Special Section on New Era of Transporter Science: Unraveling the Functional Role of Orphan Transporters—Minireview

Amino Acid Solute Carrier Transporters in Inflammation and Autoimmunity

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ABSTRACT

The past decade exposed the importance of many homeostasis and metabolism related proteins in autoimmunity disease and inflammation. Solute carriers (SLCs) are a group of membrane channels that can transport amino acids, the building blocks of proteins, nutrients, and neurotransmitters. This review summarizes the role of SLCs amino acid transporters in inflammation and autoimmunity disease. In detail, the importance of Glutamate transporters SLC1A1, SLC1A2, and SLC1A3, mainly expressed in the brain where they help prevent glutamate excitotoxicity, is discussed in the context of central nervous system disorders such as multiple sclerosis. Similarly, the cationic amino acid transporter SLC7A1 (CAT1), which is an important arginine transporter for T cells, and SLC7A2 (CAT2), essential for innate immunity. SLC3 family proteins, which bind with light chains from the SLC7 family (SLC7A5, SLC7A7, and SLC7A11) to form heteromeric amino acid transporters, are also explored to describe their roles in T cells, Natural Killer (NK) cells, macrophages, and tumor immunotherapies. Altogether, the link between SLC amino acid transporters with inflammation and autoimmunity may contribute to a better understanding of the underlying mechanism of disease and provide novel potential therapeutic avenues.

SIGNIFICANCE STATEMENT

In this review, we summarize the link between SLC amino acid transporters and inflammation and immune responses, especially SLC1 family members and SLC7 members. Studying the link may contribute to a better understanding of related diseases and provide potential therapeutic targets useful to the researchers who have interest in the involvement of amino acids in immunity.

Introduction

Nearly half of all deaths worldwide are attributed to chronic inflammatory conditions (Furman et al., 2019). In fact, one in every five Americans suffers from at least one chronic inflammatory condition and 3%–5% of an autoimmunity disorder (Wang et al., 2015). Traditionally, inflammatory and metabolic diseases were often approached separately, but the past decades have highlighted the importance of metabolic dysbiosis in chronic inflammation and autoimmunity disorders (Pitt et al., 2000; Sospedra and Martin, 2005; Compton and Coles, 2008). For example, multiple sclerosis (MS) is exacerbated by excessive glutamate transport and excitotoxicity, mediated by SLC proteins. Similarly, L-arginine transport, also mediated by SLCs, regulates multiple innate inflammatory mechanisms such as arginase-1 activity and inducible nitric oxide synthase (iNOS, NOS2).

The SLC superfamiliy is a large group of membrane transporters with over 65 families and more than 400 members. SLCs play important roles in nutrient and metabolic sensing (Chen et al., 2019; Zhang et al., 2019) and metabolic regulation of immune cells (Song et al., 2020). Structurally SLCs can be tremendously diverse with a myriad of substrates, and although several SLCs act as drug transporters (Liang et al., 2019), the authors declare that there are no actual or perceived conflicts of interest with the contents of this article.

1L.S. and Q.L. contributed equally to this work.

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ABBREVIATIONS: ASC, alanine serine cysteine; CAT, cationic amino acid transporter; CCL5, chemokine (C-C motif) ligand 5; CD, Cluster of differentiation; c-Myc, transcriptional regulator Myc-like; CNS, central nervous system; CX, connexin; EAAT, excitatory amino acid transporter; EAE, experimental autoimmune encephalomyelitis; GS, glutamine synthetase; HERV, human endogenous retrovirus; HIV, human immunodeficiency virus; IBD, inflammatory bowel disease; IFN, interferon; IL, interleukin; iNOS, NOS2, inducible nitric oxide synthase; LAT, L-type amino acid transporter; LPI, lysine-preferring agency; LPS, lipopolysaccharide; MDSC, myeloid-derived suppressor cell; MS, multiple sclerosis; mTORC1, mechanistic target of rapamycin complex 1; NF-κB, nuclear factor kappa B; NK, Natural Killer; NO, nitric oxide; SLC, solute carrier; TCR, T cell receptor; TLR, Toll-like receptor; TNF-α, tumor necrosis factor α; UC, ulcerative colitis; XAG system, excitatory amino acid transporter; y+ system, Na+-Independent Cationic Amino Acid Transporter; y−L, lysine-prefering agency.
and SLC1A5 (ASC transporter 2) (Kanai et al., 2013). The X-amino acid transporters of the SLC1 family, SLC1A4 (ASC transporter serine cysteine (ASC) system. The ASC system includes the two neutral amino acid transporters (EAATs, also known as system X-

<table>
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<th>Substrates</th>
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<th>Relevant Molecular Mechanisms</th>
<th>Sequence Accession ID</th>
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<tr>
<td>SLC1A1</td>
<td>EAAC1, EAAC3</td>
<td>System X\textsubscript{AG}</td>
<td>Glutamate, asparagine</td>
<td>C/Na\textsuperscript{+}, H\textsuperscript{+}, and k\textsuperscript{+}</td>
<td>Brain (neurons), lung, colorectal, kidney, liver, heart, placenta</td>
<td>IFN-\beta production; NF-\kappa B pathway</td>
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<td>C/Na\textsuperscript{+}, H\textsuperscript{+}, and k\textsuperscript{+}</td>
<td>Brain (astrocytes, Bergmann glia, neurons), liver, pancreas</td>
<td>Akt/mTORC pathway; NF-\kappa B pathway</td>
<td>NM_004171, NM_001195728, NM_001252652</td>
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<td>SLC1A3</td>
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<td>System X\textsubscript{AG}</td>
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<td>C/Na\textsuperscript{+}, H\textsuperscript{+}, and k\textsuperscript{+}</td>
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<td>SLC1A4</td>
<td>ASCT1, SATT</td>
<td>System ASC</td>
<td>Cystine, serine, L-Threonine</td>
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<td>ASCT2, AAAT</td>
<td>System ASC</td>
<td>Aspartagine, glutamine</td>
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<td>Adipose tissue, lung, skeletal muscle, large intestine, kidney, testis</td>
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<td>NM_005638, NM_001145144, NM_001145145</td>
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<td>SLC7A1</td>
<td>CAT-1</td>
<td>System y\textsuperscript{-}</td>
<td>Arginine, lysine, ornithine</td>
<td>F (non-obligatory E)</td>
<td>Ubiquitous except for liver and lacrimal gland/basolateral and intracellular membranes in epithelial cells</td>
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<td>NM_003045</td>
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<tr>
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<td>CAT-2</td>
<td>System y\textsuperscript{-}</td>
<td>Arginine, lysine, ornithine</td>
<td>F</td>
<td>CAT-2A: liver, skeletal muscle, pancreas; CAT-2B: inducible in many cell types</td>
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<td>SLC7A5</td>
<td>LAT1</td>
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<td>Glutamine, leucine, methionine, tryptophan</td>
<td>E (similar intra- and extracellular selectivities, lower intracellular apparent affinity)</td>
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<td>c-Myc expression; IFN-\gamma production and granzyme B expression</td>
<td>NM_003486</td>
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<td>SLC7A7</td>
<td>y\textsuperscript{-}LAT1</td>
<td>system y\textsuperscript{-} L</td>
<td>Lysine, arginase, ornithine, methionine, leucine</td>
<td>Na\textsuperscript{+} dependent transport of extracellular large neutral L-amino acids</td>
<td>Small intestine, kidney, spleen, leukocytes, placenta, lung/basolateral in epithelial cells</td>
<td>NO production; NF-\kappa B pathway</td>
<td>NM_003982</td>
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<tr>
<td>SLC7A11</td>
<td>xCT</td>
<td>system x\textsubscript{+}</td>
<td>Cystine, glutamate</td>
<td>E (preferentially extracellular cystine against intracellular glutamate)</td>
<td>Macrophages, brain, retinal pigment cells, liver, kidney/basolateral in epithelial cells</td>
<td>Glutathione production; ROS accumulation; mTOR and NFAT activity; glycolysis and glutaminolysis</td>
<td>NM_014331</td>
</tr>
</tbody>
</table>

Akt, protein kinase B; ASCT, alanine serine cysteine transporter; C, cotransporter; E, exchanger; F, facilitated transporter; IGF, Insulin-Like Growth Factor; NFAT, nuclear factor of activated T cells; NKG2D, natural killer group 2, member D; xCT, Solute Carrier Family 7 Member 11; x\textsubscript{+}, cystine/glutamate antiporter.

2015), many others can transport amino acids across membranes, such as members of SLC1 and SLC7 families (Table 1).

The SLC1 family of transporters, named high affinity glutamate and neutral amino acid transporter family, comprises five excitatory amino acid transporters (EAATs, also known as system X\textsubscript{AG}) of the X\textsubscript{AG} system and two alanine serine cysteine transporters (ASCTs) of the alanine serine cysteine (ASC) system. The ASC system includes the two neutral amino acid transporters of the SLC1 family, SLC1A4 (ASC transporter 1) and SLC1A5 (ASC transporter 2) (Kanai et al., 2013). The X\textsubscript{AG} system includes SLC1A1 (EAAC1), SLC1A2 (GLT1, EAAT2), SLC1A3 (GLAST, EAAT1), SLC1A6 (EAAT4), and SLC1A7 (EAAT5), which are high affinity glutamate transporters responsible for L-glutamate and L/D-aspartate uptake with cotransport of three sodium ions (Na\textsuperscript{+}) and one proton (H\textsuperscript{+}) and counter-transport of one potassium ion (K\textsuperscript{+}) (Kanai et al., 2013). In the brain, SLC1A1 is mainly expressed in neurons; SLC1A2 in astrocytes, Bergmann glia, and neurons; and SLC1A3 in astrocytes and Bergmann glia (Kanai et al., 2013), all with important functions in the central nervous system (CNS) (Fig. 1).
The SLC7 family of transporters, named cationic amino acid transporter/glycoprotein-associated family, are divided into two subfamilies: the cationic amino acid transporters (CATs) and the L-type amino acid transporters (LATs). CATs include SLC7A1-4 and SLC7A14, which mediate \( \text{Na}^+ \) independent transport of cationic L-amino acids (Fotiadis et al., 2013), whereas LATs are the light or catalytic subunits of hetero- meric amino acid transporters (HATs) with a broad spectrum of substrates (Fotiadis et al., 2013), which are linked to the heavy subunits 4F2hc(SLC3A2) or rBAT(SLC3A1) through disulfide bonds. SLC7 transporters are important metabolic regulators in immune cells as summarized in Fig. 2.

In this review, the role of SLC7 amino acids transporters in inflammation and autoimmunity and its supporting literature is discussed in detail. First, the part of SLC7 family members in innate and adaptive immune cells is debated, followed by the importance of SLC1 family proteins in neural inflammation, particularly in MS. Similarly, the role of SLCs in viral and bacterial infections is also analyzed, along with a brief summary on the impact of SLCs in other inflammatory disorders. Finally, the prospect of SLC based therapeutics is explored.

**SLCs Function in Innate and Adaptive Immune Cells.** The immune system is a complex biologic network traditionally separated in innate and adaptive immune cells. Innate immune cells such as Macrophages, Dendritic cells, and NK cells are generally the first responders, driving inflammation through antigen-independent mechanisms. Adaptive immune cells, such as T and B cells, are activated by innate immune signals and drive antigen-specific memory immunity.

SLC7A2 is highly involved in both innate and adaptive immunity. Slc7a2 expression was induced in both classic (M1) and alternative (M2) activated macrophages, and Slc7a2 knockout blocked arginine transport and limited its activity after macrophage activation (Yeramian et al., 2006). Furthermore, Platonin, an inhibitor of acute inflammation, lowered nitric oxide (NO) production and arginine transport in lipopolysaccharide (LPS) stimulated mouse macrophages via iNOS and SLC7A2 inhibition (Chen et al., 2006). Slc7a2 expression in peripheral monocytes was also found to be upregulated in pregnancy and was higher in preeclampsia, during which systemic inflammation is widespread and the arginine transport is strengthened (McCord et al., 2006). The lung of SLC7A2 deficient mice shows signs of spontaneous inflammation accompanied by increased dendritic cell (DC) and alveolar macrophages activation, but with compromised NO production (Rothenberg et al., 2006). Furthermore, Platonin, an inhibitor of acute inflammation, lowered nitric oxide (NO) production and arginine transport in lipopolysaccharide (LPS) stimulated mouse macrophages via iNOS and Slc7a2 inhibition (Chen et al., 2006). Slc7a2 expression in peripheral monocytes was also found to be upregulated in pregnancy and was higher in preeclampsia, during which systemic inflammation is widespread and the arginine transport is strengthened (McCord et al., 2006). Finally, myeloid-derived suppressor cells (MDSCs) suppressed T cell activities under inflammation or tumor conditions through increased arginine metabolism, whereas Slc7a2 deficiency promoted antitumor immunity (Cimen Bozkus et al., 2015).

Epithelial and endothelial cells also contribute for early innate inflammatory signals. In endothelial cells, human umbilical vein endothelial cells (HUVEC) stimulated by tumor necrosis factor \( \alpha \) (TNF-\( \alpha \)) showed higher Slc7a2 expression (Knyazev et al., 2018); similarly, human saphenous vein endothelial cells (HSVEC) stimulated by TNF-\( \alpha \)
showed elevated SLC7A2 potentially via the nuclear factor kappa B (NF-kB) pathway, despite no effect on Slc7a1 (Visigalli et al., 2004).

SLC7A7 also affects amino acid transport, differentiation, and immune function of macrophages. Slc7a7 mRNA, SLC7A7 protein levels, and arginine transport were increased during monocyte differentiation to macrophages mediated by protein kinase C (PKC) activation. Contrastingly, the Na⁺-Independent Cationic Amino Acid Transporter (y⁺) system and lysine-prefering agency (γ⁺L) system transported arginine and lysine outwards of macrophagic cells (Barilli et al., 2011). Silencing of Slc7a7 in human Tohoku Hospital Pediatrics-1 (THP-1) macrophages and A549 epithelial cells induced secretion of interleukin-1β (IL-1β), TNF-α via the NF-κB pathway, and chemokine (C-C motif) ligand 5/regulated upon activation normal T cell expressed and secreted factor (CCL5/RANTES) stimulated by IL-1/β signaling feedback, which were independent of arginine concentration. Thus, Slc7a7 likely plays a deeper role in inflammation aside of arginine transport (Rotoli et al., 2018). Mutation of Slc7a7 could also cause lysinuric protein intolerance (LPI), in which arginine transport by system y⁺L was impaired in macrophages and phagocytic activity was severely damaged (Barilli et al., 2012). In patients with LPI, plasma proinflammatory chemokines were higher, and LPl macrophages exhibited impaired response to Toll-like receptor 9 (TLR9) stimulation, higher response to TLR2/1 and TLR4 stimulation, and lower NO production (Kurko et al., 2015).

SLC7A5 mediated leucine transport in macrophages promoted mechanistic target of rapamycin complex 1 (mTORC1) signaling and proinflammatory cytokine production (Yoon et al., 2018). Slc7a5 expression was upregulated in monocytes from rheumatoid arthritis patients and healthy monocytes after LPS stimulation. Additionally, Slc7a5 expression levels positively correlated with rheumatoid arthritis clinical condition indicating a relationship of SLC7A5 with inflammation (Yoon et al., 2018). Similarly, a natural alkaloid piperine promoted mTORC1 signaling via recruitment of membrane SLC7A5/Cluster of differentiation 98 (CD98), synthesis of IL-6 and TNF-α, and phagocytic activity against bacteria in peritoneal macrophages (Pan et al., 2015). In activated NK cells, SLC7A5 also acted as a predominant amino acid transporter and together with glutamine supply was essential for maintaining transcriptional regulator Myc-like (c-Myc) and NK cell function (Loftus et al., 2018).

Still in macrophages, treatment with amphibole asbestos increased SLC7A11 expression, whereas Slc7a11 inhibition led to oxidative stress and cell death, which could be rescued by cysteine (Pfau et al., 2012). SLC7A11 was identified as a macrophagic host factor in the vesicular stomatitis virus replication (Kandasamy et al., 2016), and in LPS stimulated macrophages, SLC7A11 deficiency caused insufficient cysteine supply, decreased nitrite in the culture medium, and an increase in reactive oxygen species (Kobayashi et al., 2018). LPS stimulation in hippocampus elevated SLC7A11 expression, and knockout of SLC7A11 relieved peripheral and central inflammation and the effect of LPS stimulation in mice (Albertini et al., 2018). SLC7A11 was also elevated in IL-4-induced M2 macrophages during parainflammation and is related to M2 genes (Wang et al., 2020a).

SLC7A11 (Solute Carrier Family 7 Member 11, xCT) forms system cystine/glutamate antiporter (xct⁻) with CD98 and is mainly expressed in the brain, macrophages, and cell lines, and acts as a Na⁺-dependent transporter of extracellular anionic cysteine and intracellular glutamate (Fotiadi et al., 2013). For T cells, although in vitro proliferation was SLC7A11-dependent, in vivo proliferation, immune response, and memory effects were SLC7A11-independent; therefore, using SLC7A11 as an antitumor therapeutic target should not affect T cell immune response (Arensman et al., 2019). Although baseline SLC7A11 levels are relatively low in T cells, thermal injury strongly induces SLC7A11, resulting in cystine import and T cell dysfunction (D’Elia et al., 2009). Glutathione production in part mediated by SLC7A11 can limit reactive oxygen species accumulation and support the activity of mTOR and nuclear factor of activated T cells to drive glycolysis and glutaminolysis in activated T cells (Mak et al., 2017).

In NK cells, IL-2 priming could upregulate SLC1A5 and SLC3A2 (CD98), which were both necessary for interferon γ (IFN-γ) production and degranulation by NK cells after stimulation of the activating receptor, natural-killer group 2 member D (Jensen et al., 2017). SLC1A5 participates in adaptive immunity as a conditionally essential glutamine transporter. SLC1A5-dependent rapid glutamine uptake occurred during naïve T cell activation, and SLC1A5 deficiency caused failure of Th1 and Th17 cell induction, as well as loss of the inflammatory T cell responses (Nakaya et al., 2014). Glutamine uptake through SLC1A5 and T cell receptor (TCR) signaling complex were both necessary for mTORC activation by TCR stimulation (Nakaya et al., 2014). Further, glucose and glutamine were both required upon B cell activation (Jiang et al., 2018). Overexpression of the microRNA cluster let-7ad reduced levels of both glucose by targeting hexokinase two and glutamate by inhibition of SLC1A5 and glutaminase, and further controlled antibody production of B cells (Jiang et al., 2018). However, SLC1A3 knockout in mice was reported to have no influence on B cell development, proliferation, or function (Masle-Farquhar et al., 2017). Blocking SLC1A5 with L-γ-Glutamyl-l-pyroglutamic acid (GPNA) to inhibit the uptake of glutamine can significantly enhance the inhibitory effect of cetuximab on the proliferation of gastric cancer and metastatic colorectal cancer in vivo and in vitro. Research provides the metabolic role of SLC1A5 as a potential therapeutic target to improve the efficacy of cetuximab for colorectal cancer and gastric cancer (Ma et al., 2018, 2021).

SLC7A1 seems to be the major system y⁺ transporter in most cell types (Fotiadi et al., 2013). Slc7a1 expression was increased in CD8⁺ T cells and naïve and memory CD4⁺ T cells to provide sufficient arginine for T cell function (Werner et al., 2016). In contrast, Slc7a1 expression was not induced by classic or alternative activation of macrophages (Yeramian et al., 2006). Meanwhile, Slc7a5⁻/- T cells showed impaired proliferation, differentiation, or metabolically reprogramming upon antigen stimulation, and leucine transport by L system was required for mTORC1 activity and c-Myc expression in activated T cells (Sinclair et al., 2013). The lack of methionine may also be responsible for the halt of protein production in Slc7a5⁻/- T cells, similar to the effect of Myc deletion (Marchingo et al., 2020). SLC7A5 inhibition as well as amino acid starvation triggered expression of homeobox B9 in activated T cells, which attenuated production of selective cytokines (Hayashi et al., 2016). SLC7A7 participated in the pathogenesis of T-cell acute lymphoblastic leukemia (Ji et al., 2018).

SLC3A2 in Neural Inflammation and Autoimmunity (Multiple Sclerosis). Neurologic diseases afflict 3%–5% of the global population. Multiple sclerosis alone affects 59/100,000 habitants in Europe to a total of almost 700,000 people in 2017 (Deuschl et al., 2020). Transient inflammation and restorative neurologic dysfunction often occur during early MS stages, although widespread microglial activation and chronic neurodegeneration gradually develop (Compston and Coles, 2008). MS has traditionally been considered an autoimmune disease primarily mediated by CD4⁺ Th1 cells, but other immune factors likely influence disease progression. SLC1A2 is expressed in astrocytes, neurons, and axonal terminals where it regulates glutamate concentrations in the CNS, often together with SLC1A3. Thus, these two transporters are mechanistically important in preventing excitotoxicity. In the inflammatory CNS microenvironment of MS, SLC1A3 and SLC1A2 levels and glutamate uptake were elevated in optic nerves and reduced...
downstream-regulated gene 2 on EAAT1 expression was dependent on taurine more SLC1A3 and SLC1A2, and the inhibitory effect of N-Myc induction, mice lacking N-Myc downstream-regulated gene 2 main-
mice is widely used as a demyelinating model for MS. After EAE extracellular glutamate rose and led to excitotoxicity (Pampliega et al., 2011).

Upon SLC7A11 upregulation by immune activation, excitotoxicity mainly by controlling extracellular nonsynaptic glutamate concen-
tration. In the brain, SLC7A11 participates in glutamate excitotox-
icity (Vallejo-Illarramendi et al., 2007). In the inflammation of MS, Th-17 cells function by releasing IL-17A, which promotes glutamate excitotoxicity by decreasing astrocyte SLC1A2, SLC1A3, and glutamine synthetase (GS) expression, and also by stimulating Ca2+-dependent glutamate release, indicating an association between inflammation and neurodegeneration in MS (Kostic et al., 2017). In the early stages of neuroinflammation, glutamate released by activated microglia stimulated an increase in extracell-
ular and intracellular glutamate levels of astrocytes and, in turn, resulted in reduced astrocytic SLC1A3 levels and failure of extracellular glutamate clearance (Takaki et al., 2012). SLC1A3 was also upregulated in the hypothalamus of long-living growth hormonereceptor-knockout (KO) mice, together with higher expression of hypothalamic NF-κB, insulin like growth factor (IGF)-1 receptor, and the GluA1 subunit of the glutamate receptor; α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid receptor (AMPAR) expression; and lower IL-1β in many brain regions. These data support the importance of decreased brain inflammation in early adulthood and maintained homeostasis of the glutamatergic and inflammatory systems in extended longevity (Hascup et al., 2016). In the brain, SLC7A11 participates in glutamate excitotoxicity mainly by controlling extracellular nonsynaptic glutamate concentra-
tion. Upon SLC7A11 upregulation by immune activation, extracellular glutamate rose and led to excitotoxicity (Pampliega et al., 2011).

Experimental allergic (autoimmune) encephalomyelitis (EAE) in mice is widely used as a demyelinating model for MS. After EAE induction, mice lacking N-Myc downstream-regulated gene 2 main-
tained more SLC1A3 and SLC1A2, and the inhibitory effect of N-Myc downstream-regulated gene 2 on EAAT1 expression was dependent on protein kinase B (Akt/PKB) rather than on NF-κB activity (Lee et al., 2018). SLC1A3 expression can be altered by xenobiotics, and astrocytic SLC1A3 expression was associated with intraperitoneal injection of a synthetic Toll-like receptor (TLR)-3 ligand, polyinosinic acid, which also promoted IFN-β transcription in the CNS (Costello and Lynch, 2013). Moreover, dietary cocoa stimulated SLC1A3 expression while suppressing inflammatory cytokine expression during prolonged activation of trigeminal ganglion neurons and glia by close Freund’s adjuvant (Cady et al., 2013), whereas Acrolein, a neurotoxin produced in the brain during ischemic stroke, caused astrocytic in
vivo downregulation of SLC1A3 (Park et al., 2020). Myelin-specific CD4+ Th1 cells stimulated glutamate release by SLC7A11 in microglia, and SLC7A11 inhibition improved the conditions of EAE mice and decreased T cell infiltration into the CNS (Evonuk et al., 2015). Additionally, Slc1a1−/− mice have elevated levels of inflammatory cytokines in the brain (Afshari et al., 2017), and a Slc1a1 suppressor microRNA (miR-26a) affected the response to IFN-β treatment in patients with MS (Potenza et al., 2018). Although peripheral nerve injury resulted in both upregulation of glucocorticoid receptors and downregulation of SLC1A1, inhibition of glucocorticoid receptors rescues SLC1A1 expression levels, possibly through the NF-κB signaling pathway (Wang et al., 2006). Furthermore, 1,25(OH)2D3 regulates both Slc1a1 and lipopolysaccharide (LPS)-binding protein CD14 in human osteo-
clasts (Tarromi et al., 2012).

Increased human endogenous retrovirus (HERV) gene activity occurs in immunologically activated glia, and HERV-W encoded glycoprotein syncytin is upregulated in glial cells within acute demyelinating lesions of MS patients (Antony et al., 2004). SLC1A4 was found to be a recep-
tor of the HERV-W envelope protein syncytin-1, which could induce iNOS via old astrocyte specifically induced substance (OASIS), and OASIS suppressed astrocytic SLC1A4 (Antony et al., 2007). SLC1A5 was reported to be another syncytin-1 receptor and was highly expressed in human umbilical vein endothelial cells (Yan et al., 2017).
Syncytin-1 could be induced by TNF-α via the Wnt/β-catenin pathway in squamous cell carcinoma cells 9, indicating that the interaction of SLC1A5-syncytin-1 may promote cancer-endothelial cell fusion (Yan et al., 2017).

SLC1A2 is also relevant to other nervous system disorders. The autoantibody neumyelitis optica (NMO)-IgG, a biomarker of neumyelitis optica, targets the aquaporin 4 water channel on astrocytes (Hinson et al., 2008). SLC1A2 expression levels vary according to changes in aquaporin 4 expression, suggesting that SLC1A2 might form complexes with aquaporin 4, and thus pathologically produced neuromyelitis optica (NMO)-IgG might cause excitotoxicity via aquaporin 4 binding (Hinson et al., 2008). Upregulation of SLC1A2 by an antibiotic, ceftriaxone, was shown to accompany downregulation of proinflammatory cytokines in rats with traumatic brain injury (Wei et al., 2012), and in amyotrophic lateral sclerosis, a stearyl-norleucine-vasoactive intestinal peptide rescued the levels and function of SLC1A2 via suppression of TNF-α and downregulation of NF-κB (Goursaud et al., 2015). SLC1A2 was also found to be reduced in brains of patients with Alzheimer’s disease. SLC1A2 deprivation in astrocytes resulted in both innate and adaptive immune function failure, with gene expression pattern changes similar to those caused by inflammation and synaptic function changes in Alzheimer’s disease or aged brains, which has been associated with early onset deficits in short-term memory; meanwhile, SLC1A2 deprivation in neurons was associated with late onset deficits in long-term memory (Sharma et al., 2019).

The SLC1A family also plays a key role in chronic pain, and arachidonic acid is a critical regulator of inflammatory pathways that increases pain sensitivity after nerve injury by activating inflammatory pathways and affecting microglia and astrocytes. The expression/activity of the glutamate transporter in the middle of the synaptic cleft leads to a sustained increase in the concentration of glutamate in and/or around the synaptic cleft, ultimately leading to the continued development of neuropathic pain (Gegelashvili and Bjerrum, 2019).

**SLCs During Infection.** Several studies suggested that SLC1A2 participates in viral infections, primarily in the CNS. Immunological macrophage activation during human immunodeficiency virus (HIV) infection caused CNS symptoms and was associated with glutamate excitotoxicity. However, macrophages were less affected by compensatory increased SLC1A2 expression and GS inhibition due to a reduction in glutamate transport during HIV replication, supporting a potential replacement of affected astrocytes (Porcheray et al., 2006). Astrocyte elevated gene-1 was found to promote HIV-1-associated neuroinflammation via suppression of SLC1A2 and the NF-κB pathway (Vartak-Sharma et al., 2014). During HIV-associated neurocognitive disorders, trace amine receptor 1 negatively regulated SLC1A2 expression and glutamate uptake, and trace amine receptor 1 disruption prevented the decrease in SLC1A2 mediated by methamphetamine, a trace amine receptor agonist (Cisneros and Ghorpade, 2014). Japanese encephalitis virus infection in neurons caused astroglisis, elevated SLC1A3 and SLC1A2 expression to detoxify glutamate, and induced other neuroprotective changes, which were nonetheless insufficient to overcome neuronal injuries (Mishra et al., 2007). In acute flaccid paralysis caused by the West Nile virus, the immune response to West Nile virus in the spinal cord influenced astrocytic glutamate reuptake, leading to higher extracellular glutamate and, thus, cells without direct virus infection were also damaged by excitotoxicity (Blakely et al., 2009). In the early stage of Borna disease virus infections, zebrin II/SLC1A6 expression was reported to be a marker for subsets of Purkinje cells with different susceptibility to the virus (Williams et al., 2007). SLC7A11 was identified as a receptor for Kaposi’s sarcoma-associated herpesvirus, promoting cell fusion and virion entry of the virus (Kaleeba and Berger, 2006). In primary effusion lymphoma caused by Kaposi’s sarcoma-associated herpesvirus, targeting SLC7A11 promoted apoptosis of primary effusion lymphoma cells, and inhibitors of SLC7A11 or downstream genes were potential therapeutic targets (Tai et al., 2015).

SLCs transportsers have also been studied during bacterial infection. Inflammation in astrocytes could weaken gap junctions, and in the short term, hemichannel activity adjacent to Staphylococcus aureus-infected areas were directly correlated with an increased expression of connexin 43 (Cx43), Cx30, Panxinn 1 (Panx1), SLC1A3, and SLC1A2 (Karpuk et al., 2011). During *Helicobacter pylori* infection, Slc7a2a knockout not only inhibited the innate immune response of mice, but also skewed the adaptive immune response from Th1 to Th2 (Barry et al., 2011). During *Mycobacterium tuberculosis* infection, avirulent strains led to higher SLC7A2 expression levels in macrophages than virulent strains, suggesting a role of SLC7A2 in controlling immune response of macrophages toward bacterial infection (Lee et al., 2019). Finally, proinflammatory signals and Slc7a5 expression were both upregulated by *Shigella flexneri* infection in a new model of intestine named human intestinal endoeroids (Koestler et al., 2019).

The impact of SLCs during parasitic and helmimt infections is less known, but BALB/c mice, which are more susceptible to *Leishmania major* infection, showed higher Slc7a2a expression in macrophages after IFN-γ or IL-4 treatment, and increased arginine might favor the growth of *Leishmania major* (Sans-Fons et al., 2013).

**SLCs in Other Chronic or Autoimmune Diseases.** SLCs have also been implicated in numerous other chronic inflammatory or autoimmune diseases. Inflammatory bowel disease (IBD) mainly includes two distinct clinical conditions, Crohn’s disease and ulcerative colitis (UC), and is thought to be caused by an abnormally activated immune response to normal luminal flora (Podolsky, 2002). Activating transcription factor 4 was downregulated in inflamed intestinal mucosa of patients with IBD, whereas Slc1a5 transcription was suppressed by activating transcription factor 4 deficiency in mice, leading to lower glutamine uptake and antimicrobial peptide synthesis in intestinal epithelial cells (Hu et al., 2019). During active UC, tissue SLC7A2 and arginase-1 expression levels and arginine concentration were decreased, whereas NOS2, arginase-2 expression were higher (Coburn et al., 2016). Dextran sulfate sodium induced more severe UC in Slc7a2a knockout mice. Similarly, in an azoxymethane-dextran sulfate sodium model of *Citrobacter rodentium* infection, targeting SLC7A11 promoted apoptosis of primary effusion lymphoma cells, and inhibitors of SLC7A11 or downstream genes were potential therapeutic targets (Tai et al., 2015).

During UC also reduced chromosome-associated protein D3 upregulating protumorigenic M2 activation of macrophages (Coburn et al., 2019). UC also reduced chromosome-associated protein D3 upregulating Slc7a5/CD98 expression, and system L or mTORC1 inhibition restored the bacterial clearance defects of colon epithelial cells lacking chromosome-associated protein D3 (Schuster et al., 2015).

Citrinocodentum is a widely used mouse model for human intestinal diseases including IBD. Arginine transporters are involved in conditions such as infections and IBD. In mice, Slc7a2a expression is upregulated in colitis tissues after *Citrobacter rodentium* infection, and Slc7a2a knockout weakened the immune response and attachment of *C. rodentium* to the epithelium (Singh et al., 2016). Another study showed that elevated arginine levels in the mouse colon at the peak of *C. rodentium* infection was correlated with downregulation of host Slc7a2a and upregulation of *C. rodentium* virulence gene expression, indicating that the balance between host and pathogen was affected by arginine (Menezes-Garcia et al., 2020).

SLC1A3 and SLC1A2 are also enriched in the joints of the osteoarthritis rabbit model, resulting in higher concentrations of glutamate and aspartate (Hascup et al., 2016). In addition, in the rat retinal Müller cell line rMC-1 induced by high glucose, lower GS and SLC1A3 levels led
to higher glutamate levels, and higher IL-17A production and IL-17 receptor A, Glial Fibrillary Acidic Protein (GFAP), and vascular endothelial growth factor (VEGF) expression, indicating involvement of SLC1A3 in diabetic retinopathy, a complication of autoimmune diabetes (Qiu et al., 2017). During psoriasis, CD69 in skin gamma delta (γδ) T cells altered aryl hydrocarbon receptor-dependent IL-22 secretion and skin inflammation via its regulatory effect on surface expression of SLC7A5-CD98, L-tryptophan uptake, and tryptophan-derived aryl hydrocarbon receptor activators (Cibrian et al., 2016). Finally, in the murine lung during asthma, Arg1 deficiency improved the function and adaptive regulation of Scl7a1 together with Arg2, Nos2, Slc7a7, Ccl2, Ccl11, Tnfα, and Ifnγ, but failed to relieve airway inflammation (Zhu et al., 2021). Scl7a1 expression was also upregulated in mammary alveolar epithelial cells by LPS stimulation in mouse mammary glands (Kobayashi et al., 2013).

**SLC-Targeted Therapeutics and Conclusion.** Over the past decades, a number of inhibitors targeting SLC1 and SLC7 transporters (Table 2) and many SLC-targeted therapies have been developed. However, for SLC1 and SLC7 family transporters only one Riluzole (SLC1A3) has been approved for the treatment of amyotrophic lateral sclerosis (Lin et al., 2015), leading to the development of a virus-like particle immunotherapeutic approach to target SLC7A11 protein (Bolli et al., 2017). Furthermore, SLC7A1 expression was enhanced in a arginine starvation model that mimics an important tumor immune evasion mechanism. Under arginine deprivation SLC7A1 inhibition resulted in arginine uptake and secretion of CD4+ T cells, and the inflammatory response of both cells via the IL-23 and IL-1β-induced PI3K/protein kinase B (AKT/PKB)/mTOR pathway in psoriasis (Cibrian et al., 2020). For neurologic disease, astrocytes have high transport capacity and affinity for the SLC7A5 substrate [14C]-L-leucine, followed by neurons and microglia; hence, such prodrug can use Lat1 for cellular uptake with much higher activity than one of its parent drugs (Huttunen et al., 2018).

In patients with obesity, a population of T cells called mucosal-associated invariant T cells were disregulated and showed defective glycolytic metabolism and amino acid transport by SLC7A5 necessary for downstream mTORC1 signaling (O’Brien et al., 2019). SLC7A5 inhibition controlled the proliferation of gamma delta (γδ) T cells, IL-17 secretion of CD4+ T cells, and the inflammatory response of both cells via the IL-23 and IL-1β-induced PI3K/protein kinase B (AKT/PKB)/mTOR pathway in psoriasis (Cibrian et al., 2020). For neurologic disease, astrocytes have high transport capacity and affinity for the SLC7A5 substrate [14C]-L-leucine, followed by neurons and microglia; hence, such prodrug can use Lat1 for cellular uptake with much higher activity than one of its parent drugs (Huttunen et al., 2019).

Currently, there are no reports on the gene single nucleotide polymorphisms (SNPs) of SLC1 and SLC7 family members directly in inflammatory and autoimmune diseases. The diseases related to SLC1 family single nucleotide polymorphisms (SNPs) were mainly obsessive-compulsive disorder, schizophrenia, epilepsy, essential tremor, stress depression, and multiple system atrophy (Soma et al., 2008; Wendland et al., 2009; Gadow et al., 2010; Jiménez-Jiménez et al., 2015; Ritter et al., 2016; Yu et al., 2018; Ghosh et al., 2020). The SLC7 family is mostly associated with susceptibility to leprosy, multiple myeloma,
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