic flux. Both chemical and genetic inhibition of autophagy suppressed ciliogenesis in mefloquine-treated RPE cells. Taken together, these results suggest that autophagy induced by mefloquine positively regulates the elongation of primary cilia in RPE cells.

Key Words: Mefloquine, Autophagy, Primary cilia, Retinal pigmented epithelial cells

INTRODUCTION
Primary cilia are highly conserved, dynamic, microtubule-based organelles that emanate from the surface of many human cell types. The major role of cilia is to sense extracellular signals such as hormones, growth factors, and nutrients (Singla and Reiter, 2006; Berbari et al., 2009). Ciliary defects have been implicated in many human diseases called ciliopathies, including primary ciliary dyskinesia, hydrocephalus, polycystic liver and kidney disease, and some forms of retinal degeneration (Goetz and Anderson, 2010). Therefore, the targeting the mechanism of regulation of ciliogenesis may represent a new therapeutic strategy for treatment of various ciliopathies.

Cilia are generated through ciliogenesis, which regulates the intraflagellar transport (IFT) mechanism. The IFT not only helps in the transport of building material from the cell body to the growing cilium but also carries disassembled material from the cilium assembly site back to the cell body for recycling (Hao et al., 2011). Primary cilia play an important role in developmental, cell migration, the cell cycle and apoptosis by signal transduction, including sonic hedgehog (SHH), the Wnt pathway and calcium signaling (Quinlan et al., 2008; Ishikawa and Marshall, 2011). The mammalian SHH signaling pathway has major signaling components localized in the cilium, and IFT proteins are important for trafficking of SHH molecules (Goetz and Anderson, 2010). SHH signaling is inhibited by a lack of HH ligand through the inhibitory effect of Patched 1 (Ptc1), on Smoothened (Smo), 7-transmembrane-domain protein (Goetz and Anderson, 2010). In addition, the primary cilium regulates canonical and non-canonical Wnt signaling pathways (Gerdes and Katsanis, 2008). It was recently demonstrated that autophagy promotes ciliogenesis by degrading proteins involved in cilia formation (Tang et al., 2013). Furthermore, both autophagy and ciliogenesis are regulated by the mammalian target of rapamycin (mTOR) signaling (DiBella et al., 2009), suggesting that autophagy is associated with ciliogenesis.

Autophagy is a lysosome-dependent, degradation mechanism for the removal of long-lived cytoplasmic constituents,
cellular organelles, and protein aggregates (Rubinsztein, 2006; Klionsky, 2007). Under basal autophagy, ciliary growth is prevented through degradation of proteins such as IFT20. In early-starvation autophagy, the endogenous inhibitor of ciliogenesis OFD1 is degraded, and ciliogenesis is promoted through the delivery of IFT20. Ciliary growth, in turn, leads to the recruitment of autophagy-related (ATG) proteins, such as ATG16L. Excessive activation of autophagy, however, leads IFT20 degradation to prevent unlimited growth of the cilia (Tang et al., 2013). The critical role of autophagy is to help cells survive under stressful conditions by enhancing cellular homeostasis. In contrast, defective autophagy leads to many diseases such as ciliopathies, neurodegenerative diseases, and cancer (Kiprilov et al., 2008; Mizushima et al., 2008; Lista et al., 2011). However, the precise mechanism of autophagy in ciliogenesis is not fully understood.

We previously demonstrated that mefloquine, a medicine for malaria, induces autophagy and autophagy-associated cell death in SH-SY5Y neuroblastoma cells (Shin et al., 2012b). In the present study, we showed that mefloquine induces autophagy and ciliogenesis in human telomerase-immortalized retinal pigmented epithelial (htRPE) cells. We also showed that inhibition of autophagy suppressed the elongation of primary cilia in mefloquine-treated htRPE cells. These findings suggest that regulation of autophagy may provide a new strategy to minimize ciliopathies.

MATERIALS AND METHODS

Cell culture and stable cell line

htRPE cells and htRPE cells stably expressing a Smo-green fluorescence protein (GFP) fusion protein (htRPE/Smo-GFP) were kindly provided by Dr. J. Kim (KAIST, Daejeon, South Korea) (Kim et al., 2010). To generate a GFP-LC3 stable cell line (htRPE/GFP-LC3), htRPE cells were transfected with pGFP-LC3 and selected by G418 (1 mg/mL) for 7 days. The stable transfecants were identified by a fluorescence microscope. Cells were maintained in Dulbecco’s modified Eagle’s medium (DMEM) containing 10% fetal bovine serum (FBS) and 1% penicillin/streptomycin (Invitrogen, Carlsbad, CA, USA) and cultured at 37°C in a 5% CO2 incubator.

Chemical screening for regulators of autophagy

The htRPE/Smo-GFP cells were seeded in 96-well plates (2,000 cells per well). After 24 h, each chemical from the Lopac® 1280 compound library (Sigma-Aldrich Co., St. Louis, MO, USA) and the Prestwick Chemical Library® (Prestwick Chemical, Illkirch, France) was separately added to a well at a final concentration of 10 μM. After further incubation for 24 h, the ciliated cells were observed under a fluorescence microscope.

Reagents

Mefloquine, bafilomycin A1, 3-methyladenine, and cytochalasin D were purchased from Sigma-Aldrich (St. Louis, MO, USA). Ciliobrevin A1 was purchased from Tocris (St. Louis, MO, USA). Previously validated siRNA targeting human ATG5 (5'-GCAACUCUGGAUGGGAUU-3’) and negative scrambled siRNA (5'-CCUACGCACCAUUUUCGU-3’) were synthesized from Genolution (Seoul, Korea) (Shin et al., 2012a).

Measurement of autophagy activation and length of primary cilia

Autophagic cells were determined by counting the number of cells with GFP-LC3 punctate structure under a fluorescence microscope (IX71, Olympus, Japan). Ciliated cells were determined by counting the number of cells with elongated Smo-GFP under a fluorescence microscope (IX71, Olympus, Japan). The cilium length was determined with the cellSens® standard digital imaging software (Olympus Imaging Corp., Tokyo, Japan). The average cilium length was calculated using the cellSens® freehand line selection tool. The lengths of cilia from randomly selected cells were examined, and the images were captured and digitized using the cellSens® standard digital imaging software (≥15 cells per experiments, n=3).

Western blot analysis

Cell lysates were prepared with 2×Laemmli sample buffer (62.5 mM Tris-HCl, pH 6.8, 25% glycerol, 2% SDS, 5% β-mercaptoethanol, 0.01% bromophenol blue) (BioRad, Hercules, CA, USA). Proteins (approximately 50 μg) were quantitated by using the Bradford solution (BioRad) according to the manufacturer’s instructions. Then the samples were separated by 10-15% SDS-polyacrylamide gel electrophoresis, and transferred to PVDF membrane (BioRad). After blocking with 4% skim milk in TBST (25 mM Tris, 150 mM NaCl, 0.05% Tween20), the membranes were incubated overnight with specific primary antibodies at 4°C. Anti-ATG5 (ab54033, 1:2000) was from Abcam (Cambridge, UK); anti-LC3 (NB100-2220, 1:10,000) antibody was from NOVUS Biologicals (Littleton, CO); anti-IFT20 antibody was obtained from Proteintech (13615-01-AP, 1:2,000); anti-Actin (MAB1501, 1:10,000) antibody was from Millipore (Temecula, CA, USA). For protein detection, the membranes were incubated with HRP-conjugated secondary antibodies (Pierce, Rockford, IL, USA).

Statistical analysis

Data were obtained from least three independent experiments, and presented as means ± S.E.M. Statistical evaluation of the results was performed with one-way ANOVA (*p<0.05).

RESULTS

Mefloquine regulates formation of primary cilia by suppressing disassembly in htRPE cells

Ciliary defects are associated with various diseases. Recently, several groups have independently identified molecules regulating ciliogenesis as new therapeutic targets. The Smo protein is accumulated on the primary cilium and is widely used as a cilium marker (Kim et al., 2010). To identify chemical modulators of ciliogenesis, we developed a cell-based screening system by using htRPE cells that stably express GFP fused Smo (htRPE/Smo-GFP). Using this assay, we screened the LOPAC® 1280 compound library (a collection of 1,280 pharmacologically active compounds) and the Prestwick Chemical Library® (a collection of 1,120 chemicals, 85% of which are marketed drugs). Based on the screening results, we selected mefloquine (C25H22N2O) for further analysis as a potent ciliogenesis regulator (Fig. 1A). Mefloquine is an orally administered medication used in the prevention and treatment of malaria. However, the effect of mefloquine on ciliogenesis has not been examined. Therefore, we studied the effect of this drug...
on ciliogenesis. To confirm the screening results, hRPE/Smo-GFP cells were treated with 10 μM mefloquine (Meflo) or 50 nM Cytochalasin D (CytoD) for 24 h. The ciliated cells were imaged with a confocal microscope. (C, D) hRPE/Smo-GFP cells were treated with either Meflo (5 and 10 μM) or CytoD (50 nM). Cilium length and IFT20 expression were analyzed. (E) hRPE/Smo-GFP cells were treated with 10 μM Ciliobrevin A1 (CilioA1) in the presence or absence of Meflo (10 μM). After 24 h, the ciliated cells were observed and counted under a fluorescence microscope. Data were obtained from at least three independent experiments, and values are presented as the means ± S.E.M. (*p<0.05).

**Fig. 1.** Mefloquine induces cilia formation in hRPE cells. (A, B) hRPE/Smo-GFP cells were treated with 10 μM mefloquine (Meflo) or 50 nM Cytochalasin D (CytoD) for 24 h. The ciliated cells were imaged with a confocal microscope. (C, D) hRPE/Smo-GFP cells were treated with either Meflo (5 and 10 μM) or CytoD (50 nM). Cilium length and IFT20 expression were analyzed. (E) hRPE/Smo-GFP cells were treated with 10 μM Ciliobrevin A1 (CilioA1) in the presence or absence of Meflo (10 μM). After 24 h, the ciliated cells were observed and counted under a fluorescence microscope. Data were obtained from at least three independent experiments, and values are presented as the means ± S.E.M. (*p<0.05).

Mefloquine induces autophagy in hRPE cells

We previously demonstrated that mefloquine induces autophagy and autophagy-associated cell death in a neuroblastoma cells. To examine whether mefloquine induces autophagy in hRPE cells, we generated the cell line hRPE/GFP-LC3, which stably expresses LC3, a molecular marker for activation of autophagy as a fusion protein with GFP. In accordance with previous results, treatment of hRPE cells with mefloquine also increased the level of IFT20, which participates in trafficking of ciliary membrane proteins from the Golgi apparatus to the base of the cilium (Follit et al., 2009), indicating that mefloquine induces ciliogenesis in hRPE cells (Fig. 1D). We further examined the cilium elongation activity of mefloquine with an inhibitor of ciliogenesis, Ciliobrevin A1 (Cilio A1), which suppresses ciliogenesis by inhibiting cytoplasmic dynein. Consistently, treatment of mefloquine-treated hRPE cells with CilioA1 significantly reduced the number of ciliated cells induced by mefloquine (Fig. 1E). Taken together, these results suggested that mefloquine induces the formation of primary cilia in hRPE cells.

Not only increased assembly but also decreased disassembly of cilia results in elongation of primary cilium. To determine the effect of mefloquine on cilial dynamics, we employed serum-deprivation conditions, which promote elongation of cilia (Tang et al., 2013). According to previous reports, cilium elongation was increased in serum-starved cells (Fig. 2A). After 48 h of incubation under such serum-deprived conditions, the cells were further incubated in a normal growth medium in the presence or absence of mefloquine. Notably, re-feeding the cells with serum gradually disassembled the cilia over a period of 24 h, while the disassembly of the cilia was almost completely prevented in the mefloquine-treated cells (Fig. 2A, B). These results suggested that mefloquine regulates the ciliogenesis by suppressing the disassembly of the primary cilia in hRPE cells.

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**Fig. 2.** Mefloquine inhibits primary cilia disassembly in hiRPE cells. (A, B) hiRPE/Smo-GFP cells cultured in a serum-deprived medium for 48 h were further incubated with normal growth medium in the absence (A) or presence (B) of Meflo (10 μM) for the indicated times; thereafter, ciliated cells were counted. Data were obtained from at least three independent experiments, and values are presented as the means ± S.E.M. (*p<0.05).

**Fig. 3.** Mefloquine induces autophagy in hiRPE cells. (A) hiRPE/GFP-LC3 cells were treated with Meflo (10 μM) and imaged by confocal microscopy. (B) hiRPE/GFP-LC3 cells treated with Meflo (5, 10 μM) or Cyto D (50 nM) does and time dependent manner were fixed, and cells with autophagic punctate structures were counted under a fluorescence microscopy. (C) hiRPE cells were treated with Meflo with different concentration and protein expression was detected by Western blotting with indicated antibodies. (D) hiRPE cells were treated with Meflo (10 μM) in the presence or absence of bafilomycin A1 (Baf). The conversion of LC3 protein was detected by Western blotting. (E) hiRPE cells treated with 3-methyladenine (3MA) were further incubated with Meflo (10 μM); the conversion of LC3 protein was detected by western blotting. (F) hiRPE cells were transfected with scrambled siRNA (Sc) or a specific siRNA against ATG5 (siATG5). Three days later, the cells were incubated with or without Meflo (10 μM) for an additional 24 h. LC3 and ATG5 expression levels were examined by western blot analysis. Data were obtained from at least three independent experiments, and values are presented as the means ± S.E.M. (n>3, *p<0.05).
tation of primary cilia in hRPE cells, we further investigated the effect of autophagy on the formation of primary cilia in mefloquine-treated cells. Interestingly, inhibition of autophagy by 3MA significantly suppressed the number of ciliated cells induced by treatment with mefloquine (Fig. 4A). Consistently, down-regulation of ATG5 also markedly blocked the mefloquine-induced formation of primary cilia in hRPE cells (Fig. 4B). These results suggested that autophagy positively regulates the elongation of primary cilia in mefloquine-treated RPE cells.

DISCUSSION

Dysregulation of primary cilia is implicated in human diseases, including various ciliopathies (Goetz et al., 2010). Thus, chemical modulators of ciliogenesis may offer some potential for the treatment of ciliopathies. We screened approximately 2,400 bioactive chemicals to identify novel regulators of ciliogenesis and selected mefloquine as a ciliogenesis inducer. Mefloquine has been used as an anti-malarial drug. However, its exact mode of action is not fully elucidated (Toovory, 2009). Mefloquine binds to a number of receptors in the brain and has a high affinity to serotonin receptors (Janowsky et al., 2014). In cortical neurons, mefloquine also induces oxidative stress which is involved in many diseases, such as neurodegenerative diseases, cancer, diabetes, and ciliopathies (Hood et al., 2010; Kim et al., 2013). In this study, we found that treatment with mefloquine elongates primary cilia in hRPE cells. It was recently reported that ROS regulates the length of primary cilia through ERK activation in ischemic damaged kidney cells (Kim et al., 2013). Subsequently, we showed that mefloquine increases ROS production in neuroblastoma cells (Shin et al., 2012b). Therefore, the effect of oxidative stress on mefloquine-mediated ciliogenesis remains to be further elucidated.

Previously, we demonstrated that autophagy attenuates mefloquine-mediated cytotoxicity in neuroblastoma cells. Inhibition of autophagy aggravates cell death in mefloquine-treated cells (Shin et al., 2012b). Autophagy basically is a cellular protective event in response to various stress conditions (Kroemer et al., 2010). Therefore, dysregulation of autophagy is also strongly linked to many pathophysiological conditions, including certain ciliopathies, neurodegenerative diseases and cancer (Tang et al., 2013). Recently, it was shown that rapamycin, a well-known autophagy inducer has a therapeutic effect in rats and mice on polycystic kidney disease, which is an example of ciliopathies (Huber et al., 2012; Ravichandran and Edelstein, 2014). Despite its potential relevance, the underlying molecular mechanism between autophagy and ciliogenesis is largely unknown. Tang et al. recently showed an interesting result that autophagy might promote ciliogenesis by accelerating the autophagic degradation of a ciliopathic protein, oral-facial-digital syndrome-1 (OFD1) (Tang et al., 2013). Here, we found that mefloquine increases activation of autophagy as well as enhances formation of primary cilia in hRPE cells. Furthermore, we also showed that inhibition of autophagy significantly suppressed the formation of primary cilia in cells treated with mefloquine. These results further implicate that autophagy positively regulates ciliogenesis. In contrast, Pampliega et al. suggested a controversial result that inhibition of autophagy enhances the growth of primary cells.
cilia and cilia-associated signaling while activation of autophagy reduces the growth of cilia (Pampliega et al., 2013). Hence, further studies are needed to address the complex functional relationship between autophagy and primary cilia and illustrate the molecular mechanisms of ciliogenesis. In summary, present findings show that autophagy positively regulates ciliogenesis in mefloquine-treated hRPE cells.

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