L-Type Amino Acid Transporter 1–Mediated L-Leucine Transport at the Inner Blood–Retinal Barrier

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Purpose. L-type amino acid transporters (LATs) prefer branched-chain and aromatic amino acids, including neurotransmitter precursors. The objective of this study was to clarify the expression and function of LAT at the inner blood–retinal barrier (BRB).

Methods. [^{3}H]L-Leucine transport at the inner BRB was characterized by using in vivo integration plot analysis and a conditionally immortalized rat retinal capillary endothelial cell line (TR-iBRB2). The expression of the LAT1 was demonstrated by quantitative real-time RT-PCR, immunoblot, and immunohistochemical analyses.

Results. The apparent influx permeability clearance of [^{3}H]L-leucine in the rat retina was found to be 203 μL/(min · g retina), supporting a carrier-mediated influx transport of L-leucine at the BRB. [^{3}H]L-Leucine uptake by TR-iBRB2 cells was an Na^+-independent and concentration-dependent process with a K_m of 14.1 μM. This process was more potently *cis* inhibited by substrates of LAT1, D-leucine, D-phenylalanine, and D-methionine, than those of LAT2, L-alanine, and L-glutamine. [^{3}H]L-Leucine efflux from TR-iBRB2 cells was *trans*-stimulated by substrates of LAT1. The expression of LAT1 mRNA was 100- and 15-fold greater than that of LAT2 in TR-iBRB2 and magnetically isolated rat retinal vascular endothelial cells, respectively. The expression of LAT1 protein was observed in TR-iBRB2 and primary cultured human retinal endothelial cells and immunostaining of LAT1 was observed along the rat retinal capillaries.

Conclusions. LAT1 is expressed at the inner BRB and mediates blood-to-retina L-leucine transport. This transport system plays a key role in maintaining large neutral amino acids as well as neurotransmitters in the neural retina. (*Invest Ophthalmol Vis Sci.* 2005;46:2522–2530) DOI:10.1167/iovs.04-1175

L-Glutamate and its metabolic product, γ-aminobutyric acid (GABA) are the main neurotransmitters in the retina. The retinal L-glutamate pool is exclusively derived from de novo L-glutamate synthesis in the retina, since there is virtually no uptake of plasma L-glutamate into the retina.[1] Therefore, the retina requires branched-chain amino acids (leucine, isoleucine, and valine), particularly leucine, and glucose as, respectively, the main nitrogen and carbon precursors of retinal L-glutamate synthesis.[2,3] Branched-chain amino acids also serve as a source of carbon skeletons for the tricarboxylic acid cycle, and a substrate of protein synthesis, since branched-chain amino acids are essential amino acids. The nutrient supply to the retina from the circulating blood is regulated by the blood–retinal barrier (BRB), which is composed of retinal capillary endothelial cells (inner BRB) and retinal pigment epithelial cells (RPE, outer BRB).[4,5] It is well established that glucose is supplied from the circulating blood to the retina via GLUT1 at the BRB,[6,7] and this evidence prompted the hypothesis that the BRB has a supply system(s) to provide the branched-chain amino acids to maintain retinal concentrations of L-glutamate and GABA as well as branched-chain amino acids, per se.

The transport of branched-chain amino acids at the BRB was first described by Hjelle et al.[8] in 1978. They demonstrated that [^{3}H]L-leucine uptake by isolated retinal capillaries takes place in a concentration-dependent and Na^+-independent manner and is inhibited by L-valine and L-dihydroxyphenylalanine, suggesting that the amino acid transporter, system L, mediates L-leucine transport at the inner BRB. L-Leucine uptake into the retina has also been observed in vivo using the retinal uptake index method.[1] System L mediates the Na^+-independent transport of branched-chain and aromatic amino acids and L-type amino acid transporter 1 (LAT1/Slc7a5)[9] and LAT2 (Slc7a8)[10,11] have been shown to encode as system L. These transporters are unique because they require an additional protein, the heavy chain of 4F2 cell surface antigen (4F2hc/CD98/Slc3a2), for functional expression. The expression of LAT1 is localized in certain cells, such as brain capillary endothelial cells,[12–14] trophoblasts,[15] and corneal epithelial cells,[16] whereas LAT2 is expressed ubiquitously.[10,11] Recently, Nakauchi et al.[17] reported that LAT1, LAT2, and 4F2hc mRNA are expressed in a cultured human RPE cell line, an in vitro model of the outer BRB, although their contribution to amino acid transport has not yet been clarified. We previously reported[18] that 4F2hc mRNA is expressed in a conditionally immortalized rat retinal capillary endothelial cell line (TR-iBRB2 cells), which has been used as an in vitro model of the inner BRB,[19] and mediates L-cystine transport by combining with xCT. It presently remains unclear whether 4F2hc is involved in system L transport at the inner BRB. Consequently, our knowledge of the transport systems of branched-chain amino acids at the BRB, especially at the inner BRB, is still incomplete. It is important to elucidate the branched-chain amino acid transporter(s) at the inner BRB, since the inner two thirds of the human retina is nourished by a direct blood supply through the inner BRB.

We report evidence supporting the hypothesis that branched-chain amino acids in the retina are supplied from the

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circulating blood across the inner BRB. The characteristics and functions of L-leucine transport at the inner BRB were examined by in vivo integration plot analysis and using TR-iBRB2 cells. The localization of LAT1 at the inner BRB was determined by immunohistochemical analysis.

Materials and Methods

Animals

Male Wistar rats (250–300 g) and female Hartley guinea pigs (350–400 g) were purchased from SLC (Shizuoka, Japan). The investigations involving animals that are described in this report conformed to the provisions of the Animal Care Committee, Toyama Medical and Pharmaceutical University (no. 2003-48) and the ARVO Statement on the Use of Animals in Ophthalmic and Vision Research.

Blood-to-Retina [^{3}H]L-Leucine Transport Studies

The L-[4,5-^{3}H(*N*)]-leucine ([^{3}H]L-leucine, 42.5 Ci/mmol, PerkinElmer Life Science, Boston, MA) transport from the circulating blood to the retina was measured as described previously.[20,21] Briefly, the rats were anesthetized with an intramuscular injection of ketamine-xylazine (1.22 mg xylazine/kg and 125 mg ketamine/kg) and then [^{3}H]L-leucine (3 μCi/rat) was injected through the femoral vein. After collection of blood samples, rats were decapitated, and their retinas were removed. All samples were dissolved in 2 N NaOH and subsequently neutralized. The radioactivity was measured in a liquid scintillation counter (LS6500; Beckman-Coulter, Fullerton, CA). The apparent tissue-to-plasma concentration ratio (V_d) was used as an index of the tissue distribution characteristics of [^{3}H]L-leucine. This ratio [$V_d(t)$] (milliliters per gram of retina) was defined as the amount of [^{3}H] per gram of retina divided by that per milliliter plasma, calculated over the time-period of the experiment (t). The apparent influx permeability clearance of [^{3}H]L-leucine in the retina ($K_{in,retina}$) (microliters per minutes per gram of retina) was determined by integration plot analysis. In brief, $K_{in,retina}$ can be described by the following equation:

$$V_d(t) = K_{in,retina} \times AUC(t)/C_p(t) + V_i$$

where AUC(t) (dpm · minute per milliliter), $C_p(t)$ (dpm per milliliter), and V_i (milliliters per gram of tissue) represent the area under the plasma concentration time curve of [^{3}H]L-leucine from time 0 to t, the plasma [^{3}H]L-leucine concentration at time t, and the rapidly equilibrated distribution volume of [^{3}H]L-leucine, respectively.

Isolation of Rat Retinal Vascular Endothelial Cells

Magnetic beads coated with anti-rat CD31 antibodies were used to collect purified retinal vascular endothelial cells (RVECs), as described previously.[22] Briefly, mouse anti-rat CD31 antibodies (Chemicon, Temecula, CA) were incubated with Dynabeads pan-mouse IgG (Dynal Biotech, Lake Success, NY) overnight at 4°C to obtain magnetic beads coated with anti-rat CD31 antibodies. Rat retinas were minced and digested in 0.1% collagenase type I (Invitrogen, Carlsbad, CA) and 0.01% DNase I (Roche, Mannheim, Germany) in Ca^{2+}- and Mg^{2+}-free Hanks' balanced salt solution (HBSS) for 30 minutes at 37°C with agitation. Digests were filtered through a 30-μm nylon mesh and centrifuged at 200*g* for 10 minutes. The pellets were resuspended in Dulbecco's modified Eagle's medium (DMEM) containing 10% fetal bovine serum (FBS) and incubated with magnetic beads coated with anti-rat CD31 antibodies for 1 hour at room temperature. RVECs labeled with the magnetic beads were positively selected by affinity binding to the magnet.

Cell Culture

Primary cultured human retinal endothelial cells were obtained from Dainippon Pharmaceutical (Osaka, Japan) and cultured in endothelial cell basal medium containing growth supplement (Cell Applications, San Diego, CA) at 37°C. TR-iBRB2 cells were cultured in DMEM containing 10% FBS at 33°C. The permissive temperature for TR-iBRB2 cell culture is 33°C due to the presence of temperature-sensitive SV-40 large T-antigen.[19] All cells were seeded onto rat tail collagen type I–coated tissue culture plates (BD Biosciences, Bedford, MA) and cultured in a humidified atmosphere of 5% CO_2 and air.

Transport of [^{3}H]L-Leucine in TR-iBRB2 Cells

The [^{3}H]L-leucine uptake by TR-iBRB2 cells was measured according to a previous report.[21] Briefly, cells were incubated with 0.1 μCi [^{3}H]L-leucine (12 nM) in extracellular fluid (ECF) buffer consisting of 122 mM NaCl, 25 mM $NaHCO_3$, 3 mM KCl, 1.4 mM $CaCl_2$, 1.2 mM $MgSO_4$, 0.4 mM K_2HPO_4, 10 mM D-glucose and 10 mM HEPES (pH 7.4) at 37°C in the absence or presence of inhibitors. Na^+-free ECF buffers were prepared in two different ways: the choline ECF buffer was prepared by equimolar replacement of NaCl and $NaHCO_3$ with choline chloride and choline bicarbonate, respectively, whereas the Li ECF buffer was prepared by equimolar replacement of NaCl and $NaHCO_3$ with LiCl and $KHCO_3$, respectively. Cells were solubilized in 1 N NaOH and subsequently neutralized. An aliquot was taken for measurement of the radioactivity and protein content using, respectively, a liquid scintillation counter and a DC protein assay kit (Bio-Rad, Hercules, CA) with bovine serum albumin as a standard. The uptake of [^{3}H]L-leucine by TR-iBRB2 cells was expressed as the cell-to-medium ratio (microliters per milligram protein) as follows:

$$\text{Cell-to-medium ratio} = ([^3\text{H}]\text{ dpm in the cells per mg protein})/([^3\text{H}]\text{ dpm in the medium per } \mu\text{L})$$

For kinetic studies, the Michaelis-Menten constant (K_m) and maximum rate (J_{max}) of L-leucine uptake were calculated from the equation, by using the nonlinear least-squares regression analysis program, MULTI.[23]

$$J = J_{max} \times C/(K_m + C)$$

where J and C are the uptake rate of L-leucine at 5 minutes and the concentration of L-leucine, respectively.

The 50% inhibition concentration (IC_{50}) for [^{3}H]L-leucine uptake by TR-iBRB2 cells was calculated by fitting the data to a sigmoidal inhibition model[21] using MULTI.[23]

$$J = J_0/[1 + ([I]/IC_{50})^n]$$

where J and J_0 are the uptake of [^{3}H]L-leucine in the presence and absence of inhibitors, respectively, [I] is the concentration of inhibitors and n is the Hill coefficient.

In the [^{3}H]L-leucine efflux studies, TR-iBRB cells were washed three times with ECF buffer and incubated with 0.1 μCi [^{3}H]L-leucine in ECF buffer for 5 minutes at 37°C to preload [^{3}H]L-leucine. Cells were then washed three times with ice-cold ECF buffer and incubated with ECF buffer in the absence or presence (control) of 2 mM amino acids at 37°C. After 4 minutes, incubated ECF buffer was taken to measure the efflux of preloaded [^{3}H]L-leucine from cells. The radioactivity in the cells was measured as just described. The efflux of [^{3}H]L-leucine by TR-iBRB2 cells was expressed as follows:

$$\text{Fractional outflow}(\%) = ([^3\text{H}]\text{ dpm in the medium})/([^3\text{H}]\text{ dpm in the cells} + [^3\text{H}]\text{ dpm in the medium}) \times 100$$

Reverse Transcription–Polymerase Chain Reaction Analysis

Total cellular RNA was prepared using a kit (RNeasy; Qiagen, Hilden, Germany). Single-strand cDNA was made from total RNA by reverse transcription (RT) using an oligo dT primer. The polymerase chain

TABLE 1. Oligonucleotide Primers Used for PCR Amplification of cDNAs

Target mRNA	Accession Number	Upstream Primer (5′ to 3′)	Downstream Primer (5′ to 3′)	Product Size (bp)
LAT1 (Slc7a5)	NM_017353	CTC AAG CTC TGG ATC GAG CTG CTC	TTC CTG TAG GGG TTG ATC ATC TCC	440
LAT2 (Slc7a8)	NM_053442	CCT CGT CGC TCT GGC TTT CCT C	CGG GGG ATG TCA GGC TTC TTC CAG	558
4F2hc (Slc3a2)	NM_019283	CTC CCA GGA AGA TTT TAA AGA CCT TCT	TTC ATT TTG GTG GCT ACA ATG TCA G	141
β-Actin	NM_031144	TCA TGA AGT GTG ACG TTG ACA TCC GT	CCT AGA AGC ATT TGC GGT GCA CGA TG	285

reaction (PCR) was performed with LAT1, LAT2, or 4F2hc specific primers (Table 1) through 40 cycles of 94°C for 30 seconds, 60°C for 30 seconds, and 72°C for 1 minute. The PCR products were separated by electrophoresis on an agarose gel in the presence of ethidium bromide and visualized under ultraviolet light. The PCR products of the expected length were then cloned into a plasmid vector using a kit (p-GEM-T Easy Vector System I; Promega, Madison, WI) and amplified in *Escherichia coli*. Several clones were then sequenced from both directions using a DNA sequencer (Prism 310; Applied Biosystems Inc., [ABI] Foster City, CA).

Quantitative Real-Time PCR

Quantitative real-time PCR was performed on a sequence detector system (Prism 7700; ABI) with 2× SYBR Green PCR Master Mix (ABI) according to the manufacturer's protocol. To quantify the amount of specific mRNA in the samples, a standard curve was generated for each run using the plasmid (pGEM-T Easy Vector; Promega) containing the gene of interest. This enabled standardization of the initial mRNA content of cells relative to the amount of β-actin. The PCR was performed using LAT1-, LAT2-, or β-actin-specific primers (Table 1) and the cycling parameters are those given for RT-PCR.

Antibody Preparation

A peptide containing 13 amino acids of rat LAT1 (CRFKKPELERPIK, positions 424-435) was linked to maleimide-activated keyhole limpet hemocyanin (KLH; Pierce, Rockford, IL). The KLH-linked peptide (200 μg/injection) was emulsified by mixing with an equal volume of Freund's adjuvant (Difco, Detroit, MI) and injected subcutaneously into female Hartley guinea pigs at intervals of 2 weeks. Three weeks after the sixth injection, the immunoglobulin fraction was purified (HiTrap rProtein A FF column; Amersham Biosciences, Piscataway, NJ). Immunoglobulins specific to LAT1 peptide were affinity-purified (HiTrap NHS-activated HP column; Amersham Biosciences) carrying LAT1 peptide. Immunoblot analysis using rat brain extracts reported to express LAT1[12] showed that purified antibody strongly recognized a protein band at 40 kDa (Fig. 7; lane 1), the size of which is consistent with a previous report.[12] This band was abolished when purified immunoglobulins were preabsorbed with LAT1 antigen peptides (100 μg/mL; data not shown), indicating the specificity of the purified antibody for rat LAT1.

Immunoblot Analysis

Proteins were obtained by dissolving cells in sample buffer consisting of 5% sodium dodecyl sulfate (SDS), 250 mM Tris-HCl (pH 6.8), 10% glycerol, 6% 2-mercaptoethanol, and 0.01% bromophenol blue, followed by heating for 10 minutes at 95°C, and centrifugation for 10 minutes at 4°C and 9000*g*. Supernatants were separated and used as whole-cell extracts. Deglycosylation was performed by incubating the protein with *N*-glycosidase F (Roche). The protein (30 μg) was electrophoresed on an SDS-polyacrylamide gel and subsequently, electrotransferred to a polyvinylidene difluoride membrane. After incubation with blocking agent solution (Block Ace; Dainippon Pharmaceutical), the membranes were incubated with guinea pig polyclonal anti-LAT1 antibody (0.8 μg/mL) or goat polyclonal anti-4F2hc (CD98) antibody (1:300; Santa Cruz Biotechnology, Santa Cruz, CA) for 16 hours at 4°C. The membranes were subsequently incubated with horseradish peroxidase conjugated anti-guinea pig or goat IgG. The bands were visualized using an enhanced chemiluminescence kit (Amersham Biosciences).

Immunohistochemical Analysis

Under deep pentobarbital anesthesia (50 mg/kg body weight, intraperitoneally), rats were perfused transcardially with 4% formaldehyde in 0.1 M phosphate buffer. The eyeball was isolated and immersed in 0.5 M sucrose/HBSS solution. Sections (12 μm in thickness) were cut from the frozen eye with a cryostat (CM1900; Leica, Heidelberg, Germany) and mounted onto silanated glass slides (Dako, Carpinteria, CA). After incubation with 10% goat serum (Nichirei, Tokyo, Japan) for 1 hour at room temperature, sections were incubated with guinea pig polyclonal anti-LAT1 antibody (10 μg/mL) and rabbit polyclonal anti-GLUT1 antibody (1:500; Chemicon) for 36 hours at 4°C. Sections were subsequently incubated with FITC-conjugated anti-guinea pig and Cy3-conjugated anti-rabbit IgG antibodies (1:100; Chemicon) for 1 hour at room temperature. Sections were then mounted on coverslips using antifade mounting medium (Vectashield; Vector Laboratories, Burlingame, CA) and viewed using a confocal laser microscope (LSM 510; Carl Zeiss Meditec, Oberkochen, Germany).

Data Analysis

Unless otherwise indicated, all data represent means ± SEM. An unpaired, two-tailed Student's *t*-test was used to determine the significance of differences between two groups. Statistical significance of differences among means of several groups was determined by one-way analysis of variance followed by the modified Fisher's least-squares difference method.

RESULTS

L-Leucine Transport System at the Inner BRB

The in vivo blood-to-retina influx transport of L-leucine from the circulating blood to the retina through the BRB was evaluated by integration plot analysis after intravenous administration of [^{3}H]L-leucine to rats (Fig. 1). The $K_{in,retina}$ of [^{3}H]L-leucine was determined to be 203 ± 35 μL/(min · g retina) from the slope representing the apparent influx permeability clearance across the BRB. The apparent tissue-to-plasma concentration ratio (V_d) at 5 minutes was 1.88 ± 0.14 mL/g retina, far greater than that of [^{3}H]D-mannitol (0.058 mL/g retina at 15 minutes),[20] which is used as a nonpermeable paracellular marker. This result indicates that L-leucine is transported from the blood to the retina across the BRB.

Because the in vivo retinal uptake study represents L-leucine influx transport across both the inner and outer BRB, to determine the kinetic parameters of L-leucine and characterize L-leucine transport at the inner BRB, [^{3}H]L-leucine uptake and

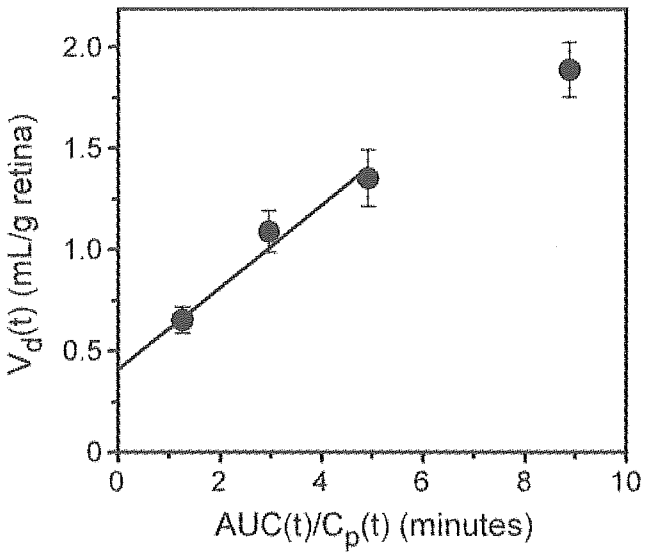

FIGURE 1. Integration plot of the initial uptake of [^{3}H]L-leucine by the retina after intravenous administration. [^{3}H]L-leucine (3 μCi/rat) was injected into the femoral vein. Each point represents the mean ± SEM (n = 3–5).

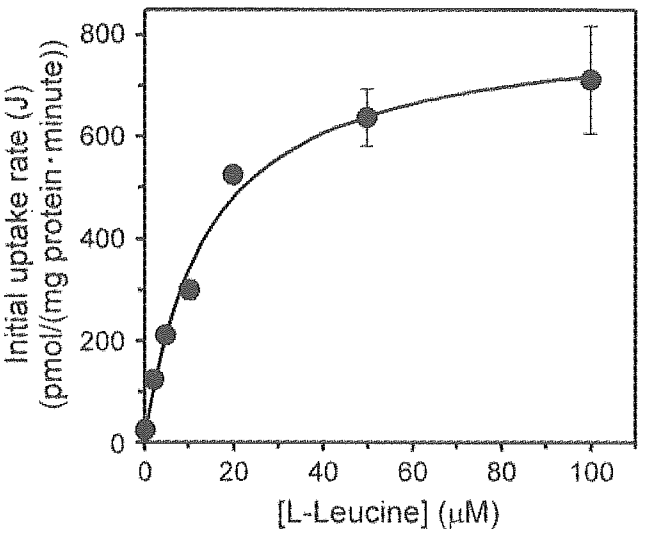

FIGURE 3. Concentration-dependence of L-leucine uptake by TR-iBRB2 cells. The [^{3}H]L-leucine (12 nM) uptake was performed at 5 minutes and 37°C. Each point represents the mean ± SEM (n = 4). The K_m is 14.1 ± 1.9 μM, and J_{max} is 819 ± 37 picomoles/(min · mg protein) (mean ± SD).

efflux studies were performed using TR-iBRB2 cells as an in vitro model of the inner BRB. The time-course of [^{3}H]L-leucine uptake by TR-iBRB2 cells is shown in Figure 2. [^{3}H]L-Leucine uptake increased linearly for 10 minutes, and the initial uptake rate was 20.1 μL/(min · mg protein). The inhibitory effect of Na^+-free conditions on [^{3}H]L-leucine uptake by TR-iBRB2 cells was examined under two different sets of conditions. Both choline ECF buffer and Li ECF buffer had little effect on [^{3}H]L-leucine uptake (94.2% ± 28.1% and 85.3% ± 14.1%, respectively; data not shown). This confirms that [^{3}H]L-leucine uptake by TR-iBRB2 cells is mediated by an Na^+-independent process.

Figure 3 shows the concentration-dependent uptake of L-leucine by TR-iBRB2 cells. The intracellular L-leucine uptake was saturable, and nonlinear least-squares regression analysis showed that the K_m and J_{max} were 14.1 ± 1.9 μM and 819 ± 37 picomoles/(min · mg protein) (mean ± SD), respectively.

The *cis* inhibition study was performed to characterize the [^{3}H]L-leucine uptake by TR-iBRB2 cells (Table 2). [^{3}H]L-Leucine uptake was inhibited by 2 mM L-leucine, L-phenylalanine, L-methionine, L-isoleucine, L-valine, L-tyrosine, and L-tryptophan, all of which are substrates of system L encoded by LAT1 or LAT2.[9–11] The system L-specific inhibitor, 2-aminobicyclo-(2,2,1)-heptane-2-carboylic acid (BCH) at a concentration of 2 mM strongly inhibited [^{3}H]L-leucine uptake. [^{3}H]L-Leucine uptake was also inhibited by more than 50% in the presence of substrates of LAT1, such as D-leucine, D-phenylalanine, and D-methionine, at a concentration of 2 mM.[9] However, it was only inhibited by 30% in the presence of substrates of LAT2, such as L-alanine and L-glutamine, at a concentration of 2 mM.[10,11] L-Glutamic acid, L-arginine, and L-proline had no effect

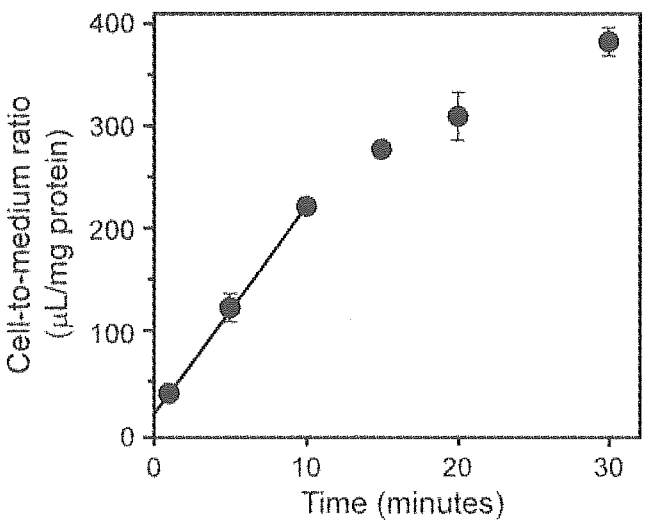

FIGURE 2. Time-course of [^{3}H]L-leucine uptake by TR-iBRB2 cells. The [^{3}H]L-leucine (12 nM) uptake was performed at 37°C. Each point represents the mean ± SEM (n = 4).

TABLE 2. Effect of Several Inhibitors on [^{3}H]L-Leucine Uptake by TR-iBRB2 Cells

Inhibitors	Percentage of Control
Control	100 ± 2
2 mM L-Leucine	2.88 ± 0.32*
2 mM L-Phenylalanine	20.0 ± 0.3*
2 mM L-Methionine	52.6 ± 1.8*
2 mM D-Leucine	45.7 ± 1.4*
2 mM D-Phenylalanine	39.7 ± 0.6*
2 mM D-Methionine	47.5 ± 1.9*
2 mM L-Isoleucine	36.5 ± 2.1*
2 mM L-Valine	46.9 ± 2.1*
2 mM L-Tyrosine	31.9 ± 0.2*
2 mM L-Tryptophan	17.3 ± 0.4*
2 mM L-Alanine	70.6 ± 4.4*
2 mM L-Glutamine	70.0 ± 2.3*
2 mM L-Glutamic acid	91.8 ± 5.8
2 mM L-Arginine	94.0 ± 3.3
2 mM L-Proline	87.5 ± 5.2
2 mM BCH	30.1 ± 0.8*
2 mM L-Dopa	42.1 ± 1.3*
2 mM Methyldopa	64.9 ± 1.3*
2 mM Gabapentin	79.6 ± 2.7*
100 μM Melphalan	58.4 ± 2.0*

[^{3}H]L-Leucine uptake (12 nM) was measured in the absence (control) or presence of inhibitors at 5 minutes and 37°C. Data are expressed as the mean ± S.E.M. (n = 4–24).

* $P < 0.01$, significantly different from the control.

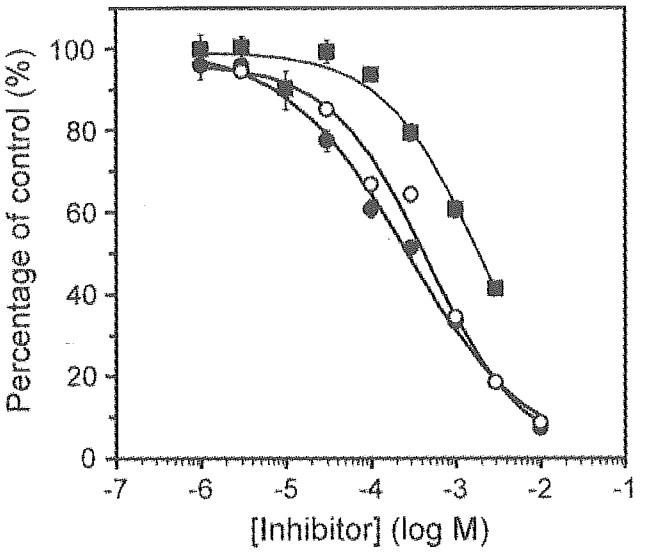

FIGURE 4. Concentration-dependent inhibition of amino acids involving the uptake of [^{3}H]L-leucine by TR-iBRB2 cells. [^{3}H]L-Leucine uptake (12 nM) was performed in the absence (control) or presence of various concentrations of L-phenylalanine (●), L-tyrosine (■), and L-tryptophan (○) at 5 minutes in 37°C. Each data point represents the mean ± SEM (n = 4). The IC_{50} was 266 ± 32 μM, 1.90 ± 0.18 mM, and 467 ± 93 μM for L-phenylalanine, L-tyrosine, and L-tryptophan, respectively (mean ± SD).

on [^{3}H]L-leucine uptake. In addition to naturally occurring amino acids, the amino acid-mimetic drugs 2 mM L-dopa, 2 mM methyldopa, 2 mM gabapentin, and 100 μM melphalan, significantly inhibited [^{3}H]L-leucine uptake by 58%, 35%, 20%, and 42%, respectively. These inhibitory characteristics of [^{3}H]L-leucine uptake by TR-iBRB2 cells are consistent with LAT1, rather than LAT2. In particular, L-phenylalanine, L-tyrosine, and L-tryptophan inhibited [^{3}H]L-leucine uptake in a concentration-dependent manner with an IC_{50} of 266 ± 32 μM, 1.90 ± 0.18 mM, and 467 ± 93 μM (mean ± SD), respectively (Fig. 4).

After preincubation of TR-iBRB2 cells with [^{3}H]L-leucine, the efflux of [^{3}H]L-leucine from TR-iBRB2 cells was measured in the absence or presence of extracellular amino acids. As shown in Figure 5, the efflux of [^{3}H]L-leucine from TR-iBRB2 cells was significantly stimulated by extracellular application of 2 mM L-leucine, L-phenylalanine, L-tryptophan, and BCH, whereas 2 mM L-arginine had no significant effect on [^{3}H]L-leucine efflux. These *trans*-stimulation effects by system L substrates are consistent with the view that system L functions as an exchanger.[24]

Expression of System L Transporters at the Inner BRB

To determine the mRNA expression at the in vivo inner BRB, RVECs were affinity purified from rat retinal homogenate by using magnetic beads coated with antibodies against CD31,[22] which is exclusively expressed on the membrane of endothelial cells. The magnetically collected and uncollected cells were isolated as the RVEC and non-RVEC fractions, respectively. The transcript levels of endothelial markers, such as CD31, Tie-2, claudin-5, occludin, and Jam-1, in the RVEC fraction were more than 100 times greater than those in the non-RVEC fraction.[22] RT-PCR analysis was performed to examine the expression of LAT1, LAT2, and 4F2hc in the rat brain as a positive control, rat retina, RVEC and non-RVEC fractions, and TR-iBRB2 cells. The bands of LAT1 and LAT2 were detected at 440 and 558 bp, respectively (Figs. 6A, 6B). The nucleotide sequence of the bands of TR-iBRB2 cells was identical with rat LAT1 and LAT2. 4F2hc was also expressed in all samples (Fig. 6C). To determine the dominant gene for system L at the inner BRB, quantitative real-time PCR analysis was performed to quantify the mRNA expression levels of LAT1 and LAT2 (Fig. 6D). The expression of LAT1 mRNA was 15 and 100 times greater than LAT2 mRNA in the RVEC fraction and TR-iBRB2 cells, respectively. Moreover, the expression level of LAT1 in the RVEC fraction was almost identical with that in the non-RVEC fraction, suggesting that the distribution of LAT1 is not restricted to the inner BRB. The expression of LAT2 in the RVEC fraction was 6.7-fold less than that in the non-RVEC-fraction. This result implies that LAT2 is not primarily distributed at the inner BRB of the rat retina.

The expression of LAT1 and 4F2hc protein was also determined in the rat retina, TR-iBRB2 cells, and primary cultured human retinal endothelial cells by immunoblot analysis, as shown in Figure 7. Rat brain was used as a positive control. The bands of LAT1 and 4F2hc were detected at 40 and 75 kDa, respectively, which are identical with the reported values.[12,25] Moreover, the band of 4F2hc shifted from 75 to 56 kDa in TR-iBRB2 cells after deglycosylation (Fig. 7B, lanes 5, 6), which is in agreement with the molecular mass of nonglycosylated rat 4F2hc predicted from its amino acid sequence (58 kDa). The localization of LAT1 in the rat retina was determined by immunohistochemical analysis (Fig. 8). Immunostaining of LAT1 (Figs. 8A, 8D, green) was observed along the retinal capillaries in the ganglion cell and inner plexiform layers and completely overlapped that of GLUT1 (Figs. 8B, 8E, red), which is known to be expressed in retinal capillaries.[6,7] LAT1 immunoreactivity was also detected in the ganglion cell and inner nuclear layers.

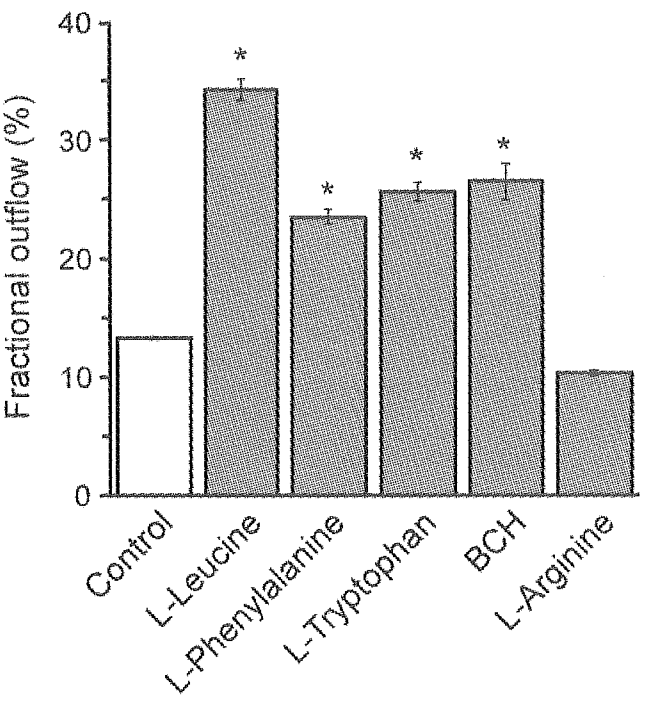

FIGURE 5. Effect of several amino acids on the efflux of [^{3}H]L-leucine from TR-iBRB2 cells. The efflux of preloaded [^{3}H]L-leucine was performed in the absence (control) or presence of extracellularly applied 2 mM L-leucine, L-phenylalanine, L-tryptophan, BCH, and L-arginine at 4 minutes in 37°C. Each column represents the mean ± SEM (n = 4). The fractional outflow (%) was 13.3 ± 0.2 (control), 34.2 ± 0.9 (L-leucine), 23.5 ± 0.6 (L-phenylalanine), 25.6 ± 0.8 (L-tryptophan), 26.5 ± 1.5 (BCH), and 10.3 ± 0.2 (L-arginine). *$P < 0.01$, significantly different from control.

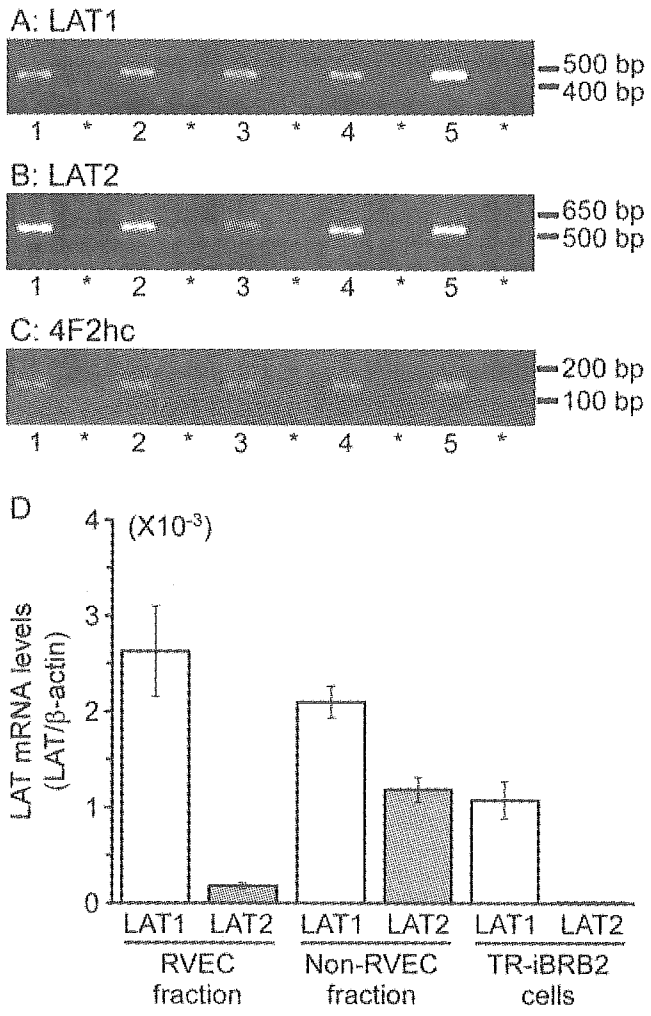

FIGURE 6. RT-PCR analysis of LAT1 (**A**), LAT2 (**B**), and 4F2hc (**C**) and the amount of LAT1 and LAT2 mRNA (**D**) in the RVEC fraction and TR-iBRB2 cells. (**A–C**) *Lane 1*: rat brain; *lane 2*: rat retina; *lane 3*: RVEC fraction; *lane 4*: non-RVEC fraction; *lane 5*: TR-iBRB2 cells. *Absence of reverse transcriptase relative to the respective *left* lane. Rat brain was used as a positive control. (**D**) The amount of LAT1 and LAT2 mRNAs were determined by quantitative real-time PCR analysis. Each column represents the mean ± SEM of at least three different samples. The quantity of LAT1 mRNA relative to β-actin mRNA (LAT1/β-actin) was (2.63 ± 0.47) × 10^{-3}, (2.10 ± 0.17) × 10^{-3}, and (1.08 ± 0.19) × 10^{-3}, and that of LAT2 mRNA (LAT2/β-actin) was (1.78 ± 0.31) × 10^{-4}, (1.19 ± 0.13) × 10^{-3}, and (1.02 ± 0.12) × 10^{-5} in the RVEC fraction, non-RVEC fraction, and TR-iBRB2 cells, respectively.

Such characteristic immunostaining of LAT1 was not seen after the use of preimmune guinea pig immunoglobulin (data not shown).

DISCUSSION

The present study demonstrates L-leucine transport from the circulating blood to the retina and provides the first evidence that LAT1 is localized in retinal capillary endothelial cells. Furthermore, the characteristics of [^{3}H]L-leucine influx and efflux transport in TR-iBRB2 cells used as an in vitro model of the inner BRB confirm that LAT1 is involved in L-leucine transport at the inner BRB.

[^{3}H]L-Leucine was transported from the blood to the retina across the BRB with a $K_{in,retina}$ of 203 ± 35 μL/(min · g retina) (Fig. 1), far greater than that of [^{14}C]sucrose (approximately 0.5 μL/(min · g retina), used as a nonpermeable paracellular marker.[26] This evidence suggests that L-leucine is transported by some carrier-mediated transport process, rather than by passive diffusion at the BRB. Although the estimated $K_{in,retina}$ reflects the transport across the inner and outer BRB, the presence of L-leucine transport at the inner BRB is strongly suggested by the fact that [^{3}H]L-leucine uptake occurs in TR-iBRB2 cells (Fig. 3). The K_m of 14.1 μM for [^{3}H]L-leucine uptake by TR-iBRB2 cells is in good agreement with that obtained for L-leucine uptake by rat LAT1 and 4F2hc expressed *Xenopus laevis* oocytes (K_m = 18 μM),[9] and different from that of rat LAT2 (K_m = 120 μM).[11] The K_m of L-leucine uptake by TR-iBRB2 cells is lower than the rat plasma concentration of L-leucine (84–160 μM).[27–29] In addition to L-leucine, LAT1 also prefers other branched-chain and aromatic amino acids such as L-phenylalanine and L-tyrosine circulating in the blood. These findings show that the inner BRB has the ability to supply L-leucine to the retina, although the LAT1-mediated amino acid transport at the inner BRB is saturated by substrate amino acids in the blood. In patients with phenylketonuria, the retinal concentration of LAT1-substrate amino acids, except phenylalanine, would be decreased by increasing the plasma concentration of phenylalanine relative to other amino acids, because of the competition for LAT1-mediated blood-to-retina transport between phenylalanine and other substrate amino acids. Children with phenylketonuria are reported to have impaired visual contrast sensitivity,[30] which is a behavioral measure sensitive to retinal dopamine levels, since reducing the concentration of a dopamine precursor, tyrosine, in phenylketonuria reduces the level of dopamine synthesis in the retina.

[^{3}H]L-Leucine uptake by TR-iBRB2 cells was Na^+-independent and inhibited by substrates and inhibitors of system L (Table 2). In particular, the degree of inhibition by substrates of LAT1,[9] D-leucine, D-phenylalanine, and D-methionine, was greater than that produced by the substrates of LAT2,[10,11] L-alanine and L-glutamate. System $b^{0,+}$, which is also an Na^+-independent transporter, mediates the transport of neutral and basic amino acids, such as L-leucine and L-arginine.[31] [^{3}H]L-Leucine uptake by TR-iBRB2 cells excludes the involvement of system $b^{0,+}$, since L-arginine produced no marked inhibition. However, the IC_{50} for L-phenylalanine (266 μM), L-tyrosine (1.90 mM), and L-tryptophan (467 μM) are large (Fig. 4), compared with the K_m for the transport of these amino acids via rat LAT1 (13 μM for L-phenylalanine and L-tyrosine and 19 μM for L-tryptophan).[32,33] Mouse LAT2 is also reported to exhibit

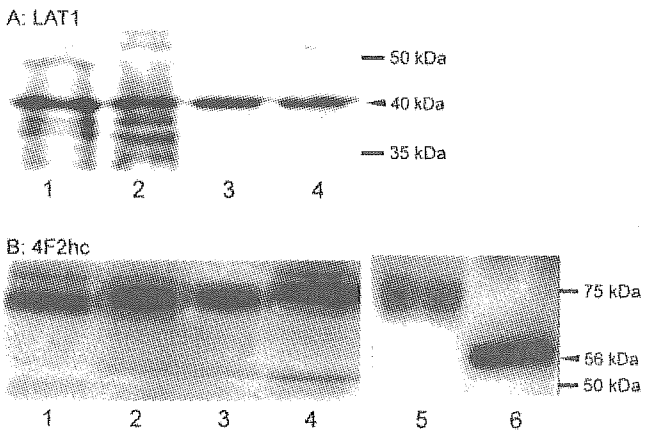

FIGURE 7. Immunoblot analysis of LAT1 (**A**) and 4F2hc (**B**). *Lane 1*: rat brain; *lane 2*: rat retina; *lane 3*: TR-iBRB2 cells; *lane 4*: primary cultured human retinal endothelial cells; *lane 5*: TR-iBRB2 cells without *N*-glycosidase F; *lane 6*: TR-iBRB2 cells with *N*-glycosidase F. Rat brain was used as a positive control.

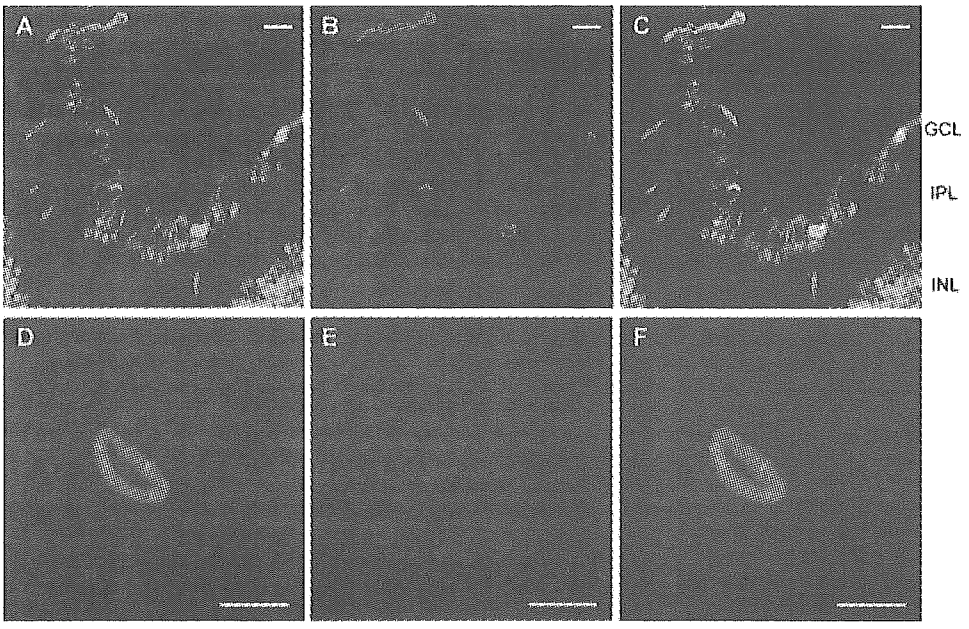

FIGURE 8. Localization of LAT1 in rat retinal capillary endothelial cells. The rat retina was stained with (**A**, **D**) anti-LAT1 antibody (*green*) and (**B**, **E**) anti-GLUT1 antibody (*red*). The images are merged in (**C**) and (**F**). LAT1 immunoreactivity was observed in retinal capillary endothelial cells as well as some other neural cells in the ganglion cell (GCL) and inner nuclear (INL) layers at lower magnification (**A**). Overlapped immunostaining of GLUT1 and LAT1 was observed at lower (**C**) and higher (**F**) magnifications. IPL, inner plexiform layer. Scale bar: (**A**–**C**) 20 μm; (**D**–**F**) 5 μm.

higher affinity transport for L-phenylalanine, with a K_m of 12 μM.[34] The corresponding kinetic parameters for rat LAT2-mediated transport of these amino acids have not been reported yet. Therefore, low- and high-affinity transport via LAT1 seems to take place in TR-iBRB2 cells, although nothing is presently known about the low-affinity process.

The efflux of [^{3}H]L-leucine from TR-iBRB2 cells was *trans*-stimulated by the extracellularly applied system L substrates, such as L-leucine, L-phenylalanine, L-tryptophan, and BCH (Fig. 5), supporting the view that LAT1 functions as an obligatory amino acid exchanger.[24] Therefore, LAT1 at the inner BRB requires intracellular substrate(s) to mediate the influx transport of L-leucine and other substrate amino acids from the blood. It has been reported that α-methylaminoisobutyric acid, which is a specific substrate of system A, is taken up in an Na^+-dependent manner into isolated bovine retinal capillaries,[35] suggesting that system A exists on the abluminal membrane of the inner BRB. At the blood–brain barrier, systems ASC, N, and A on the abluminal membrane mediate the Na^+-dependent uptake of neutral amino acids from the brain.[36–38] Although further studies are necessary to clarify the transport mechanism on the abluminal membrane of the inner BRB and identify neutral amino acids for the retina-to-blood efflux transport, the concentrative amino acid transport system(s) on the abluminal membrane accelerate the supply of intracellular substrates for LAT1 and the blood-to-retina transport of large neutral amino acids by LAT1 at the inner BRB.

Although the rat RVEC fraction and TR-iBRB2 cells express LAT1 and LAT2 mRNA (Figs. 6A, 6B), quantitative real-time PCR analysis clearly demonstrated that LAT1 is the main system L transporter in the RVEC fraction and TR-iBRB2 cells (Fig. 6D). Immunoblot analysis revealed that LAT1 protein is expressed in TR-iBRB2 cells and primary cultured human retinal endothelial cells (Fig. 7A), suggesting the expression of LAT1 at the inner BRB in rats as well as humans. Moreover, immunohistochemical analysis confirmed that LAT1 protein is localized in retinal capillary endothelial cells (Figs. 8A, 8D). The immunostaining image of LAT1 overlapped that of GLUT1 (Figs. 8C, 8F), which is known to be expressed in both the luminal and abluminal membranes of retinal capillary endothelial cells.[6,7] This observation is comparable with that at the blood–brain barrier, since LAT1 is reported to be localized at the luminal and abluminal membranes of brain capillary endothelial cells.[13] LAT1 immunoreactivity was also detected in other cells, especially in the inner nuclear layer (Fig. 8A), consistent with LAT1 mRNA expression in the non-RVEC fraction (Fig. 6D). Further studies are needed to identify those cells, apart from endothelial cells, expressing LAT1 in the retina. The expression of 4F2hc was also detected in the rat RVEC fraction, primary cultured human retinal endothelial cells, and TR-iBRB2 cells (Figs. 6C, 7B), as previously described for mRNA expression in TR-iBRB2 cells.[18] 4F2hc protein is reported to be a glycosylated protein[9] and the molecular weight of 4F2hc in TR-iBRB2 cells was reduced after deglycosylation treatment, indicating that 4F2hc in TR-iBRB2 cells is present as a glycosylated form. Taking these results into consideration, it appears that the heterodimer of LAT1 and 4F2hc is localized in retinal capillary endothelial cells and plays an important role in transporting L-leucine from the circulating blood to the retina across the inner BRB.

LAT1 mediates the transport of several essential amino acids, such as L-leucine, L-isoleucine, L-valine, L-histidine, L-methionine, L-phenylalanine, and L-tryptophan.[9] Therefore, LAT1-mediated essential amino acids must be supplied to the retina to synthesize retinal proteins. Moreover, LAT1-mediated branched-chain amino acids supplied to the retina are essential as nitrogen precursors of L-glutamate and GABA, which are the main excitatory and inhibitory neurotransmitters in the retina, respectively.[2,3] LAT1 also transports precursors of dopamine and serotonin, such as L-tyrosine and L-tryptophan. Dopamine is the main catecholamine in the retina and plays an essential role in the visual pathway as a neurotransmitter in amacrine and interplexiform cells.[39] Although serotonin synthesis in the retina has not been demonstrated, Chanut et al.[40] recently found that serotonin synthesis and its light–dark variation occur in the retina. Therefore, it is suggested that L-leucine supplied to the retina is converted to other retinal components, and then LAT1 at the inner BRB plays a physiological role in supplying precursors of proteins and neurotransmitters in the retina. Although the V_d of [^{3}H]L-leucine at 5 minutes (1.88 ± 0.14 mL/g retina) indicates that L-leucine uptake into the retina is apparently concentrative (Fig. 1), the leucine concentration in the rat retina (54 nanomoles/g retina)[41] is lower than that in rat plasma (84–160 μM).[27–29] This information implies that L-leucine supplied to the retina is converted to other retinal components. Moreover, it is speculated that the

impairment of LAT1 at the inner BRB limits neurotransmitter biosynthesis in the retina and markedly affects visual functions.

From a pharmacological viewpoint, LAT1 at the inner BRB could be useful for drug delivery into the retina. L-Dopa is the most widely used drug for Parkinson's disease, because L-dopa and its metabolite, 3-*O*-methyldopa, are transported through LAT1 at the blood–brain barrier.[12] [^{3}H]L-Leucine uptake by TR-iBRB2 cells is inhibited by 2 mM L-dopa and methyldopa (Table 2), supporting the possibility that L-dopa and methyldopa are transported by LAT1 at the inner BRB. Many patients with Parkinson's disease have blurred vision or other visual disturbances, which are reflected in the reduced retinal dopamine concentration and the delayed visual evoked potentials.[42] L-Dopa has been reported to reduce these delayed visual evoked potentials in Parkinson's disease.[43] Moreover, 2 mM gabapentin and 100 μM melphalan, neutral amino-acid–mimetic drugs, significantly inhibited [^{3}H]L-leucine uptake by TR-iBRB2 cells by 20% and 42%, respectively (Table 2). This result is consistent with the previous report that LAT1-mediated [^{3}H]L-phenylalanine transport is inhibited by gabapentin and melphalan with K_i of 340 and 49 μM, respectively.[33] Gabapentin has been shown to be an effective treatment in some patients with acquired pendular nystagmus.[44] Chemotherapy with melphalan is used in patients with retinoblastoma.[45] Therefore, it appears that LAT1 at the inner BRB plays a key role in transporting these drugs from the circulating blood to the retina and contributes to their pharmacological actions in the retina.

In conclusion, this is the first study to demonstrate the expression of LAT1 in retinal capillary endothelial cells. Although the responsible transporter for L-leucine at the inner BRB has remained unknown for a quarter of a century, we have now demonstrated that LAT1 is predominantly involved in blood-to-retina L-leucine transport at the inner BRB and seems to be closely involved in visual functions by supplying neurotransmitter precursors. These findings provide important information to improve our understanding of the physiological role of the inner BRB and drug delivery to the neural retina.

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