

Longitudinal changes in zinc transport kinetics, metallothionein and zinc transporter expression in a blood–brain barrier model in response to a moderately excessive zinc environment

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Abstract

A blood–brain barrier (BBB) model composed of porcine brain capillary endothelial cells (BCEC) was exposed to a moderately excessive zinc environment (50 $\mu\text{mol/L}$ Zn) in cell culture, and longitudinal measurements were made of zinc transport kinetics, ZnT-1 (*SLC30A1*) expression and changes in the protein concentration of metallothionein (MT), ZnT-1, ZnT-2 (*SLC30A2*) and Zip1 (*SLC39A1*). Zinc release by cells of the BBB model significantly increased after 12–24 h of exposure, but decreased back to control levels after 48–96 h, as indicated by transport across the BBB from both the abluminal (brain) and the luminal (blood) directions. Expression of ZnT-1, the zinc export protein, increased by 169% within 12 h, but was no longer different from controls after 24 h. Likewise, ZnT-1 protein content increased transiently after 12 h of exposure, but returned to control levels by 24 h. Capacity for zinc uptake and retention increased from both the luminal and the abluminal directions within 12–24 h of exposure and remained elevated. MT and ZnT-2 were elevated within 12 h and remained elevated throughout the study. Zip1 was unchanged by the treatment. The BBB's response to a moderately high zinc environment was dynamic and involved multiple mechanisms. The initial response was to increase the cells' capacity to sequester zinc with additional MT and to increase zinc export with the ZnT-1 protein. But the longer-term strategy involved increasing ZnT-2 transporters, presumably to sequester zinc into intracellular vesicles as a mechanism to protect the brain and to maintain brain zinc homeostasis.

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1. Introduction

Zinc has many critical functions in the brain that require its presence in precise concentrations [1]. Adequate zinc nutrition is essential for optimal neurological development and function [1,2]. Zinc excess has a profound negative effect on neurological cells, which are highly susceptible to extremes in extracellular zinc concentrations [3]. For instance, a brief exposure of cortical cells to high levels of zinc in culture led to widespread neuronal degeneration [4] and oxidative-stress-related neuronal death [5]. An elevated concentration of zinc induced the aggregation of the amyloid- β protein in senile plaques of Alzheimer's disease [6], and the

senile plaques contained elevated concentrations of zinc [7]. It seems that zinc may protect against amyloid- β toxicity at low concentrations, but excess zinc may enhance amyloid- β toxicity [8,9]. Extracellular zinc in the brain has also been implicated in the development of cerebral amyloid angiopathy [10] and advanced Alzheimer's disease [11]. There are several potential mechanisms by which an impairment in brain zinc homeostasis might influence the progression of Alzheimer's disease and other neuropathologies [3,12].

The blood–brain barrier (BBB) is a specialized system of capillary endothelial cells that protects the brain from harmful substances in the bloodstream while supplying the brain with the required nutrients for proper function [13]. Zinc enters the brain through the BBB [14], even though the BBB is relatively impermeable to zinc [15]. Prevailing evidence indicates that there are specific zinc transport sites on the luminal surface of brain capillary endothelial cells (BCEC) [16]. Therefore, it is reasonable to anticipate that the

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BBB has a role in maintaining brain zinc homeostasis. Limited evidence on this includes enhanced uptake by the brains of zinc-deficient rats [17,18] and enhanced transport of zinc across an in vitro model of the BBB that was exposed to zinc-deficient conditions [19]. Less is understood about brain zinc homeostasis during zinc excess.

Cells rely upon a complex and dynamic set of molecular mechanisms to maintain zinc homeostasis through the regulated expression of proteins for zinc import, zinc export and zinc sequestration [20,21]. Additionally, zinc homeostatic mechanisms appear to be tissue specific, as cells from various tissues rely upon differential strategies such that specific transporters are used in certain tissues [22,23], and the expression of these transporters may vary with zinc status and time [23,24]. Since the brain's neurons are highly vulnerable to zinc excess, we hypothesized that the BBB would be the first line of defense against neurological injury during periods of excessive zinc intake. We found that the BBB could adjust zinc transport rates to the prevailing zinc status, thereby protecting brain cells from zinc toxicity. We also measured a variety of putative mediators of zinc homeostasis that we thought were most likely to be involved in the maintenance of brain zinc homeostasis: metallothionein (MT), ZnT-1 (*SLC30A1*), ZnT-2 (*SLC30A2*) and Zip1 (*SLC39A1*). This is the first report of longitudinal changes in any zinc transporter of the BBB.

2. Materials and methods

2.1. Cell isolation

BCEC were isolated from Yucatan miniature swine (*Sus scrofa*) as previously described [19,25]. BBB models were constructed as previously described [19] by subculturing 4- to 5-day-old primary cultures of BCEC at 85,000 cells/cm² onto permeable 12-mm Transwell cell culture inserts with 0.4 µm pore size (no. 3401; Corning Costar, Park Ridge, IL). The inserts were suspended between two chambers of culture medium, and BCEC formed an endothelial barrier analogous to the BBB. For mRNA expression studies, BCEC were seeded at 12,000 cells/cm² into T-25 tissue culture flasks (Corning Costar). All culturing surfaces were fibronectin coated (2 µg/cm²).

2.2. BBB model validation

BCEC isolations were monitored daily for endothelial characteristics, including density-inhibited growth and recognizable endothelial cell morphology (a slightly ellipsoid nucleus surrounded by a cigar-like plasma membrane) [26]. BCEC tested positive for acetylated low-density-lipoprotein uptake [27] and Factor-VIII-related antigen [28], which are classic endothelial cell characterization assays. Transendothelial electrical resistance (TEER) of the BBB models was recorded daily as a physiological measure of monolayer integrity and barrier function [29]. TEER reflects impedance of the passage of small ions through the

physiological barrier and is widely recognized as one of the most accurate and sensitive measures of BBB integrity [29,30]. A decrease in TEER reflects an increase in permeability and a loss of barrier function. The TEER of the BBB model was recorded by an Endohm chamber connected to an EVOM resistance meter (World Precision Instruments, Inc., Sarasota, FL). The TEER of each BBB model was calculated by subtracting the TEER of a permeable Transwell membrane without BCEC and is reported as ohm × centimeter squared.

2.3. Induction of altered zinc status

Growth medium was composed of 2% fetal bovine serum and 13% platelet-poor horse serum in minimum essential medium with Earl's salts, L-glutamine and bicarbonate, plus 100 mg of heparin, 50 mg of endothelial cell growth supplement, 5 mg of amphotericin B and 50 mg gentamicin/L. The zinc concentration of the growth medium was determined by flame atomic absorption spectrophotometry to be 3 µmol/L. The in vitro induction of moderately excessive zinc environments was achieved by adding ZnCl₂ to the growth medium to raise the zinc concentration to 50 µmol/L. Longitudinal measurements were made at six time points (0, 12, 24, 48, 72 and 96 h). The experiments ended with simultaneous measurements being made in all treatment groups, so treatment beginnings were staggered. For example, the 96-h group was switched from the growth medium to the high-zinc medium 2 days after seeding; 24 h later, the medium was switched for the 72-h group. The 0-h treatment group was never switched to the high-zinc medium and was considered as the control group. Fresh medium was applied every 48 h in all groups.

2.4. Analysis of MT

Assessment of MT content was conducted using the cadmium–hemoglobin affinity assay [31,32] as previously described. Protein concentration was measured with bicinchoninic acid [33]. MT is reported in picomoles per milligram of cellular protein.

2.5. Analysis of zinc uptake and transport

Zinc uptake and retention by — as well as zinc transport across — the BBB models were measured as described [19]. The medium used to measure the kinetics of zinc transport in all treatments of all experiments was the growth medium. Since this test medium was the same for all treatments, all differences in the rates of zinc transport were due to differences in the cells because of their culturing environments. Briefly, luminal and abluminal growth media were removed. Cell monolayers on Transwell inserts were briefly rinsed four times in HEPES buffer at 37°C, followed by the application of ⁶⁵Zn-labeled (3.7 × 10⁴ Bq/ml) growth medium on one side and nonlabeled control medium on the other side. For the measurement of uptake and transport from the “blood” side of the cells, the labeled medium was applied to

the luminal chamber; for the measurement of uptake and transport from the “brain” side of the cells, the labeled medium was applied to the abluminal chamber. Cells were incubated for 60 min on an orbital shaker at 30 rpm inside an incubator at 37°C. Media were collected for analysis of radioactivity, and the results were converted to picomoles of Zn based on the specific activity of the labeled transport medium. [Zinc transport across the BBB was expressed as pmol Zn/(h×cm² cell monolayer).] Zinc uptake and retention by BCEC during the 60-min incubation were estimated by briefly rinsing the Transwell insert twice in HEPES/EDTA buffer and then rinsing six times in HEPES buffer, and removing the membrane with cells for analysis of radioactivity. [The results were converted to pmol Zn/(h cm² cell monolayer) based on the specific activity of the radiolabeled incubation medium.] TEER was measured immediately before and after all zinc transport measurements to ensure that our measurements did not impair the BBB model’s integrity.

2.6. Identification of the porcine ZnT-1 gene

The BCEC in our BBB model were derived from miniature swine (*S. scrofa*). Although miniature swine are commonly used in biomedical research, their genome remains relatively unknown. Therefore, we first identified the gene for ZnT-1 (*SLC30A1*) in the porcine genome orthologous to the human gene. The moderately excessive zinc medium was applied to primary cultures of BCEC for 18 h to induce the transcription of the zinc efflux transporter. BCEC were lysed, total RNA was isolated with TRIzol reagent (Invitrogen Life Technologies) and its quality was established by agarose gel electrophoresis. The concentration was determined through spectrophotometry. Double-stranded cDNA was generated using the Creator SMART cDNA Library Construction Kit (Clontech, Palo Alto, CA). At that point, polymerase chain reaction (PCR) with degenerate primers was used to isolate zinc transporter transcripts. ZnT-1-specific degenerate primers were designed by comparing translated sequences of mRNA from available species (human, rat, mouse and frog) for ZnT-1. These sequences were obtained from GenBank and aligned using DNA Star software (DNASTAR, Inc., Madison, WI) such that conserved domains between species could be identified. A 626-bp PCR product representing a partial coding sequence of ZnT-1 was identified and sequenced. This partial coding sequence was then used as a query in a BLAST search of the National Center for Biotechnology Information trace file archives of shotgun genomic clones of *S. scrofa*. Matching clones were assembled using Sequencer 4.6 (Gene Code Corporation, Ann Arbor, MI).

2.7. Analysis of ZnT-1 expression

Once the mRNA transcript of the porcine ZnT-1 had been sequenced, highly specific primers and probes were designed for real-time PCR expression studies. The BBB models were

maintained in the moderately excessive zinc environment for the six durations (0, 12, 24, 48, 72 and 96 h). Total RNA was isolated using the GenElute Mammalian Total RNA Kit (Sigma Chemical Co., St. Louis, MO), treated with DNase I and quantified with the RiboGreen RNA Quantitation Reagent and Kit (Molecular Probes, Inc., Eugene, OR). The SuperScript III First-Strand Synthesis System for RT-PCR (Invitrogen Life Technologies) was used for making cDNA. The primers and probe for real-time PCR were designed using Primer Express software (Applied Biosystems) based upon the sequence of the porcine ZnT-1 gene (GenBank accession no. AY918800), specifically for use with *TaqMan* polymerase. The polymerase, primers and probe were ordered from Applied Biosystems (forward primer: AGACCATTAAGGACGTTTTCCATAA; reverse primer: GACTTAGAGCCTACGCTAGCAAACCTC; probe: CACGGAATTCACGCTACCACCATTCA).

The samples were run in the GenAmp 5700 thermal cycler (Applied Biosystems) for 40 cycles of the following program: 95°C for 15 s, 55°C for 30 s and 65°C for 1 min. The probe was affixed with a fluorescent dye, 6-carboxyfluorescein, at the 5' end and with a quenching molecule, 6-carboxytetramethylrhodamine, at the 3' end. Data were adjusted for PCR efficiency with the equation, $\ln T = k - C_t \ln(1 + E)$, where T is template concentration, C_t is the critical cycle, k is a constant specific to the GenAmp 5700 thermal cycler and E is efficiency.

2.8. Relative concentrations of ZnT-1, ZnT-2 and Zip1 transporters

Cell lysates were collected from the BBB models following treatment, denatured in Laemmli buffer containing β-mercaptoethanol (50 g/L) and boiled for 4 min. Western blot analysis was performed on equal amounts of protein (10 μg) diluted 1:1 in Laemmli sample buffer and resolved by sodium dodecyl sulfate–polyacrylamide gel electrophoresis (10% Tris–glycine and 0.2% sodium dodecyl sulfate). Proteins were transferred to a nitrocellulose membrane for 90 min at 100 V. The membrane was then blocked overnight at 4°C in 5% nonfat dry milk in PBS-T (0.1% Tween-20 in phosphate-buffered saline). After the membranes had been washed thrice in PBS-T, they were incubated in a 1:1000 dilution of primary antibody for 45 min. Primary antibodies against ZnT-1 (GTRPOVHSGKE), ZnT-2 (GKFNHFTMTI-QIESYSEDMKSCQECQGPSE) and Zip1 (SGPSPLEE-TRALLGTVNGGPPQHWHDGPGVQPASGAPATPSA) were generously provided by Kelleher and Lonnerdal [34]. The ZnT-1 and ZnT-2 antibodies were generated in rabbits by Zymed Laboratories (San Francisco, CA), and Zip1 antibodies were generated in chickens by Jackson Immuno-Research (West Grove, PA). After the membranes had again been washed thrice in PBS-T, they were incubated in secondary antibodies: for ZnT-1 and ZnT-2, alkaline phosphatase goat anti-rabbit IgG (1:2000 in PBS-T); for Zip1, alkaline phosphatase goat anti-chicken IgY (1:2000 in PBS-T). After four washes in PBS-T, the membranes were

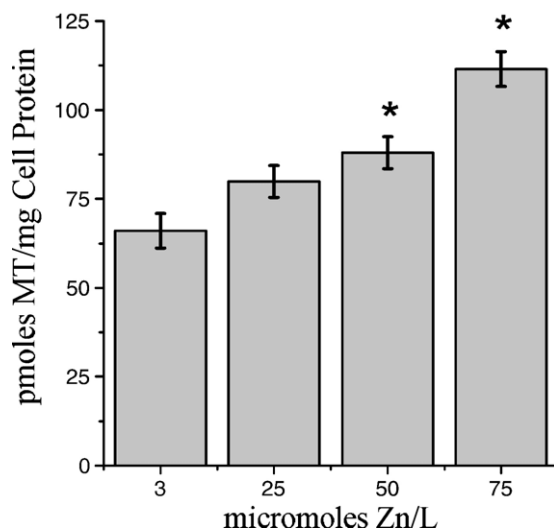


Fig. 1. Influence of zinc status on the MT content of BCEC. Cells were supported in treatment media with different zinc concentrations for 12 h prior to the measurement of MT. Columns are presented as mean±S.E.M. ($n=7$). Columns with asterisks are significantly different from controls at $P<.01$.

incubated in chemiluminescent substrate (Biomolecular Probes, Eugene, OR) for 5 min then exposed to Kodak BioMax MR photographic film for 3–7 min for visualization, and the film was then developed using Konica SRX-101. Densitometric analysis was performed using UN-SCAN-IT gel software (version 6.1; Silk Scientific, Orem, UT). Controls for nonspecific binding of the antibodies were performed with normal serum; none was detected. Membranes were stripped and reprobed for β -actin as a loading control. Preliminary studies demonstrated no significant effect of our high-zinc treatment on the β -actin content of BCEC.

2.9. Statistical analysis

Studies were analyzed as a randomized complete block, with each experiment as a block and with replicates over time as the block [35]. Analysis of variance and nonlinear fitting of the experimental data were performed with Systat, version 9 (Systat, Chicago, IL). Data from replications of the same experimental design were pooled if they passed the test of homogeneity. Fisher's Protected Least Significant Difference test was used for pairwise comparisons of multiple groups. Dunnett's test was used for the comparison of multiple groups with a control group. Differences were considered significant at $P<.05$.

Data from real-time PCR allowed the comparison of the relative difference between two samples. Each of the five treatments was compared to the control sample for that experiment. In each experiment, the amount of ZnT-1 transcripts in the control sample was set as a constant (1). The amount of ZnT-1 transcripts in each of the treated samples was calculated as a ratio of the control or as a ratio of 1. PCR results are presented as the mean±S.D. of

four distinct experiments. The amount of zinc transporter protein measured by Western blot analysis was similarly calculated as a ratio of 1. A modified Dunnett's test for multiple comparisons to a constant was performed to assess statistical significance.

2.10. Reagents

Reagents were obtained through Sigma Chemical Co., unless otherwise stated in the text.

3. Results

The moderately excessive zinc environment had no significant effect on the growth or morphology of BCEC. We conducted several iterations of preliminary experiments in order to establish culturing conditions that would significantly alter zinc status without discernable alterations in cell health, which we henceforth refer to as 'moderate zinc excess.' We selected cellular MT concentration as a sensitive indicator of high cellular zinc status [36]. The lowest zinc concentration that would consistently induce an elevation of MT after 12 h of exposure was 50 $\mu\text{mol/L}$ Zn (Fig. 1). This was in agreement with previous studies from our laboratory [32]. Thus, 50 $\mu\text{mol/L}$ was chosen as the zinc concentration

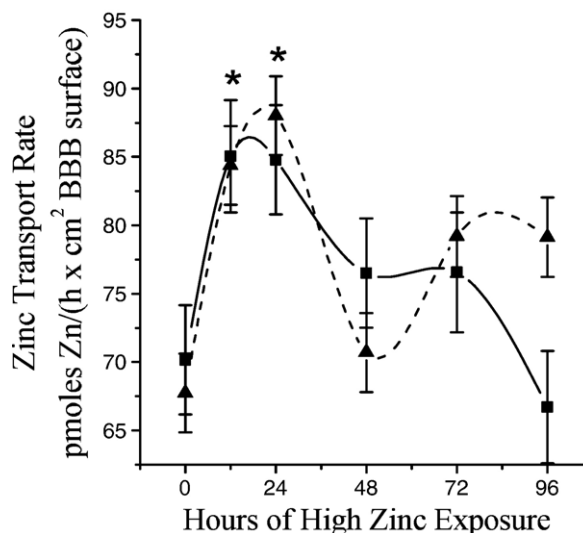


Fig. 2. Longitudinal changes in the rate of zinc transport across the BBB model exposed to a moderately excessive zinc environment. The rate from the luminal (blood) side to the abluminal (brain) side is represented by the solid line and square symbols. The rate from the abluminal (brain) side to the luminal (blood) side is represented by the dashed line and triangle symbols. Release from BBB cells is presumed to be the rate-limiting step. BBB models were supported in the control medium (3 $\mu\text{mol/L}$ Zn) and then switched to the treatment medium (50 $\mu\text{mol/L}$ Zn) for the designated durations; the zinc transport rate was measured during a 60-min incubation using radiolabeled control medium. Data are expressed as the mean±S.E.M. of combined data from three experiments ($n=18$). The rates in both directions were significantly greater ($P<.05$) at 12 and 24 h of exposure to the moderately high zinc environment, compared to the control group at 0 h of exposure.

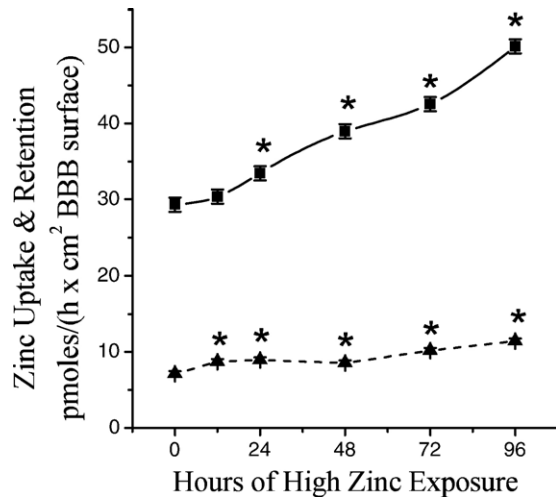


Fig. 3. Longitudinal changes in the rate of zinc uptake and retention by BBB models exposed to a moderately excessive zinc environment. The rate from the abluminal (brain) side is represented by the solid line and square symbols. The rate from the luminal (blood) side is represented by the dashed line and triangle symbols. Cells were supported in the control medium ($3 \mu\text{mol/L Zn}$) and then switched to the treatment medium ($50 \mu\text{mol/L Zn}$) for the designated durations; zinc uptake was measured during a 60-min incubation using radiolabeled control medium. Data are expressed as mean \pm S.E.M. from three experiments ($n=18$). Symbols with an asterisk are significantly different from controls ($3 \mu\text{mol/L}$) at $P<.05$.

for use in subsequent studies of moderate zinc excess. TEER was selected as the most sensitive indicator of BCEC function, and it was not affected by treatment with $50 \mu\text{mol/L Zn}$.

Based on our previous work [19], we hypothesized that zinc homeostatic response would be multifaceted and dynamic, varying over time. Therefore, we conducted longitudinal experiments that measured the kinetics of zinc transport in both directions across the BBB model after different times of exposure to the moderately high zinc environment. Zinc transport was measured simultaneously in all treatments with radiolabeled incubation media that had a similar zinc concentration ($3 \mu\text{mol/L Zn}$) across all treatments, independent of the media in which cells were cultivated. Therefore, differences in zinc transport by the cells reflect molecular changes within the cells in response to the treatments. In cells treated with the moderately high zinc medium for 12 and 24 h, the rate of zinc transport across the BBB from the abluminal (brain) side to the luminal (blood) side was increased by 20% (Fig. 2). However, zinc transport was no longer elevated after 48–96 h. In fact, the zinc transport rate at 96 h appeared to trend downward toward a rate slower than the rate for controls. Zinc transport across the BBB from the luminal (blood) chamber to the abluminal (brain) chamber increased by 25% at 12 h and by 30% at 24 h of moderately high zinc exposure (Fig. 2). However, zinc transport was no longer elevated after 48–96 h. The cells of the BBB responded to the excess zinc environment by transiently increasing their ability to export zinc in both directions, presumably as a means of survival. They

subsequently resumed a control level of zinc export capacity. Thus, adjusting zinc export was not a principal long-term homeostatic mechanism.

Zinc uptake and retention within the BBB models were examined from both directions. The capacity for zinc uptake and retention from the luminal (blood) side of the BBB was significantly higher than that for controls after only 12 h of exposure to the moderately high zinc environment (Fig. 3) and increased by 60% after 96 h. The capacity for zinc uptake and retention from the abluminal (brain) side of the cells was not different after 12 h of excess zinc exposure (Fig. 3), but significantly increased after 24 h and increased by 70% after 96 h. The ability to take zinc from the brain side was consistently about four (3.5–4.6) times greater than from the blood side. This could facilitate the ‘mopping up’ of any excess zinc from the brain.

We hypothesized that the cells of the BBB retain zinc in complex with MT. We observed that the MT content increased by 36% within 12 h of exposure to the moderately high zinc environment (Fig. 4). MT remained elevated throughout the study but trended back downward toward control levels as the duration of exposure lengthened.

We next wanted to investigate whether the zinc efflux transporter ZnT-1 was involved in the cellular response to excess zinc. Since no porcine zinc transporters have been identified to date, it was first necessary to isolate and sequence the porcine ZnT-1 gene. Degenerate primers were used to amplify a 626-bp product from mRNA (GenBank accession no. AY918800). Subsequent comparison to genomic sequences identified the ZnT-1 coding region matching this partial cDNA. The sequence has a 92% homology to human ZnT-1 mRNA and an 82% homology to

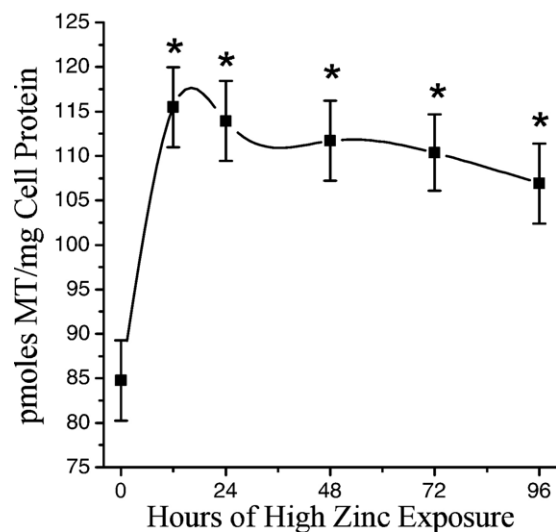


Fig. 4. Longitudinal changes in the MT content of a BBB model exposed to a moderately excessive zinc environment. MT was measured after cells had been supported in the control medium ($3 \mu\text{mol/L Zn}$) and then switched to the treatment medium ($50 \mu\text{mol/L Zn}$) for the designated durations. Data are expressed as mean \pm S.E.M. from two experiments ($n=9-10$). Symbols with asterisks are significantly different from controls at $P<.05$.

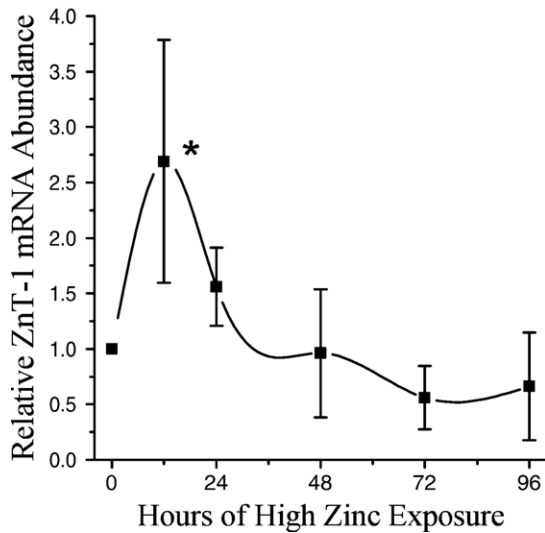


Fig. 5. Longitudinal changes in the relative amounts of ZnT-1 mRNA in a BBB model exposed to a moderately excessive zinc environment. Cells were supported in the control medium (3 $\mu\text{mol/L}$ Zn) and then switched to the treatment medium (50 $\mu\text{mol/L}$ Zn) for the designated durations; porcine ZnT-1 mRNA was measured using real-time PCR. Data points represent the mean ratio \pm S.D. of ZnT-1 transcripts in the 12-, 24-, 48-, 72- and 96-h samples as compared to controls in each of the four experiments. Only the 12-h sample exhibited a statistically significant difference from control at a confidence level of $P < .05$.

rat ZnT-1 mRNA. Real-time PCR was used to measure the influence of a moderately excessive zinc environment on the ZnT-1 mRNA content of BCEC (Fig. 5). ZnT-1 mRNA expression was 169% greater ($P < .05$) than controls after 12 h, but declined back to control levels by 24 h and trended lower after that.

We identified two partial gene sequences that corresponded to two exons of the human ZnT-1 gene. Fig. 6 displays an alignment of the amino acid sequences of the two porcine exons with their corresponding human sequences. They share a 94% amino acid identity. Thus, we had confidence in the antibody against ZnT-1 (generously provided by Kelleher and Lonnerdal), even though we were unable to extend the sequence through the region of the peptide used to generate the antibody. When we exposed the BBB models to the moderately high zinc environment, there was a similarly transient increase in ZnT-1 protein after 12 h (Fig. 7). The relative amount of ZnT-2 was increased after 12 h and remained elevated throughout 96 h of exposure, while the amount of Zip1 transporter protein was not different at any time point studied (Fig. 7).

4. Discussion

There is a concern that elevated concentrations of zinc in the brain contribute to the progression of Alzheimer's disease and other neuropathologies [3,12]. Zinc supplements are being consumed in amounts that exceed the recom-

mended dietary allowance [37]. Yet, very little is known about whether the brain can withstand these excesses. The current study investigated whether the BBB protects the brain from excess zinc in the blood. The BBB model responded dynamically to the moderately high zinc environment in a manner consistent with a strategy to avoid excessive zinc accumulation in the brain. The cells of the BBB initially increased their ability to export zinc with a transient increase in the zinc export protein ZnT-1, which might be interpreted as self-protective. This transient response was followed by a more altruistic strategy that enhanced the BBB's ability to sequester zinc — an ability that was four times greater from the BBB surface facing the brain than from the surface facing the blood. This coincided with an increase in MT and ZnT-2 proteins in the BBB, which bind zinc intracellularly and pump zinc into intracellular vesicles, respectively. This enhanced ability to uptake and sequester zinc from the brain is presumably aimed to enhance the BBB's ability to maintain brain zinc homeostasis.

An in vitro model of the BBB enabled us to exquisitely manipulate the environment and to precisely measure molecular changes in brain zinc homeostasis. The longitudinal nature of this project required a moderately excessive zinc environment that would induce cellular responses while being tolerated by the cells for 4 days. We

Exon 1:

Human: MGCWGRNRGRLLCMLALTFMFMVLEVVSRVTSSLAMLS
Porcine: -----L-----A

Human: SLAMLSDSFHMLSDVLALVVALVAERFARRTHATQKNTFGW
Porcine: -----

Human: IRAEVMGALVNAIFLTGLCFAILLEAIERFIEPHEMQQLVVL
Porcine: -----V-----

Human: GVGVAGLLVNVLGLCLFHHHSGFSQDSGHHSHGGHGHG
Porcine: S-----EG-GA-----

Human: HGLPKG
Porcine: -----A-----

Exon 2:

Human: RAGQLNMRGVFLHVLGDALGSVIVVNALVFYFSWKGCSE
Porcine: -----F-----R-----P--

Human: GDFCVNPFDPCKAFVEIINSTHASVYEAGPCWVLYLDPTL
Porcine: -EM-----V-----T-----

Human: CVVMVCILLYTTYPLLKESALILLQTPVKQIDIRNLIELRNVE
Porcine: --- -----R-----D---

Human: GVEEVHELHVWQLAGSRIIATAHIKCEDPTSYMEVAKTIKDV
Porcine: -----A-----Q-----

Human: FHNHGIHATTIQPEFASVSGSKSSVPCELACRTQCALKQC
Porcine: -----

Fig. 6. Two partial fragments of the porcine ZnT-1 gene were translated into their corresponding amino acid sequences and aligned with their counterparts from the human ZnT-1 gene. The porcine and human sequences shared a 94% amino acid identity. Regions of similarity are indicated by dashes on the porcine sequence; discrepancies are indicated in the porcine translation.

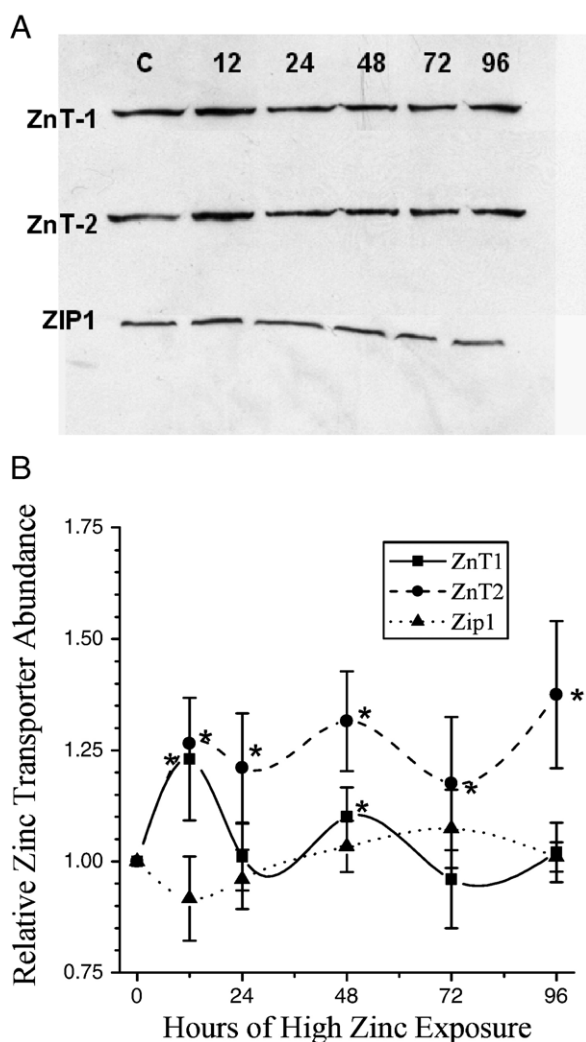


Fig. 7. (A) Representative Western blot analyses of ZnT-1, ZnT-2 and Zip1 protein levels in BBB models exposed to a moderately excessive zinc environment in response to high zinc at different times throughout a 96-h period. (B) Longitudinal changes in the relative amounts of ZnT-1, ZnT-2 and Zip1 in a BBB model exposed to a moderately excessive zinc environment. Cells were supported in the control medium (3 $\mu\text{mol/L}$ Zn) and then switched to the treatment medium (50 $\mu\text{mol/L}$ Zn) for the designated durations. The relative protein concentrations were determined by Western blot analysis. Data points represent the mean ratio \pm S.D. of each protein in the 12-, 24-, 48-, 72- and 96-h samples as compared to the control in each of the three experiments. Asterisks indicate that a mean exhibited a statistically significant difference from control at a confidence level of $P < 0.05$.

adopted 50 $\mu\text{mol/L}$ because this amount consistently induced a significant increase in cellular MT without any discernable injury to the cells, including having no impact on BBB permeability as determined by TEER. The BBB model included capillary endothelial cells derived from pig brains. Plasma zinc is 12 $\mu\text{mol/L}$ in pigs, but can rise to 28 $\mu\text{mol/L}$ after chronic zinc supplementation [38]. Human plasma zinc is typically 15 $\mu\text{mol/L}$, but can rise up to 183 $\mu\text{mol/L}$ during acute zinc toxicity [39].

Endothelial cells that form the walls of blood vessels are analogous to epithelial cells, possessing luminal and

abluminal surfaces that are functionally distinct. Since tight intercellular junctions between endothelial cells are relatively impermeable to zinc, passage across the BBB would necessitate transport through both luminal and abluminal cellular membranes. Transport across could be regulated at either location or at some intracellular location. Our evidence indicates that zinc transport across the BBB initially increased in both the luminal and the abluminal directions, but declined back toward control values within 48 h of high zinc exposure. This initial increase in transport is counterproductive to the maintenance of brain zinc homeostasis, but may be explained as the cells' efforts at self-preservation. This increase coincided with a transient increase in the zinc export protein ZnT-1 at 12 h of exposure to the moderately excessive zinc environment. This protein also increased in response to zinc toxicity in cultured neurons [40]. Conversely, ZnT-1 decreased in the brain tissues of rat pups on a zinc-deficient diet [18]. ZnT-1 may be responsible for the release of zinc from the epithelial cells of the small intestine, where its expression correlated with changes in MT [41,42] during high zinc exposure. However, the subsequent decline in ZnT-1 expression and ZnT-1 protein content observed in our longitudinal study indicates that its enhanced role in the BBB is transient.

The capacity for zinc uptake significantly increased from both directions within 12–24 h and continued to increase with continued exposure. While the capacity to release zinc was remarkably similar in each direction, the capacity to take up and retain zinc from the brain side was consistently four times greater than from the blood side. Since zinc transport was measured with the same (control) growth medium for all treatments, no matter how long was the exposure to the high-zinc environment, differences in transport were due to changes in the cells resulting from their treatments. It is difficult to discern which particular step in the transport process through the cell is most affected based solely on kinetic evidence. Since uptake was measured during a 60-min incubation (simultaneously with transport through the BBB), we did not measure the initial velocity of uptake. Initial velocity is best measured during a 10-min incubation [43], since a significant amount of the zinc taken up from one side already exits the other side within 20 min [19]. Thus, 'uptake' in our experimental design also includes retention.

After 48 h (48–96 h) of exposure to the moderately high zinc environment, the capacity for zinc transport across the BBB in either direction was no longer different from controls and trended lower, while zinc uptake and retention continued to increase from both directions. This is in agreement with our previous study [19], which found an increase in zinc uptake into the cells of the BBB but a decline in transport across the BBB when it was exposed to high zinc for 5 days (120 h, as compared to 96 h in the present study). The prevailing evidence indicates that zinc 'retention,' rather than the capacity for 'uptake,' was the component that increased. A high-zinc environment also did not influence the rate of zinc uptake (measured as initial velocity) of bovine arterial

endothelial cells [44]. In agreement with this observation, Zip1 was not significantly changed in the BBB models throughout this study. Zip1 was critical in responding to zinc deficiency in pregnant mice but was dispensable when zinc was replete [45]. The overall conclusion is that the cellular response to zinc deficiency was an increase in zinc importers without affecting exporters. The response to zinc excess was an increase in zinc sequestration and zinc exporters; it does not appear to alter the number of zinc importers (at least not Zip1).

MT and ZnT-2 were the zinc proteins that remained elevated after their initial increase within 12 h of the moderately high zinc exposure. However, the MT concentration trended downward toward control levels during the 4 days of chronic exposure. MT is widely recognized as an intracellular protein that binds zinc and other divalent cations to protect cells when their concentrations become elevated [20]. The procedure used for measuring MT was the Cd-binding assay of Eaton and Cherian [31]; thus, it is possible that some Cd-binding proteins other than MT were elevated, although we are unaware of other Cd-binding proteins that are induced by chronic zinc exposure. ZnT-2 has been localized to the membranes of intracellular vesicles in BHK cells [46] and pancreatic acinar cells [47], where ZnT-2 is presumed to function by transporting zinc from the cytosol into the vesicle (zincosome) for sequestration [21]. MT and ZnT-2 presumably perform a similar function in the cells of the BBB, sequestering zinc that has been withdrawn from the brain.

Thus, after an initial period of self-preserving enhanced zinc extrusion, the cells of the BBB attempted to maintain brain zinc homeostasis by increasing their ability to take up zinc from the brain (and the blood) and to sequester the zinc into intracellular vesicles and/or bind it with MT.

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