Inhibition of LPA$_5$ Activity Provides Long-Term Neuroprotection in Mice with Brain Ischemic Stroke

Arjun Sapkota, Sung Jean Park and Ji Woong Choi*

College of Pharmacy, Gachon University, Incheon 21936, Republic of Korea

Abstract

Stroke is a leading cause of long-term disability in ischemic survivors who are suffering from motor, cognitive, and memory impairment. Previously, we have reported suppressing LPA$_5$ activity with its specific antagonist can attenuate acute brain injuries after ischemic stroke. However, it is unclear whether suppressing LPA$_5$ activity can also attenuate chronic brain injuries after ischemic stroke. Here, we explored whether effects of LPA$_5$ antagonist, TCLPA5, could persist a longer time after brain ischemic stroke using a mouse model challenged with tMCAO. TCLPA5 was administered to mice every day for 3 days, starting from the time immediately after reperfusion. TCLPA5 administration improved neurological function up to 21 days after tMCAO challenge. It also reduced brain tissue loss and cell apoptosis in mice at 21 days after tMCAO challenge. Such long-term neuroprotection of TCLPA5 was associated with enhanced neurogenesis and angiogenesis in post-ischemic brain, along with upregulated expression levels of vascular endothelial growth factor. Collectively, results of the current study indicates that suppressing LPA$_5$ activity can provide long-term neuroprotection to mice with brain ischemic stroke.

Key Words: Ischemic stroke, LPA$_5$, TCLPA5, Long-term neuroprotection, Neurogenesis, Angiogenesis

INTRODUCTION

Stroke is a leading cause of death and long-term disability globally. Stroke survivors suffer from motor, cognitive, and memory impairment. They face various difficulties in their daily lives. To date, many drugs and strategies have been successful in experimental models for acute ischemic stroke. However, they have failed in clinical translation. Most of previous studies that find effective treatments have focused on whether these drugs can work for acute injury after ischemic stroke (around 24 h after challenge) by determining brain infarction volume and neurological score with little consideration of their long-term neuroprotection. The importance for long-term protection has been emerged in drug development to treat ischemic stroke (Gladstone et al., 2002; Girard et al., 2014; Schmidt-Pogoda et al., 2020).

Lyosphosphatidic acid (LPA) affects six G protein-coupled receptors (LPA$_1$-LPA$_6$) and influences various biological functions (Choi and Chun, 2013). Among these receptors, LPA$_1$ (Gaire et al., 2019) and LPA$_5$ (Sapkota et al., 2020) have been identified as pathogenic factors in acute ischemic injury. In particular, the latter is upregulated in injured brain after acute ischemic stroke and suppressing its activity can successfully attenuate acute brain injuries (i.e., brain injuries at 1 or 3 days after ischemic challenge) by reducing inflammatory responses in the injured brain (Sapkota et al., 2020). However, it remains unknown whether suppressing LPA$_5$ activity can also be effective for a longer time (up to a few weeks).

The main objective of the current study was to address whether suppressing LPA$_5$ activity with TCLPA5, an LPA$_5$ antagonist, could lead to long-term protection after ischemic challenge using a mouse model of stroke with a transient middle cerebral artery occlusion (tMCAO). Effects of TCLPA5 administration were determined up to 21 days after tMCAO challenge. To determine underlying mechanisms associated with long-term neuroprotection, we determined whether TCLPA5 administration could promote neurogenesis and angiogenesis in the post-ischemic brain of mouse at 21 days after challenge and upregulate vascular endothelial growth factor (VEGF) upregulation, a core factor for both neurogenesis and angiogenesis.
MATERIALS AND METHODS

Animals
Male ICR mice (7 weeks old) were obtained from the Orient Bio (Seongnam, Korea). All animal experiments were performed following Center of Animal Care and Use (CACU) guidelines (approved animal protocol number: LCDI-2019-0027) of Lee Gil Ya Cancer and Diabetes Institute (LCDI) at Gachon University (Incheon, Korea). Mice were housed in controlled temperature and humidity condition with a 12 h light cycle. Mice had free access to food and water ad libitum.

Challenge with tMCAO
Mice were challenged with tMCAO as previously described (Sapkota et al., 2020). Briefly, mice were anesthetized with 3% isoflurane for induction and 1.5% for maintenance in oxygen and nitrogen (30:70% ratio, respectively). Mice were kept in a supine position on an operation plate. The right common carotid artery was separated carefully from the vagus nerve. A small hole in bifurcation was then made. The middle cerebral artery was occluded by inserting monofilaments coated with silicon (9-mm-long 5-0) monofilament. Blood flow was restored at 90 min after occlusion by withdrawing the monofilament. For the sham group, the same surgical procedure was performed without MCAO.

TCLPA5 administration
After tMCAO challenge, mice were randomly divided into either a vehicle group (10% cremophor EL and 10% ethanol in distilled water)- or a TCLPA5-administered group. Vehicle or TCLPA5 (10 mg/kg, i.p., Tocris Bioscience, Bristol, UK) was administered to mice at 0 (immediately after reperfusion), 1, 2, and 3 days after tMCAO challenge. In this study, TCLPA5 was used at 10 mg/kg because the neuroprotective effects of TCLPA5 against an acute brain injury following ischemic challenge were most pronounced at 10 mg/kg in our previous study (Sapkota et al., 2020).

Determination of functional neurological deficit score
Modified neurological severity score (mNSS) scale was used for assessing the functional neurological deficit score in the motor, sensory, reflex, and balance tests every day for 21 days. The functional neurological deficit score ranged from 0 to 18 points (0 point for normal and 18 points for maximal deficit mice) as previously reported (Chen et al., 2001).

Histological assessment
Measurement of brain tissue loss and preparation of brain sections: To determine brain tissue loss at the end of experiment, whole brain was used and the area of viable tissues was calculated as previously described (Wang et al., 2017). Briefly, mice were anesthetized with a mixture of Zoletil 50® (10 mg/kg, i.m., Virbac Laboratories, Carros, France) and Rompun® (3 mg/kg, i.m., Bayer HealthCare LLC, KS, USA), perfused with ice-cold PBS, and fixed with 4% paraformaldehyde (PFA). Brains were collected and post-fixed with 4% PFA overnight. Surface water of brains was removed using tissue paper. Brains were photographed. Area of the brain was measured using Image J software (National Institute of Mental Health, MD, USA) and calculated according to the following formula: (Contralateral area - ipsilateral are)/Contralateral area×100%.

To prepare brain sections for histological assessment, post-fixed brains were cryoprotected with 30% sucrose, embedded in Tissue-Tek® Optimal Cutting Temperature compound, and sectioned (20 µm in thickness) using a cryostat (RD-2230, Roundfin, Liaoning, China).

Determination of cell apoptosis: Cell apoptosis in post-ischemic brain was analyzed through TUNEL assay. Brain sections were post-fixed with 4% PFA, washed with PBS, and stained with a mixture of Enzyme solution and Label solution (In Situ Cell Death Detection Kit, Roche, Mannheim, Germany) for 1 h at room temperature. These sections were rinsed with PBS and distilled water and then mounted with VECTASHIELD® (Vector Laboratories, Burlingame, CA, USA).

Determination of neurogenesis and angiogenesis: Neurogenesis and angiogenesis were determined by double immunofluorescence staining against a cell-specific marker (DCX or CD31) and 5-Bromo-2'-deoxyuridine (BrdU), respectively, as previously described (Sapkota et al., 2020). Briefly, BrdU (50 mg/kg, i.p., Sigma-Aldrich, St. Louis, MO, USA) was given to mice for 2 days at 12 h intervals, starting from 19 days after tMCAO or sham operation. Coronal brain sections were post-fixed with 4% PFA, incubated with 2N HCl at 37°C for DNA denaturation, neutralized with borate buffer (0.1 M, pH 8.5), blocked with 1% fetal bovine serum (FBS), and incubated with proper primary antibodies including rat anti-BrdU (1:200, Abcam, Cambridge, UK), mouse anti-BrdU (1:200, ImmunobioScience Corp., Mukilteo, WA, USA), goat anti-DCX (1:200, Santa Cruz Biotechnology, Dallas, TX, USA), and rat anti-CD31 (1:300, Dianova, Hamburg, Germany) overnight at 4°C. Sections were further incubated with secondary antibodies conjugated with Cy3 or AF488 (1:1,000, Jackson Immunolab., West Grove, PA, USA) and coverslipped using VECTASHIELD® (Vector Laboratories).

Determination of VEGF expression: Brain sections were post-fixed with PFA 4%, subjected to antigen retrieval by heating them in a solution containing sodium citrate (0.01M) at 90-100°C for 30 min, and blocked with 1% FBS. Sections were then incubated with a primary antibody against VEGF (1:200, Santa Cruz Biotechnology) overnight at 4°C, labeled with an anti-rabbit secondary antibody conjugated with AF488 (1:1,000, Jackson Immunolab.) for 2 h at room temperature, counterstained with DAPI, and mounted with VECTASHIELD® (Vector Laboratories).

For double immunofluorescence staining, sections were incubated with goat anti-Iba1 (1:500, Abcam), mouse anti-NeuN (1:200, Millipore, Burlington, MA, USA), mouse anti-GFAP (1:500, Sigma-Aldrich), or rat anti-CD31 (1:300, Dianova) primary antibody overnight at 4°C. These sections were then incubated with Cy3- or AF488-conjugated (1:1,000, Jackson Immunolab.) secondary antibodies for 2 h at room temperature, manually counted and presented as the number of cells per unit area.

Statistical analysis: All data are presented as mean ± stan-
To investigate whether suppressing LPA$_5$ activity with TCLPA5 administration could lead to long-term protection against tMCAO challenge, vehicle or TCLPA5 (10 mg/kg, i.p.) was administered to mice every day for 3 days, starting immediately after reperfusion. TCLPA5 administration significantly improved neurological deficit scores of mice at all determined time points (from day 1 to day 21) compared to vehicle-administration control mice (Fig. 1A). Next, brain tissue loss was measured at 21 days after tMCAO challenge. In the vehicle-administered tMCAO group, a significant brain tissue loss was observed (Fig. 1B, 1C). This brain tissue loss was significantly attenuated by TCLPA5 administration (Fig. 1B, 1C). In addition, we determined whether suppressing LPA$_5$ activity with TCLPA5 could affect survival of mice with tMCAO challenge by analyzing survival rate with a log-rank test. Although the survival rate was not significantly different between vehicle and TCLPA5 administration groups, the survival rate in the latter group was overall higher than that in the former group (Fig. 1D). Moreover, cohorts exposed to tMCAO challenge with vehicle administration showed survival of 31.58% (6 of 19 mice survived), whereas those with TCLPA5 administration showed survival of 61.11% (11 of 18 mice survived) (Fig. 1E). These results indicate that suppressing LPA$_5$ activity can provide long-term neuroprotection in mice after ischemic challenge, along with a slight beneficial effects on survival of these mice.

Next, we determined whether suppressing LPA$_5$ activity with TCLPA5 could attenuate cell apoptosis in the injured brain at a chronic phase after ischemic challenge. The extent of cell apoptosis was assessed by TUNEL assay at 21 days after tMCAO challenge (Fig. 2). In vehicle-treated tMCAO mice, the number of apoptotic cells was markedly increased in the penumbra and the ischemic core regions (Fig. 2A) and quantification of the number of TUNEL-positive cells in the ischemic core region (A) and quantification of the number of TUNEL-positive cells in the penumbra and the ischemic core regions (B) are shown. Scale bar, 50 μm. *n=5 mice per group. ***p<0.001 vs. sham; *p<0.05 vs. vehicle-administered tMCAO group.

TCLPA5 administration enhances neurogenesis in the injured brain of mouse with tMCAO challenge

Neurogenesis has been regarded as an important event for brain repair following ischemic injury (Koh and Park, 2017; Palma-Tortosa et al., 2017). It occurs mainly in the subventricular zone (SVZ) of the neurogenic niche of the brain (Koh and Park, 2017; Palma-Tortosa et al., 2017). To determine whether suppressing LPA$_5$ activity with TCLPA5 could promote neurogenesis in injured brain after ischemic challenge, the number of DCX and BrdU double-immunopositive cells was analyzed in the SVZ of post-ischemic brain at 21 days after tMCAO challenge, whereas such apoptotic cell death was significantly attenuated by TCLPA5 administration (Fig. 2). These results suggest that suppressing LPA$_5$ activity may suppress cell apoptosis in post-ischemic brain at a chronic phase.

**RESULTS**

**TCLPA5 administration exerts long-term neuroprotective effects in mice with tMCAO challenge**

To determine whether suppressing LPA$_5$ activity with TCLPA5 administration on neurological deficit score were assessed daily up to 21 days after tMCAO challenge. (B, C) Effects of TCLPA5 administration on brain tissue loss were assessed at 21 days after tMCAO challenge. Representative images for brain tissue loss (B) and quantification (C) are shown. The colored region in black indicates lost area. (D) Effects of TCLPA5 administration on survival rate were assessed daily up to 21 days after tMCAO challenge. (E) Survival of mice was quantified for each group; Numbers in parentheses indicate the number of survived mice/cohort. n=6 for tMCAO+Veh and n=11 for tMCAO+TCLPA. *p<0.05 and ***p<0.001 vs. vehicle-administered tMCAO group.
challenge. In the vehicle-administered group, the number of new-born neurons (DCX+/BrdU+) was significantly increased in the SVZ of post-ischemic brain (Fig. 3). Interestingly, in the TCLPA5-administered group, the number of new-born neurons was significantly higher than that in the vehicle-administered group (Fig. 3). These results indicate that suppressing LPA5 activity can enhance neurogenesis in the post-ischemic brain after tMCAO challenge, possibly leading to its long-term neuroprotection.

**TCLPA5 administration enhances angiogenesis in the injured brain of mice with tMCAO challenge**

angiogenesis is another important event for brain repair following ischemic injury (Ergul et al., 2012). To investigate whether suppressing LPA5 activity with TCLPA5 could increase angiogenesis in injured brain after ischemic challenge, the number of new-born endothelial cells (CD31+/BrdU+) was also significantly increased in the penumbra region of post-ischemic brain than that in the sham group (Fig. 4A, 4B). The number of new-born endothelial cells (CD31+/BrdU+) was also significantly increased in the penumbra region of post-ischemic brain (Fig. 4C, 4D). Intriguingly, in the TCLPA5-administered group, lengths of endothelial cells (Fig. 4A, 4B) and the number of new-born endothelial cells (Fig. 4C, 4D) were significantly longer and higher than those in the vehicle-administered group, respectively. These results indicate that suppressing LPA5 activity can enhance angiogenesis in post-ischemic brain after tMCAO challenge, possibly leading to its long-term neuroprotection in post-ischemic brain.

**VEGF signaling participates in long-term neuroprotection provided by TCLPA5 administration in tMCAO-challenged mice**

VEGF signaling plays a key role in angiogenesis and neurogenesis in post-ischemic brain (Sun et al., 2003). To address the link between VEGF signaling and long-term neuroprotection provided by TCLPA5 in stroke, we determined VEGF expression levels in the penumbra region at 21 days post-tMCAO challenge by VEGF immunofluorescence staining. The number of VEGF-immunopositive cells was significantly increased in the vehicle-administered group compared to the sham group (Fig. 5A, 5B). This number was significantly higher in the TCLPA5-administered group than in the vehicle-administered group (Fig. 5A, 5B). Next, we specified cell types responsible for the upregulated VEGF expression in the brain through double immunofluorescence staining for VEGF combined with specific cell markers: NeuN (neuron), Iba1 (activated microglia), GFAP (activated astrocyte), or CD31 (endothelial cell). Double immunofluorescence staining was performed for brain sections obtained from TCLPA5-treated mice at 21 days after tMCAO challenge. VEGF was expressed in endothelial cells at the highest level. VEGF signals were observed in approximately 85% of CD31-immunopositive cells (Fig. 5C, 5D). They were also observed in GFAP- (56%), Iba1- (19%),

---

**Fig. 3.** Suppressing LPA5 activity with TCLPA5 promotes neurogenesis in injured brains after tMCAO challenge. Mice were challenged with tMCAO. TCLPA5 was administered daily to mice for 3 days. Effects of TCLPA5 on neurogenesis were determined by DCX and BrdU double immunofluorescence staining at 21 days after tMCAO challenge. Representative images of DCX and BrdU double-immunopositive cells in the SVZ (A) and quantification (B) are shown. Scale bar, 20 \( \mu m \). \( n=5 \) mice per group. **\( p<0.01 \) vs. sham; *\( p<0.05 \) vs. vehicle-administered tMCAO group.

**Fig. 4.** Suppressing LPA5 activity with TCLPA5 promotes angiogenesis in injured brains after tMCAO challenge. Mice were challenged with tMCAO. TCLPA5 was administered daily to mice for 3 days. Effects of TCLPA5 on angiogenesis were determined by CD31 and BrdU double immunofluorescence staining at 21 days after tMCAO challenge. (A) Representative images of CD31-immunopositive cells in the penumbra region of post-ischemic brain. (B) Quantification of the length of CD31-immunopositive cells. Scale bar, 20 \( \mu m \). \( n=5 \) mice per group. (C) Representative images of CD31 and BrdU double-immunopositive cells in the penumbra region of post-ischemic brain. (D) Quantification of the number of double-immunopositive cells. Scale bar, 10 \( \mu m \). \( n=5 \) mice per group. *\( p<0.05 \) and **\( p<0.01 \) vs. sham; *\( p<0.05 \) vs. vehicle-administered tMCAO group.
and NeuN-immunopositive cells (7%) (Fig. 5C, 5D). These results indicate that suppressing LPA₅ activity can regulate VEGF expression in post-ischemic brain, mostly in endothelial cells and activated astrocytes.

**DISCUSSION**

LPA₅ has been recently identified as a novel pathogenic factor for acute brain injuries following ischemic stroke (Sapkota et al., 2020). Its antagonism can lead to neuroprotection for acute brain injuries, along with attenuation of proinflammatory responses including activation of microglia and production of pro-inflammatory cytokines in post-ischemic brains (Sapkota et al., 2020). In the current study, we demonstrated that suppressing LPA₅ activity with TCLPA5 could provide long-term neuroprotection against chronic brain injuries following ischemic stroke based on the findings that TCLPA5 administration significantly attenuated neurological functional deficit, brain tissue loss, and neural cell death at 21 days after tMCAO challenge. In fact, validation of long-term neuroprotection in experimental models of ischemic stroke is believed to be important for developing drugs to treat ischemic stroke. Although most of neuroprotective compounds have demonstrated their effects in experimental models of ischemic stroke, they are unexpectedly less effective in clinical settings (Gladstone et al., 2006; Luo et al., 2007). It is well-defined that the number of new-born neurons could be increased in the SVZ of the lateral ventricle and the dentate gyrus of the hippocampus after an ischemic stroke and then migrate to injured areas for self-repair of injured areas following an ischemic challenge (Arvidsson et al., 2002). In addition, angiogenesis is regarded as a self-repair event in an injured brain following an ischemic challenge (Ergul et al., 2012). Therefore, it has been suggested that promoting neurogenesis and angiogenesis could slow down disease progression and improve symptoms of ischemic stroke (Sun et al., 2003; Koh and Park, 2017). In fact, improving neurological functions has become an ultimate goal in the development of therapeutics to treat ischemic stroke. In the present study, long-term neuroprotective effects of LPA₅ antagonism were demonstrated to be possibly associated with enhanced neurogenesis and angiogenesis.

The current study also demonstrated that suppressing LPA₅ activity with TCLPA5 could upregulate VEGF in the injured brain at 21 days after tMCAO challenge. VEGF is a well-known growth factor that is present in different brain cells, including endothelial cell, astrocyte, neuron, and microglia (Plate et al., 1999; Lee et al., 2009; Huang et al., 2016; Shen et al., 2016). It exerts neuroprotective activity against ischemic stroke by reducing brain infarct size, improving neurological functions,

---

**Fig. 5.** Suppressing LPA₅ activity with TCLPA5 enhances VEGF upregulation in injured brains after tMCAO challenge. Mice were challenged with tMCAO. TCLPA5 was administered daily to mice for 3 days. (A, B) Effects of TCLPA5 on VEGF expression were determined in injured brains at 21 days after tMCAO challenge by VEGF immunofluorescence. Representative images of VEGF-immunopositive cells in the penumbra region (A) and quantification (B) are shown. (C, D) Cellular localization of upregulated VEGF was determined in the penumbra regions of brains from TCLPA5-treated mice at 21 days after tMCAO challenge through double immunofluorescence staining. Representative images for VEGF expression in endothelial cells (CD31), reactive astrocytes (GFAP), activated microglia (Iba1), or neurons (NeuN) (C) and quantification (D) are shown. Arrowheads indicate VEGF and brain cell markers double-immunopositive cells. Scale bars, 20 μm.

r=5 mice per group. *p<0.05 vs. sham; **p<0.05 vs. vehicle-administered tMCAO group.
and enhancing brain recovery through multiple mechanisms (Zhang et al., 2000; Sun et al., 2003; Greenberg and Jin, 2013). In particular, enhanced brain recovery by VEGF can be closely associated with neurogenesis and angiogenesis in a post-ischemic brain (Sun et al., 2003; Greenberg and Jin, 2013). VEGF can regulate angiogenesis by different actions such as enhancing proliferation, migration, and survival of new-born endothelial cells in neonatal ischemic stroke and other experimental models for studying angiogenesis (Flamme et al., 1995; Caron et al., 2009; Shimotake et al., 2010; Kinugasa et al., 2012; Claesson-Welsh and Welsh, 2013). VEGF can also regulate neurogenesis by enhancing axonal out-growth, proliferation of progenitor cells and their survival in the SVZ, and migration of new-born neurons in various experimental models including ischemic stroke (Jin et al., 2002; Sun et al., 2003; Jin et al., 2006; Li et al., 2011). Therefore, the long-term efficacy of T CPLA 5 in T MCAO-challenged mice might be due to production of VEGF which could then lead to increased functional recovery via enhanced neurogenesis and angiogenesis in ischemic stroke. Other than VEGF, it might be possible that other types of neurotrophic factors, such as nerve growth factor, insulin growth factor, and brain-derived neurotrophic factor, contribute to the observed T CPLA 5-enhanced neurogenesis and/or angiogenesis because they have also been reported as regulators of, at least, neurogenesis in post-ischemic brain (Schabitz et al., 2007; Zhu et al., 2009; Yang et al., 2020). Therefore, such issue might be tempting to be addressed in the future independent studies.

In summary, we demonstrated that suppressing LPA 5 activity with T CPLA 5 could provide long-term neuroprotection to mice challenged with ischemic stroke based on the findings that neuroprotective effects of LPA 5 antagonism could persist up to 21 days after T MCAO challenge. Regarding its underlying mechanisms, we demonstrated that T CPLA 5 administration could enhance neurogenesis and angiogenesis in post-ischemic brain possibly via VEGF upregulation. Considering that suppressing LPA 5 activity with T CPLA 5 can provide neuroprotection against both acute (Sapkota et al., 2020) and chronic (the current study) phases of ischemic stroke, targeting LPA 5 could be a promising strategy for drug development to treat ischemic stroke.

CONFLICT OF INTEREST

The authors declare no conflict of interests.

ACKNOWLEDGMENTS

This work was supported by grants from the National Research Foundation (NRF) funded by the Korean government to JWC [NRF-2020R1F1A1067154 and NRF-2020R1A6A1A03043708]. We thank CH Lee for providing assistance for a blind determination.

REFERENCES


