

## EXCITATORY AMINO ACID NEUROTRANSMISSION. PATHWAYS FOR METABOLISM, STORAGE AND REUPTAKE OF GLUTAMATE IN BRAIN

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### 1. ABSTRACT

In the nervous system, glutamate is an excitatory amino acid which at higher concentrations has been implicated in a number of disorders. Glutamate is stored in presynaptic vesicles and is released by calcium-dependent exocytosis. After its action on ionotropic receptors (iGluR, related to ionic channels) or metabotropic receptors (mGluR, related to metabolic formation of second messengers), glutamate can be removed from the synaptic cleft through two processes: re-uptake back into presynaptic terminals or diffusion out of synaptic cleft for uptake by glial cells. This is achieved by glutamate transporters. In pre-synaptic terminals, glutamate is packed into the specialized secretory vesicles by means of a specific vesicular transporter. The level of glutamate available for neurosecretion is regulated by the vesicular transport activity. In order to achieve a proper concentration of the neurotransmitter in synaptic vesicles, glutamate must be synthesized. Glutamine is obtained in astroglial cells from the glutamate reuptaken, and as it has no neurotransmitter activity, it is the metabolite which regenerates glutamate in neurones (glutamate-glutamine cycle). Moreover, glutamate is also obtained from glucose by an intermediate of TCA cycle. In this paper we want to introduce some aspects of glutamate biosynthesis and release: glutamate receptors, neurotransmitter uptake by the glutamate transporters and

neurotransmitter inactivation and new formation by metabolism.

### 2. INTRODUCTION

Aspartate and glutamate are the simple and common excitatory amino acids, and the inhibitory ones are GABA, glycine and taurine. Of these amino acids, two are intimately associated with CO<sub>2</sub> fixation in the brain, and may be therefore particularly relevant to central ventilation drive, namely, glutamate and GABA. These two amino acids are intimately related to CO<sub>2</sub> fixation in the brain and are derived from the same amino acid, glutamine. Their metabolism is interrelated, and they have opposite and profound effects centrally on ventilatory and cardiovascular functions. Specifically, glutamate may well be the key central neurotransmitter released with stimulation of peripheral chemoreceptors (1,2). Metabolism of glutamate and GABA in the brain are also related to ammonia metabolism. Decrease in brain ammonia is associated with a reduction in  $\alpha$ -ketoglutarate and glutamic acid content and an increase in glutamine via the detoxification pathway for NH<sub>3</sub>.

The influx of glutamate from plasma across the blood-brain barrier is much lower than the efflux of

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glutamate from brain (3-5). Therefore, metabolism of brain glutamate must play an important role in regulating the brain glutamate level. Due to the many different roles associated to glutamate, it is not surprising that its synthesis and metabolism are complex. Thus, administration of the two general precursors, glucose and acetate, in a labeled form indicates that glucose and acetate are synthesizing glutamate via two different citrate cycles in brain. Glucose yields a low specific radioactivity of glutamine via glutamate whereas the opposite is true for acetate. Other metabolites behaving as glucose include glycerol, lactate, pyruvate,  $\alpha$ -ketoglutarate and  $\beta$ -hydroxybutyrate; whereas propionate, butyrate, citrate, leucine, GABA, aspartate, proteins and ammonia behave as acetate (6). It seems that glucose is metabolized in neurones (7,8) whereas acetate in astroglial cells (9), where there is a higher glutamine synthase activity (10,11).

In this paper three key aspects of the amino acid neurotransmitter glutamate are reviewed: receptors, transport and metabolism (see figure 1 for a summary).

### 3. EXCITATORY AMINO ACIDS RECEPTORS

Excitatory aminoacids (aspartate and glutamate) act through two broad classes of receptors: ion channel-linked ionotropic receptors (iGluR) and metabotropic receptors (mGluR), which are coupled with G-proteins inducing intracellular messenger cascades (12).

There are different types of ionotropic and metabotropic glutamate receptors in both neurones and glial cells. Table I shows a summary of the main characteristics of those receptors. Classification of receptors has been possible due to the different affinity to specific agonists and antagonists. A summary of those molecules are given in figure 2.

Glial cells, in particular astrocytes, appear to respond to a great variety of neurotransmitters, including glutamate, hormones and growth factors with activation of metabotropic pathways, which may lead to intracellular pH and/or calcium changes. The distribution of different sets of glutamate receptors in different brain regions may classify neurones and glial cells, and appears to be functionally of some significance, both in normal physiological processes as well as during pathological states. The excitatory neurotransmitter glutamate and its large receptor family is probably the most versatile and complex signaling system in the mammalian brain, and possibly also the most susceptible for pathological disturbances.

#### 3.1. Ionotropic glutamate receptors

Four main subtypes of glutamate-gated channels have been characterized pharmacologically and they have been named according to their preferred agonist, N-methyl-D-aspartate (NMDA), high affinity kainate (KA), alpha-amino-3-hydroxy-5-methyl-4-isoxazole propionate (AMPA), and 2-amino-4-phosphobutyrate (AP4). For each of those

agonists, a large diversity of receptors have been described (see table 1).

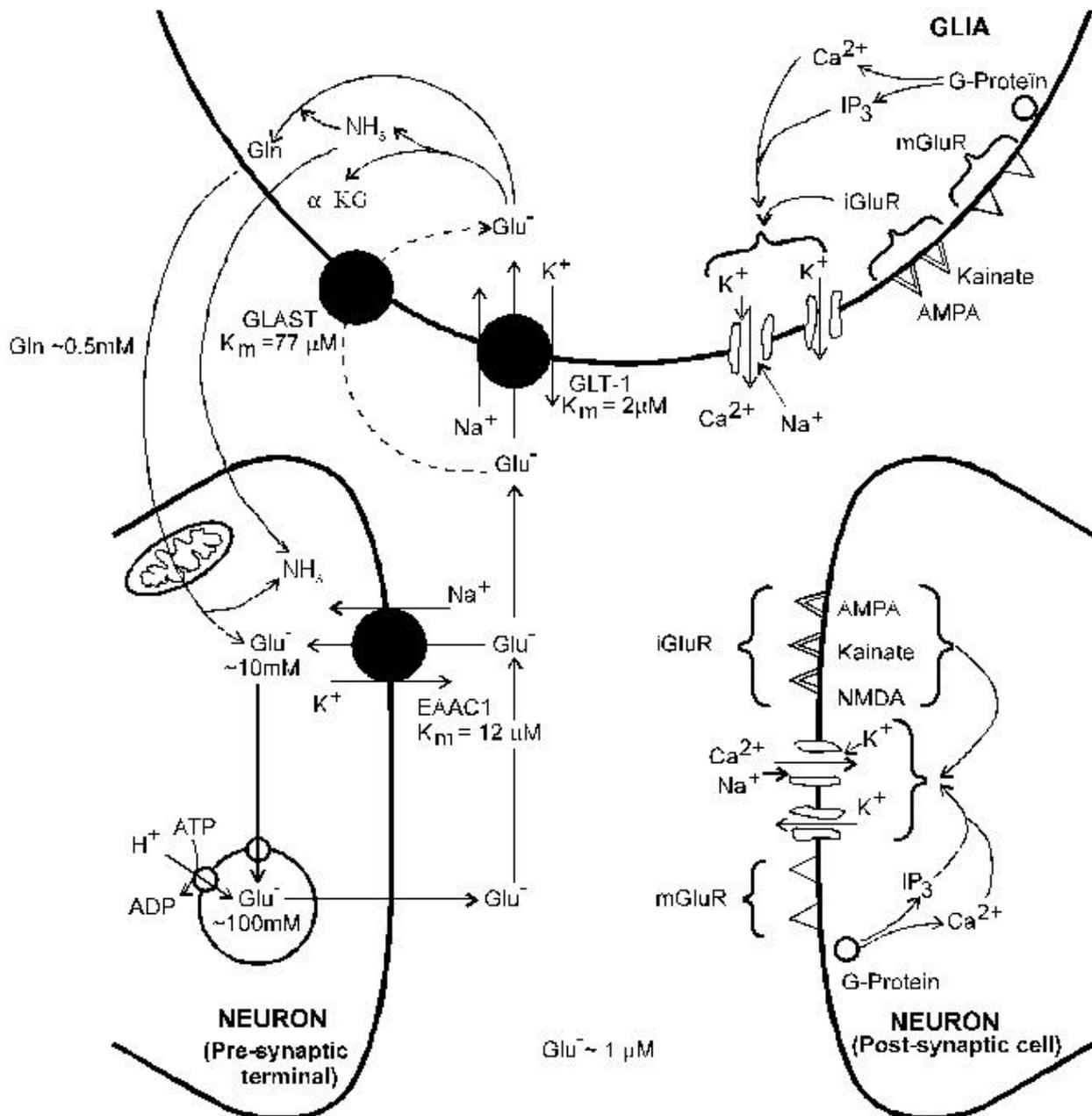
The most studied receptor is NMDA (13,14), and because of this, glutamate ionotropic receptors are often named as NMDA and non-NMDA. Activation of the ionotropic NMDA and non-NMDA receptors increases transmembrane calcium and sodium fluxes, whereas the metabotropic glutamate receptor activation results in generation of inositol triphosphate and inhibition of adenylate cyclase (15). Nevertheless, metabotropic receptors are also related in phosphorylation of NMDA and non-NMDA receptors.

It seems that glutamate ionotropic receptors, specially NMDA receptors, are related with neurodegenerative diseases, as act when glutamate concentration increases. Thus, a noncompetitive NMDA receptor antagonist (memantine) can be used for the treatment of Alzheimer's disease (16). It has also been seen that injection of kainate causes selective neuronal degeneration similar to that of Huntington's disease (17). Evidence from animal models suggests that antagonists of the different glutamate receptors might be beneficial in Parkinson's disease, Huntington's chorea and amyotrophic lateral sclerosis but the relevance of these models to the human disease is not clear. However, the identification of numerous receptor subtypes in addition to variabilities of distribution and multiple modulatory sites will provide new solutions to these common neurological disorders.

#### 3.1.1. NMDA receptors

NMDA-type ionotropic receptors have not been demonstrated in glial cells, but only in neurons. Those receptors contain (a) a transmitter binding site, which binds glutamate; (b) a regulatory or coactivator site, which binds glycine, (c) a site within the channel that binds phencyclidine and related compounds, (d) a voltage-dependent  $Mg^{2+}$  binding site, and (e) an inhibitory divalent cation site that binds  $Zn^{2+}$ . Glycine greatly enhances the actions of NMDA agonists but has no action by itself. Interaction of phencyclidine and related anesthetics to NMDA receptors reproduce most of the symptoms of schizophrenia. A major advance in the understanding of the NMDA receptor was the demonstration by McDonald and Johnston (18) and Flatman *et al.* (19) that NMDA-induced responses are voltage-dependent. The agonist-induced currents are greatest at moderately depolarized potentials (-30 to -20 mV) and are reduced at both more hyperpolarized and depolarized potentials. Consequently, NMDA receptor action is suppressed at the normal resting potential. The work of Nowak *et al.* (20) and Mayer *et al.* (21) demonstrated that the voltage dependency of the NMDA receptor is attributable to extracellular  $Mg^{2+}$  ions that block the ion channel only at potentials more negative than -20 or -30 mV.

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**Figure 1.** Glutamate mobilization at glutamatergic synapses. Glutamate stored in synaptic vesicles is released by fusion of those vesicles to the presynaptic membrane. Stimulation of ionotropic glutamate receptors (iGluR) by glutamate opens associated ion channels and induces an excitatory postsynaptic potential. Metabotropic glutamate receptors (mGluR) are associated with G proteins and, depending on the subtype they increase IP or affect cAMP concentration. Glutamate is removed from the synaptic cleft through two processes: re-uptake back into pre-synaptic terminals and diffusion out of synaptic cleft to be re-uptaken by glial cells. The rapid re-uptake of glutamate is believed to be mediated by a Na<sup>+</sup> and K<sup>+</sup> depending high-affinity glutamate transporter (EAAC1, with  $K_m$  for glutamate of 12  $\mu$ M). The low glutamate concentration is re-uptaken in glial cells by a higher-affinity transporter (GLT-1, with  $K_m$  of 2  $\mu$ M). The low affinity glial cells transporter (GLAST, with  $K_m$  of 77  $\mu$ M) is able to transport aspartate and glutamate and it is a mechanism of protection in order that glutamate concentration doesn't increase too much in brain, because of its "excitotoxic" effect. Glutamate in glial cells is thought to be metabolized to glutamine (by glutamine synthetase) and to  $\alpha$ -ketoglutarate (by glutamate dehydrogenase or glutamate oxaloacetate transaminase). Those metabolites can be used as precursors of glutamate synthesis in pre-synaptic neurones. Glutamate is packed again into synaptic vesicles by a Na<sup>+</sup> independent transport driven by the internal positive membrane potential generated by the vesicular ATP-dependent H<sup>+</sup> transport.



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**Table 1.** Glutamate receptors

Receptor	Component	Transmembrane Regions	G-Proteins	Transduction systems	Agonists potency
<b>NMDA</b>	NMDAR1	4	--	Open	GLU>NMDA
	NMDAR2A	4		ionic channels	--
	NMDAR2B	4		Na <sup>+</sup> , Ca <sup>++</sup>	--
	NMDAR2C	4			--
	NMDAR2D	4			--
<b>AMPA</b>	GluR1	4	--	Open	QA>DOM≈AMPA>GLU>KA
	GluR2	4		ionic channels	QA>AMPA>GLU>KA
	GluR3	4		Na <sup>+</sup> , K <sup>+</sup> (Ca <sup>++</sup> )	QA>AMPA>GLU>KA
<b>Kainate</b>	GluR4	4			QA>AMPA>GLU>KA
	GluR5	4	--	Open	DOM>KA>QA≈GLU>AMPA
	GluR6	4		ionic channels	DOM>KA>QA>GLU>AMPA
	GluR7	4		Na <sup>+</sup> , Ca <sup>++</sup>	DOM>KA>GLU>QA>AMPA
	KA1	4			KA>QA>DOM>GLU>AMPA
	KA2	4			KA>QA>DOM>GLU>AMPA
<b>Metabotropic</b>	mGluR1	7	G <sub>q</sub> o G <sub>i</sub> /G <sub>o</sub>	Activates PLC	QA>IBO≈GLU>tACPD
	mGluR2	7	G <sub>i</sub> /G <sub>o</sub>	Inhibits AC	GLU≈tACPD>IBO>QA
	mGluR3	7	G <sub>i</sub> /G <sub>o</sub>	Inhibits AC	GLU≈tACPD>IBO>QA
	mGluR4	7	G <sub>i</sub> /G <sub>o</sub>	Inhibits AC	AP4>GLU>tACPD (QA inactive)
	mGluR5	7	G <sub>q</sub> o G <sub>i</sub> /G <sub>o</sub>	Activates PLC	QA>GLU≈IBO>tACPD
	mGluR6	7	G <sub>i</sub> /G <sub>o</sub>	Inhibits AC	--

Glutamate receptors are classified as ionotropic (NMDA, AMPA and kainate) and metabotropic. Depending on the receptor type they show different transmembrane regions and different affinity for the agonists.

In the central nervous system the N-methyl-D-aspartate (NMDA) receptor channel plays an important role in synaptic plasticity and neuronal development. It has a heteromeric configuration consisting of the epsilon (NR2) subunits, which potentiate the channel activity and modulate the functional properties, and zeta 1 (NR1) subunit, which is essential to form functional NMDA receptors channels (22).

### 3.1.2. Non-NMDA receptors

AMPA and kainate receptors have been regarded as rather impermeable to divalent cations, in particular to Ca<sup>2+</sup> (23), although in certain neurons Ca<sup>2+</sup>-permeable kainate receptors were observed (24-26). Pharmacological studies indicate that the AMPA and kainate receptors are responsible for the voltage-independent portion of the synaptic response in many neuronal pathways. Kainate receptors could probably have multiple actions, e.g. the opening of a voltage-independent cation channel as well as a modulatory action, possibly via calcium channels.

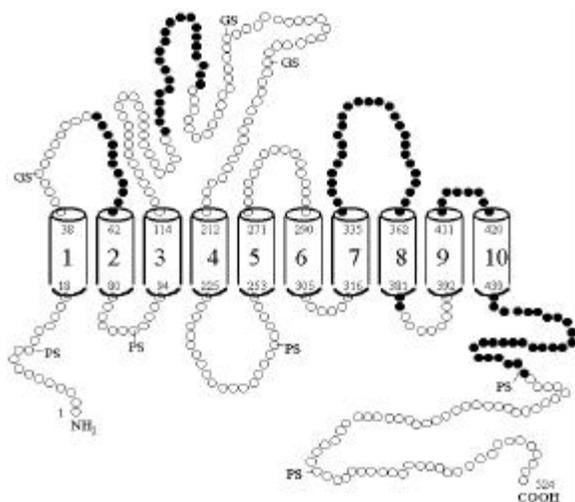
The finding that L-AP4 can potently block synaptic transmission in these systems yet is ineffective as an antagonist of the other well characterized excitatory amino acid agonists indicate that L-AP4 acts at receptors others than those identified by NMDA, kainate or AMPA. Early studies suggested that the AP4 receptor could be identified in presynaptic membranes as a sodium-independent, chloride-dependent L-glutamate binding site.

### 3.2. Metabotropic glutamate receptors

The metabotropic glutamate receptors (mGluR) are both functionally and pharmacologically different from the family of the ionotropic receptors. The mGluR is coupled to a G protein(s) and evokes a variety of functions by mediating intracellular signal transduction (27,28). It also differs from known ionotropic receptors in agonists selectivity (28,29) (See table 1 and figure 2).

Seven subtypes of mGluR are known to exist (12) but their roles in synaptic physiology are not very understood. They are classified upon their second messenger as follows: mGluR1 and mGluR5 are associated to inositol phosphate (IP) and to changes in calcium concentration and belong to the Group I. mGluR2 and mGluR3 belong to Group II and mGluR4, mGluR6-mGluR8 are related to Group III. All receptors from Groups II and III inhibit the cAMP production.

Postsynaptic group I mGlu receptors may modulate both AMPA and NMDA receptor mediated currents, probably via phosphorylation of the respective ion channels. Group II/III receptor-activation produce neuroprotective effects. In cerebellar Purkinje cells, application of the mGluR agonist *trans*-1-aminocyclopentane-1,3-dicarboxylic acid, or the active enantiomer, 1S,3R-ACPD, results in a depolarization associated with an inward current and an elevation of intracellular calcium (30).



**Figure 3.** Structural model of EAAC1. EAAC1 transporter has 10 transmembrane sections. It is a glycoprotein with 3 external glycosylation sites (GS) and has 5 internal potentially phosphorylations sites (PS). Domains corresponding to regions of extended sequence identity with GLT-1 and GLAST are shown as filled circles.

#### 4. EXCITATORY AMINO ACIDS TRANSPORTERS

Uptake of the acidic amino acids from the extracellular environment is mediated by sodium-dependent transport systems of high affinity. Five subtypes of high-affinity glutamate transporters have been cloned independently (31-35). Although they have different nomenclature, the actual nomenclature used for human glutamate transporters is EAAT (excitatory amino acid transporter) followed by a number. Those transporters have been related to the previous known transporters from other species by amino acid sequence identity. Here we describe the structure, distribution, functional expression and pharmacology of these transporter subtypes.

##### 4.1. EAAT1 and GLAST1

EAAT1 has a molecular weight of 59.5 kDa and 96% amino acid sequence identity with the rat GLAST1 sequence (33). GLAST is a specific transporter for L-glutamate and L-aspartate and plays an important role in the termination of neurotransmitter signals on excitatory synapses. It is specifically expressed in brain being distributed in glial cells. In cerebellum, GLAST message is specifically expressed in the striatum gangliosum made up primarily by Purkinje and Bergmann glia cells (33).

Storck *et al.* (33) isolated and sequenced a 3 kb clone from a rat brain cDNA library. The predicted sequence of the polypeptide consists on a 543 amino acid residues protein. A tentative model for the rat GLAST protein comprises six  $\alpha$ -helical membrane-spanning segments in its N-terminal half with approximately the same spacing as the first six helices of previously reported neurotransmitter transporters (see figure 3).

Significant sequence similarity of GLAST to the glutamate transporters of *E. coli* (36), *Bacillus staerothermophilus* and *Bacillus caldotenax* and to the dicarboxylate transporters of *Rhizobium meliloti* and *Rhizobium leguminosarium* (37). The overall amino acid sequence identities range from 26 to 32%. It shares no sequence similarity with the *E. coli* Na<sup>+</sup>-dependent glutamate transporter (38,39) or the cloned mammalian neurotransmitter transporters studies so far (40,41). The transporter function has been verified by amino acid uptake and electrophysiological studies in the *Xenopus laevis* oocyte system.

The results provide evidence for GLAST-1 carrying out a high affinity, sodium-dependent L-glutamate transport with a proposed stoichiometry of 3 Na<sup>+</sup>, 1 L-glutamate/1K<sup>+</sup>. There is no evidence for the cotransport of protons (42). Amino acid uptake shows saturation kinetics: K<sub>m</sub>(L-glu)=77 ±27 mM (33) and other amino acids including L-alanine, L-leucine, L-glutamine, L-arginine and L-methionine are not transported in significant amounts. DL-threo-3-hydroxy-aspartate, a strong inhibitor of the Na<sup>+</sup>-dependent glutamate uptake (43) and capable of causing neuronal degeneration (44), is a potent inhibitor of GLAST. A decrease in Na<sup>+</sup>-dependent L-glutamate transport in patients with Alzheimer's disease has been reported (45). Whether GLAST plays a pivotal or ancillary role in these disorders remains to be elucidated.

##### 4.2. EAAT2 and GLT-1

EAAT2 has a molecular weight of 62.1 kDa and a 95% identity with the correct sequence (46) of rat GLT-1 (32). GLT-1 is expressed in astrocytes and maintains the low extracellular glutamate concentration of approximately 1 $\mu$ M below neurotoxic levels. The L-glutamate transporter cDNA was obtained by immunoscreening of a  $\lambda$ <sub>Zap</sub> library from rat brain (47) with an antibody raised against the purified glial transporter. The cDNA sequence predicts a protein of 573 amino acids with 8-9 putative transmembrane  $\alpha$ -helices (32) (figure 3). It is a glycoprotein with 2 potential N-linked glycosylation sites and 2 phosphorylation sites (48). GLT-1 does not share significant overall homology with any known eukariotic protein, including the Na<sup>+</sup>/glucose transporter and the growing superfamily of neurotransmitter transporters but with the protein-coupled L-glutamate transporter glt-p of *E.coli*.

The transport system has three substrates: Na<sup>+</sup>, L-glutamate and K<sup>+</sup> (49-51). In an electrogenic process, the transporter takes up Na<sup>+</sup> and L-glutamate and extrudes K<sup>+</sup>. Like the others (Na<sup>+</sup>-K<sup>+</sup>)-coupled L-glutamate transporters (52), GLT-1 is stereospecific, being strongly inhibited by L-glutamate but not by the same concentration of D-glutamate. The apparent K<sub>m</sub> in intact cells is 10  $\mu$ M higher than in membrane preparations (53) and in the purified and reconstituted transporter (54).

Glutamate analogues: L-aspartate, D-aspartate, cysteine sulphinate, threo-3-hydroxy-DL-aspartate and L-trans-pyrrolidine-2,4-dicarboxylate are competitive inhibitors of GLT-1. L-trans-pyrrolidine-2,4-dicarboxylate inhibits

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transport of L-glutamate but does not prevent it from binding to its receptors (55). The GLT-1 system is potently inhibited by dihydrokainate (DHK) and L- $\alpha$ -aminoadipate (L-AAD), while the EAAC1 system (see 2.3.) is inhibited by L-AAD and is essentially DHK insensitive.

The decrease in GLT-1 function cannot be attributed to selective astrocytic degeneration as there is no loss of staining of the astrocytic marker, GFAP. In fact, previous studies have suggested that astrogliosis and not a loss of astrocytes may be present in ALS motor cortex (56). Studies have been carried out to try to identify the reason for the selective loss of GLT-1 in ALS. There is no evidence for a decrease in gene expression as there was no change in the levels of the mRNA coding for the protein in ALS patients (57). Other possible explanations for a loss of GLT-1 could involve translation mechanisms whereby the gene is transcribed into mRNA but defects in the translation could interfere with the synthesis of the protein. Alternatively, the protein may be translated normally but may be much more unstable than normal. Finally, the decrease in activity may be due to posttranslational modifications, possibly induced by an increase in the levels of cellular free radicals.

### 4.3. EAAT3 and EAAC1

EAAT3 has a molecular weight of 57.2 kDa and 92% identity with the rabbit sequence termed EAAC1 (58). EAAC1 is of both neuronal and epithelial origin. In brain it provides a presynaptic glutamate uptake mechanism to terminate the action of released glutamate at glutamatergic synapses. But it is also expressed in  $\gamma$ -aminobutyric acid (GABA)-ergic cerebellar Purkinje cells, where it provides glutamate as a precursor for GABA synthesis.

To isolate the cDNA encoding rabbit EAAC1, Kanai and Hediger (58) screened a rabbit intestinal cDNA library for their ability to induce [ $^{14}$ C] glutamate uptake in *Xenopus* oocytes. They isolated a cDNA which encodes a 524-residue protein. This protein has approximately 10 putative membrane-spanning regions but alternative models with a different number of membrane-spanning regions can be constructed. EAAC1 has a significant homology to the H<sup>+</sup>-coupled gltP glutamate transporters of *E. coli*, *B. stearothermophiles* and *B. caldotenax* and to the dctA dicarboxylate transporter of *Rhizobium meliloti*. They have sequence identities ranging between 27% and 32%. There is neither homology to the Na<sup>+</sup>-Cl<sup>-</sup>-dependent GABA/neurotransmitter transporter family (40,41,59) nor to the *E. coli* Na<sup>+</sup>/glutamate transporter gltS (38).

EAAC1-mediated transport is electrogenic and dependent on extracellular Na<sup>+</sup> but not on Cl<sup>-</sup>. Studies in salamander retinal glial cells and in oocytes expressing EAAC1 revealed that glutamate transport coupled to the cotransport of two Na<sup>+</sup> and the countertransport of one K<sup>+</sup> and one OH<sup>-</sup> (60).

Due to the presence of a large hydrophobic stretch near the C terminus (residues 357 to 444, figure 3), alternative models with a different number of membrane

spanning regions are conceivable. The N-terminal part of EAAC1 is hydrophilic and lacks a signal peptide. A motif-like cluster of serine residues is present (residues 331-334). Similar clusters have been identified in the ligand-binding sites of receptors for acetylcholine and biogenic amines.

The function and pharmacology of the expressed protein are characteristic of the high-affinity glutamate transporter already identified in neuronal tissues. Membrane currents were measured in *Xenopus* oocytes injected with EAAC1 cRNA. L-glutamate, L-aspartate and D-aspartate evoked inward currents, almost with the same amplitude, whereas currents induced by D-glutamate and L- or D-homocysteinate were smaller. The glutamate receptor ligands NMDA and kainate did not induce current whereas quisqualate evoked a significant inward current. EAAC1-mediated L-glutamate transport is saturable and the K<sub>m</sub> value is 12,2±1,2  $\mu$ M, indicative of a high-affinity transport (31).

The abnormal glutamate transport that is associated with certain neurodegenerative diseases and which occurs during ischemia and anoxia could be due to abnormalities in the function of this protein.

### 4.4. EAAT4

EAAT4 is a human L-aspartate/L-glutamate transporter which is expressed in the cerebellum and at lower levels, in brain stem, cortex and hippocampus. cDNA encoding EAAT4 was obtained from human cerebellar messenger RNA (34). The amino acid sequence exhibits 65%, 41% and 48 % amino-acid identity to the human glutamate transporters EAAT1, 2 and 3 respectively.

EAAT4-mediated transport is electrogenic, dependent on Na<sup>+</sup> and K<sup>+</sup> and it has properties of a ligand-gated chloride channel. Its transport is saturable and the K<sub>m</sub> values derived from current measurements are K<sub>m</sub> (L-asp)=184±0.46  $\mu$ M and K<sub>m</sub>(L-glu)=3.3±0.4  $\mu$ M (34). Pharmacological properties of EAAT4 are similar to those previously described to the other glutamate transporters.

Structural analogs of glutamate, L-*trans*-2,4-pyrrolidine dicarboxylic acid (PDC), L-quisqualate and L- $\alpha$ -aminoadipate, elicit currents in oocytes expressing EAAT4. This current is predominantly carried by chloride ions and chloride-dependent glutamate transport activities have been reported in synaptosomes and other brain preparations but they have not demonstrated the cotransport of chloride ions with substrates (61,62). This chloride conductance is not blocked by endogenous oocyte chloride channel blockers. Thereafter, EAAT4 functions as a transporter, reducing the amount of neurotransmitter available for activating postsynaptic receptors and as a glutamate-gated chloride channel, modifying the neuronal excitability by its capacity for enhancing chloride permeability.

### 4.5. EAAT5

EAAT5 is a human glutamate transporter whose mRNA is mostly expressed in the retina. Arriza *et al.* (35) isolated the transporter EAAT5 from a salamander retina glutamate transporter cDNA to screen a human retinal  $\lambda$ gt10

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cDNA library. The gene product is 560 amino acid residues in length. EAAT5 has 46% identity with EAAT1, 43% identity with EAAT4, 37% with EAAT3 and 36% identity with EAAT2.

The amino- and carboxy- terminal sequences of the excitatory amino acid transporters are poorly conserved. In EAAT5 C-terminus there is a sequence motif found in synaptic membrane proteins: E-S or T-X-V-COOH (63). The C-termini interact with several PDZ (a modular protein-binding motif) domains in PSD-95 (postsynaptic density-95kDa protein). The presence of this PDZ domain suggests that the transporter is a component of the signal transduction pathway. Its channel-like properties may indicate a role in retinal physiology different from neurotransmitter clearance.

EAAT5 uptake is sodium- and voltage-dependent and chloride-independent. It has stereospecificity for L-glutamate versus D-glutamate and L-aspartate versus D-aspartate with  $K_m$  values for L-glutamate and L-aspartate of  $64 \pm 6 \mu\text{M}$  and  $13 \pm 5 \mu\text{M}$ , respectively. L-*trans*-pyrrolidine-2,4-dicarboxylic acid (tPDC) and *threo*- $\beta$ -hydroxyaspartate (THA) are potent blockers but neither generated a current with a voltage dependence similar to that of glutamate (35). However, ion substitution experiments show that the currents seen are carried by chloride ions. These properties are similar to those described in retinal neurons suggesting that the transporter can be involved in visual processing (35).

### 4.6. Synaptic vesicles glutamate transporter

Glutamate is preserved in secretory vesicles at pre-synaptic terminals. A unique group of proteins found on secretory vesicles are the transporters needed for the accumulation of neurotransmitters from cytoplasm into these vesicles. The vesicular glutamate transporter is one between at least four different vesicular transporter types which have been biochemically identified (64,65).

Synaptic vesicles and microvesicles, enclosed in endocrine cells like pinealocytes, possess an active glutamate-specific transporter that is dependent on the extravesicular  $\text{Cl}^-$  concentration, on an electrochemical proton gradient across the vesicle membrane (66-69) and on the temperature (67).

The dependence of glutamate uptake on ATP-generated proton electrochemical potential was analysed in a highly purified preparation of synaptic vesicles from rat brain (70). The glutamate anion is transported into synaptic vesicle by a  $\text{Na}^+$ -independent vesicle transport, driven by the internal positive membrane potential generated by the vesicular ATP-dependent  $\text{H}^+$  transport (66,67,70). Anyway, it seems that glutamate uptake is solely dependent on  $\Delta\psi$ , suggesting that protons are not directly involved.

The vesicle carrier has a low substrate affinity ( $K_m = 1.6 \text{ mM}$ ) and is highly specific for L-glutamate (5 mM D-glutamate reduces uptake by 30% while 5 mM L-aspartate has no effect) (71). Other glutamate analogues which interact

with various glutamate receptor subtypes don't affect transport (71). It has been observed a good correlation between acidification and inhibition of glutamate uptake by glutamate analogues such as 1-aminocyclohexane-*trans*-1,3-dicarboxylic acid (72). Glutamine, aspartate and GABA do not inhibit L-glutamate uptake (67).

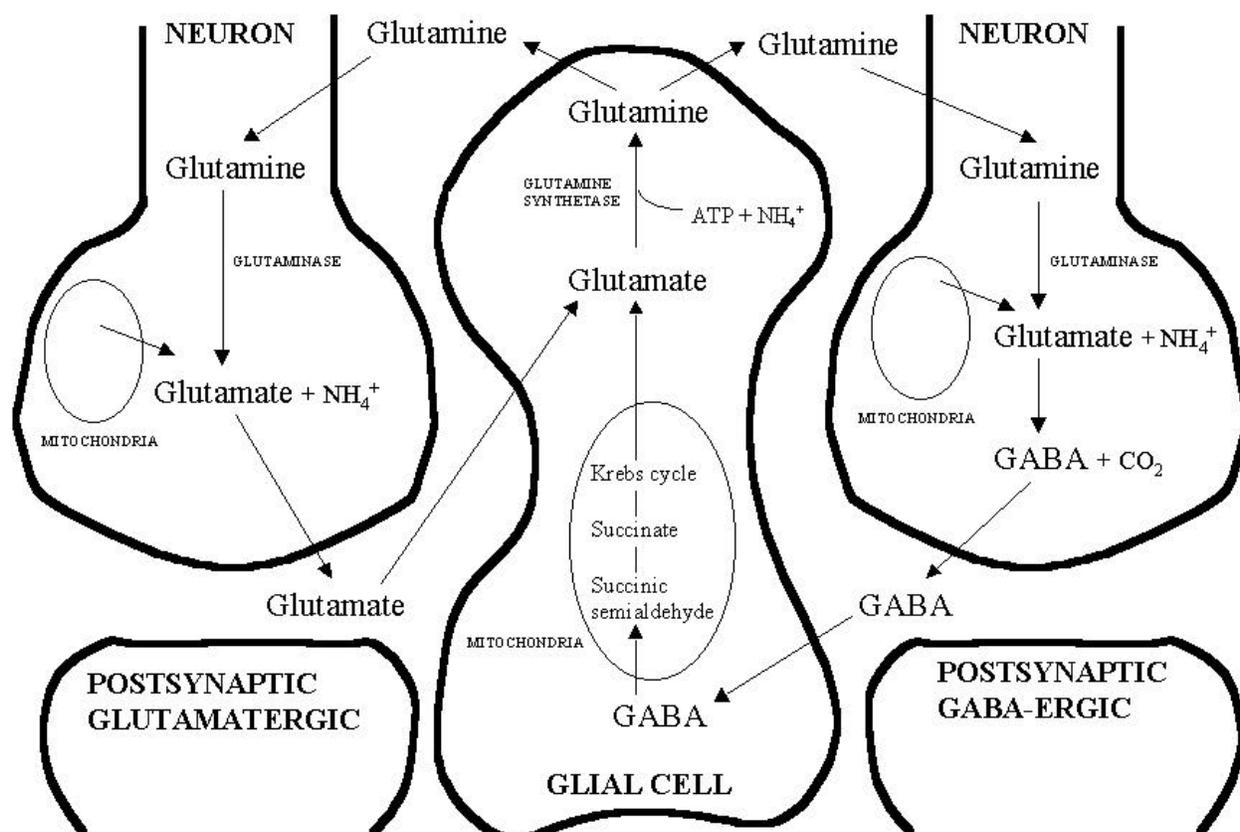
Due to the fact that the transporter has not been cloned yet, there is no knowledge about its structure, sites involved in vesicular transporter function nor the sites that determine substrate specificity. Nevertheless, future molecular analysis will help us to understand some events such as cell-specific expression, specific targeting, bioenergetic properties and neuropharmacology.

## 5. METABOLIC INTERACTIONS BETWEEN NEURONS AND ASTROCYTES

If one tries to envisage the metabolic capabilities required to maintain glutamatergic, aspartatergic, and GABA-ergic transmission (Glu, Asp, and GABA) in a simple cell type residing behind a blood-brain barrier through which there is rapid exchange of  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{NH}_3$  and a rapid net influx of glucose, but no net accumulation of either glutamate, aspartate, GABA, or glutamine (73), one would end up with a cell like that sketched in figure 4. Neurons are able to synthesize both glutamate and GABA from glutamine, and astrocytes form and release glutamine (which has no transmitter activity) after accumulation of either glutamate or GABA.

Extracellular glutamate is, to a larger extent, accumulated into astrocytes both in the intact brain (74) and in cultured cells (75,76), but much of the accumulated glutamate (how much probably depends upon the experimental conditions) is degraded as a metabolic fuel to  $\text{CO}_2$  and  $\text{H}_2\text{O}$  in astrocytes and thus not converted to glutamine (75,77). New glutamate and GABA precursor molecules will, therefore, have to be synthesized from glucose. Since carboxylation of pyruvate to oxaloacetate, an intermediate of the TCA cycle, occurs in astrocytes, net synthesis of  $\alpha$ -ketoglutarate in the TCA cycle can also take place in these cells.

The rate of glutamate metabolism to  $\text{CO}_2$  is high in astrocytes but not in the two neuronal types, especially not in the glutamatergic cerebellar granule cells. The rapid  $\text{CO}_2$  formation in astrocytes from glutamate appears to represent mainly a net utilization of glutamate (78), not just an isotope exchange between glutamate and  $\alpha$ -ketoglutarate. Utilization of glutamate or glutamine as a metabolic substrate is not restricted to cultured cells but has also been observed in brain slices and dissociated cell preparations (79,80). As long as the glutamate utilized as a metabolic fuel originally is produced from glucose behind the blood-brain barrier, this is not a violation of the well-established fact that the entire adult brain *in vivo* under normal conditions almost exclusively utilizes glucose as its substrate for energy metabolism (81).

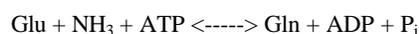


**Figure 4.** Schematic diagram of glutamate/glutamine and GABA/glutamine cycles. In neurons, glutamate and  $\gamma$ -aminobutyric acid (GABA) are synthesized from glucose or glutamine. Neurotransmitter released in synaptic cleft can then interact with receptor sites. To terminate this effect, transport to astroglial cells is performed with higher affinity than to neuron cells. In astroglial cells there is a higher glutamine synthase activity and glutamate and GABA are metabolized to glutamine, which has no neurotransmitter effects and can be recycled to neurons to form glutamate or GABA.

Exposure to very high potassium concentrations (> 20 mM) causes depolarization and a depolarization-induced increase in free intracellular calcium concentration in synaptosomes (82), neurons, and astrocytes (83) and enhances metabolic interactions between these two cell types by facilitating glutamate (and GABA) release from neurons and  $\text{CO}_2$  fixation in astrocytes, which in turn promotes astrocytic formation of transmitter precursors for neurons. During exposure to slightly elevated potassium. In the following section, we describe some properties of the enzymes involved in the glutamic acid metabolism (figure 5).

### 5.1. Glutamine synthetase (E.C. 6.3.1.2.)

Glutamine synthetase catalyzes several reactions (84), although the main reaction is the following one:

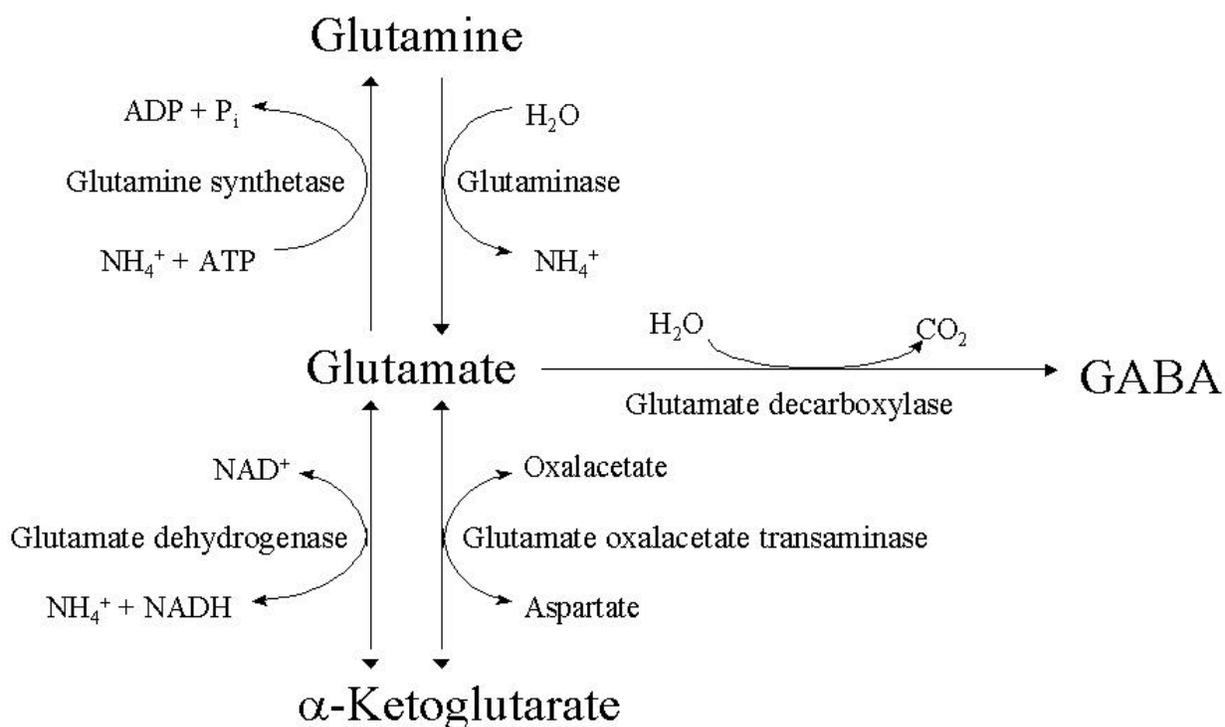


The enzyme has two important functions: assimilation of ammonia and biosynthesis of glutamine. The enzyme from brain has been studied in rat, ox, sheep, pig

and human. It has been isolated from a variety of sources and the proteins vary greatly in their ability to catalyze the reverse reaction. With the mammalian enzyme, however, the forward rate relative to the reverse rate is about 10 to 1 (85).

The purification of the enzyme usually proceeds through four steps consisting on an acetone powder extract, precipitation by acid, hydroxylapatite and DEAE-cellulose column chromatography (86); with a yield of 15-30% and a purification of about 200-fold.

Glutamine synthetase is composed of eight subunits which are identical (44,000-50,000 daltons) showing rather similar amino acid composition (84). The enzyme has a molecular weight of 400,000 daltons, distributed in two tetramers (87). Distribution of glutamine synthetase and glutaminase are uneven in central nervous system. Berl (88) determined the distribution of glutamine synthetase in 16 brain areas of the adult rat. The site of glutamine synthesis, from glutamate amidation via glutamine synthase (GS), is in glial cells (89); and with a cytosolic location (9). Additionally, glia cells contain carbonic



**Figure 5.** Glutamate metabolism. Glutamate from mammalian brain can be obtained from glutamine (glutaminase) or from  $\alpha$ -ketoglutarate (glutamate dehydrogenase and glutamate oxalacetate transaminase). Degradation of glutamate can generate  $\alpha$ -ketoglutarate by reversible reactions, GABA (glutamate decarboxylase) or glutamine (glutamine synthetase).

anhydrase, which catalyzes the CO<sub>2</sub> hydration reaction and HCO<sub>3</sub><sup>-</sup> formation. Therefore, glia cells could be important in acid-base regulation and related amino acid metabolism in CNS. Glutamine formed by GS can move into adjacent nerve endings where it is utilized either in metabolic pathways unrelated or not directly related to neurotransmitter glutamate and GABA synthesis or in formation of neurotransmitter glutamate and GABA via glutaminase and glutamate decarboxylase, respectively.

The enzyme is irreversibly inhibited by methionine sulfoxamine (MSO) (90). ATP and magnesium are necessary for the binding of glutamate to the enzyme, whereby it becomes activated. Tate *et al.* (84) calculated in rat liver  $K_m$  for ATP = 2.3 mM; and Deul *et al.* (86)  $K_m$  for ammonia = 0.3 mM. Certain anions, particularly bicarbonate and chloride, activate the enzyme when nonsaturating concentrations of L-glutamate are used. Although liver glutamine synthase is activated by 2-oxoglutarate, brain enzyme is less affected by this compound (84). The mammalian enzymes are inhibited by inorganic phosphate and carbamyl phosphate (91). This effect can be due to the reaction of ATP synthesis from ADP and carbamyl phosphate, catabolized also by glutamine synthetase.

### 5.2. Glutaminase (E.C. 3.5.1.2.)

The reverse reaction of glutamine synthase is catalyzed by the ubiquitous enzyme glutaminase, which is

present in both neurons and astrocytes (92). Nevertheless, glutaminase is predominantly a neuronal enzyme and it has been localized in mitochondria (93,94). Pig brain mitochondria have been shown to contain two major forms of glutaminase, one soluble located in the matrix and one membrane-bound enzyme located in the inner membrane and both activated by phosphate (95).

Soluble glutaminase has been purified from pig brain (96,97) and some other sources (98-100). The soluble enzyme is present as a dimer (101) with a relatively low specific activity and a highly aggregated form of the enzyme with a considerably greater specific activity. By an incubation with phosphate, the soluble enzyme is reversibly and slowly aggregated (101-103). Because of this complicated regulatory behavior, some evidences have been suggested that the membrane-bound and soluble enzyme may have different function in the brain (95).

Kinetic studies of the two enzymes have been performed by Nimmo and Tipton (101) and they show  $K_m$  values for glutamine of about 0.8-1.4 mM and 3.4-9.7 mM. One of the products, glutamate, inhibits the enzyme strongly, whereas the other product ammonia has only a slight inhibitory action on the enzyme. Glutamate inhibition is mixed ( $K_i^{\text{slope}} = 1.6$  mM and  $K_i^{\text{intercept}} = 3.3$  mM).

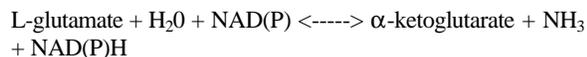
In astrocytes exposed to 1.2 mM valproate, glutaminase activity increased 80% in primary culture by day

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2 and remained elevated by day 4; glutamine synthetase activity was decreased 30% (104).

### 5.3. Glutamate dehydrogenase (E.C. 1.4.1.2.-4.)

Glutamate dehydrogenases catalyze the following reversible reaction:



although it appears that the reaction velocity is higher when the formation of glutamate is studied.

Three different enzymes are considered depending on the use of NAD/NADH (E.C. 1.4.1.2.), NADP/NADPH (E.C. 1.4.1.4.) or both (E.C. 1.4.1.3.) as coenzymes. Neural glutamate dehydrogenase (E.C. 1.4.1.3.) can use both coenzymes, although it has been shown that NAD is used more effectively than NADP (105). The direction of neural glutamic dehydrogenase (E.C. 1.4.1.3.) activity appears to be regulated in part by the tissue NAD(P)/NAD(P)H concentration ratio (105, 106). In rat brain GDH activity exists in two distinct forms differing in solubility, kinetic parameters, resistance to heat inactivation and allosteric properties (107). These forms have been designed soluble and particulate GDH (107,108).

When the ratio is high, e.g., in the absence of glucose, oxidative deamination of glutamate occurs. In the presence of glucose, when the ratio falls, and  $\alpha$ -ketoglutarate is not rate limiting, reductive amination of  $\alpha$ -ketoglutarate is favored. Kinetic parameters have been studied for both directions of the reaction (105).

GDH's from various organs of the same species are similar, if not identical. Complete cross-reaction occurs between antibodies induced by bovine liver GDH and extracts of bovine spleen, brain and heart. Most animal GDH are inhibited by GTP and activated by ADP (109). GDH from bovine brain has been partially purified by Grisolia *et al.* (106) and shows a specificity either for NAD or NADP. This enzyme has a molecular weight of 332,000 daltons, as judged from the amino acid sequence of the six identical subunits (110).

As compared with other enzymes, the  $V_{\max}$  of GDH in synaptic mitochondria from rat brain is 20-40% lower than  $V_{\max}$  of aspartate aminotransferase, but 4-5fold higher than  $V_{\max}$  of phosphate dependent glutaminase (111).

### 5.4. Transaminases

Transaminases play an important role in the aminoacid metabolism, as they are able to catabolize a reversible transference of an amino group from an aminoacid to a ketoacid acceptor. Those enzymes use pyridoxal phosphate as a coenzyme, which will perform the transference of the amino group. Among those transaminases, aspartate aminotransferase or glutamate oxalacetate transaminase (E.C. 2.6.1.1.) catabolizes the reversible transference of amino group of Asp to  $\alpha$ -

ketoglutarate and generates oxalacetate and glutamate. There have been found two isoenzymes of aspartate aminotransferase in animals: a cytoplasmic and a mitochondrial. Both are dimeric proteins of 45,000 daltons and 2,000 daltons subunits (112).

Aspartate amino transferase (AAT) activity seems to be higher than glutamate dehydrogenase (GDH). The ratio AAT/GDH is between 10 and 20 in rat brain (113) or in squid giant nerve (114). Transamination of glutamate by using aspartate amino transferase generates aspartate, which is also a neurotransmitter; whereas glutamate dehydrogenase yields ammonia but not another neurotransmitter. The higher activity of AAT can be therefore due to prevent the toxic action of ammonia.

Another transaminase is alanine aminotransferase (E.C. 2.6.1.2.), an enzyme which transfers amino from alanine to  $\alpha$ -ketoglutarate to yield pyruvate and glutamate. This enzyme presents also a cytoplasmic and a mitochondrial isoenzymes.

### 5.5. Glutamic acid decarboxylase (E.C. 4.1.1.15.)

The enzyme removes the  $\alpha$ -carboxyl group of glutamate to produce a  $\gamma$ -carboxyl amino acid called  $\gamma$ -amino butyric acid (GABA). This decarboxylation of glutamate to GABA is not very different from decarboxylation of L-DOPA or tryptophan to dopamine and serotonin. Like those enzymes, glutamic acid decarboxylase requires the cofactor pyridoxal phosphate (vitamin B<sub>6</sub>).

The enzyme is highly substrate specific, although Homola and Dekker (115) showed that some glutamate analogs can also be decarboxylated.

## 6. DYSFUNCTION OF EXCITATORY AMINOACID NEUROTRANSMISSION

It is important to maintain low levels (1-3 $\mu$ M) of extracellular glutamate as excessive receptor stimulation or excessive ammonium generated by the glutamate dehydrogenase can lead to neural injury and/or death ("excitotoxicity").

Glutamate appears to be remarkably potent and rapidly acting neurotoxin. Exposure to 100  $\mu$ M glutamate for 5 min is enough to destroy large numbers of cultured cortical neurons (116). By the way, glutamate neurotoxicity may be blocked by antagonist compounds and attenuated by antagonists added after glutamate exposure (116).

Neurodegenerative diseases, such as Alzheimer's disease (AD), Huntington's disease (HD), Parkinson's disease (PD) and amyotrophic lateral sclerosis (ALS), particularly affect old people and result in: i) a modification of the individual personality; ii) the need for constant help from relatives; iii) a high economical costs for family and institutions. In Spain alone, over 500.000 people are affected with those diseases with this increasing as the aged population increases. Due to the increased lifespan in

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developed societies, neurodegenerative diseases have been increased in the European Union and represent one third of deaths (after cancer and cardiovascular problems). It is thought that with Alzheimer's disease alone, at the beginning of next century, 8 million Europeans will be affected.

Many reports have been published on increased levels of glutamate in certain neurodegenerative diseases such as AD, HD, PD and ALS (117-120). Increased extracellular glutamate has also been implicated in the onset of neurodegeneration associated with hypoxic damage (stroke). The release in glutamate following hypoxia has been suggested to be due, at least in part, to a calcium-independent mechanism following the reversal of the neuronal glutamate uptake carrier (121). This increase in extracellular glutamate acts afterwards postsynaptically to increase cellular calcium levels with subsequent cell death.

The mechanisms by which glutamate is increased in neurodegenerative diseases is unknown. The cause of this increased extracellular glutamate has been ascribed to a decrease in the activity of glutamate dehydrogenase (PD) (122) or a decrease in the number of Na<sup>+</sup>-glutamate transporters (ALS, HD) (123). As it is a neurotoxic, it is likely that the high glutamate concentration observed in neurodegenerative diseases are the most likely cause of the neurodegeneration.

Marangos *et al.* (124) stated the glutamate hypothesis for early Alzheimer's disease: "Cell death due to neuronal toxicity could result from excessive synthesis or release of glutamate or a glutamate-like substance, faulty glutamate reuptake, decreased glutamate degradation, or decreased inhibition of excitatory neurons. Any of these aberrant processes could, early in the disease, increase local levels of glutamate and so initiate a slow, progressive degeneration and eventual death of neurons".

Several post-mortem studies have compared brain glutamate levels in Alzheimer's disease to those in control subjects. Some investigators (125-127) have found lower glutamate levels in the frontal cortex and the temporal cortex of Alzheimer's patients than in control subjects. Cerebrospinal fluid (CSF) concentration of free glutamate was significantly higher in patients with Alzheimer's disease than in comparison subjects (117). It should be noted that measurements of glutamate in CSF are likely to give better approximation of glutamate concentrations at synapses than are plasma glutamate concentrations.

In Huntington's disease, glutamate and GABA concentrations decrease in striatum and caudate nucleus from brain (118,128). However, no reduction at all was observed in the frontal cortex of patients. A likely possibility is that the low glutamate content of the caudate and the putamen in HD results from chronic failure of the normal reuptake mechanism for glutamate released at synapses, with or without any excessive rate of release of this neurotransmitter. This possibility is supported by the finding of Cross *et al.* (129), who observed large reductions in high-affinity glutamate uptake sites in autopsy specimens of caudate and putamen from HD patients.

If either excessive release or decreased reuptake of glutamate occurred in the striatum in HD, concentrations of glutamate might become high at synapses, with resulting damage to neurons. Some of the excess glutamate accumulate in synaptic clefts in HD would be carried away in the extracellular fluid, thus eventually causing a lowered glutamate content in striatal tissue. This fact is supported by an increased glutamate concentration in CSF of living HD patients as it was observed for Alzheimer's disease patients.

In Parkinson's disease, Schapire *et al.* (130) demonstrated a reduced activity of complex I of the mitochondrial respiratory chain in the region of substantia nigra in brain. Deficiencies on complex II and IV have been also observed in muscle biopsy from PD patients (131). Cedarbaum *et al.* (122) observed a deficiency of GDH but not on pyruvate dehydrogenase complex. Since complex I is the point of entry for reducing equivalents (as NADH) to the respiratory chain, a decrease in complex I activity might result in feedback endproduct inhibition of GDH. Decreased levels of GDH might exert an excitotoxic glutamate effect via NMDA receptors on striatal dopamine nerve terminals (132) and contribute to cellular degeneration in PD.

Amyotrophic lateral sclerosis (ALS) is a disease resulting in degeneration of the motor cortex, the brain-stem and the spinal chord. While there are a number of hypotheses underlying this disease, an increase in glutamatergic neurotransmission has been proposed as a key event in the disease onset and recently, this has been ascribed, at least in part, to a defect in the function of the GLT-1 glutamate transporter which is localized on astrocytes (123).

Recent *in vitro* studies have demonstrated that a blockade of the GLT-1 transporter either by transport inhibitors or by an antisense approach resulted in a slow, selective loss of motor neurons, thus strengthening the case for a critical role for GLT-1 in the etiology of ALS (120,133). Furthermore, this decrease in uptake does not appear to be associated with a decrease in transporter expression levels (57) and there is no evidence of specific protein mutations associated with the disease. Because of the potential role of free radicals in ALS and the upset in function of the superoxide dismutase enzyme in the familial form of ALS, previous studies have suggested that an increase in free radicals may impair the function of GLT-1 (134).

The role of free radicals in the etiology of ALS has been strengthened by the selection of point mutations in the cytosolic Cu/Zn superoxide dismutase (SOD-1) associated with the familial form of ALS (FALS) (135). These changes were not detected in control individuals and do not represent normal allelic variants. SOD-1 catalyses the dismutation of the superoxide radical (O<sub>2</sub><sup>-</sup>) to hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) and represents the first line of defense against oxygen toxicity. The mechanism responsible for tissue damage associated with reduced SOD activity remains to be defined. Direct toxicity due to the superoxide radical is probably minor in comparison to the generation of

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the hydroxyl radical (OH.) which is much more reactive. In addition, the superoxide may interact with endogenously formed nitric oxide to form peroxynitrite which can oxidize methionine residues in proteins and peptides as well as thiols and thioethers (136). It has therefore been suggested that an increase in free radicals in ALS may be, at least in part, responsible for the upset in functioning of the GLT-1 transporter and that the disease may have both a free radical and excitatory amino acid basis.

Glutamate, and particularly the glutamate transporter system, have also been implicated in the ischemic damage associated with anoxia/hypoxia (stroke). For the first few minutes of ischemia, there is a slow acid shift of the cellular pH with a slow rise of extracellular potassium concentration and a subsequent decrease in extracellular sodium and calcium. The rise in potassium depolarizes the cells to around -20mV (anoxic depolarization) and the release of glutamate (137). The mechanism by which glutamate is released in ischemia has been controversial. Some reports suggest that the release is calcium-dependent, suggesting conventional vesicular release, while others claim that the release is calcium-independent, implying a non-exocytotic mechanism such as the reversed operation of the glutamate uptake carrier (138).

## 7. REFERENCES

1. Hoop B., Masjedi M.-R., Shih V.E. & Kazemi H.: Brain glutamate metabolism during hypoxia and peripheral chemodenervation. *J. Appl. Physiol.* 69, 147-154 (1990)
2. Housley G.D. & Sinclair J.D.: Localization by kainic acid lesions of neurones transmitting the carotid chemoreceptor stimulus for respiration in rat. *J. Physiol. Lond.*, 406, 99-114 (1988)
3. Oldendorf W.H.: Brain uptake of radiolabeled amino acids, amines, and hexoses after arterial injection. *Am J Physiol.* 221(6), 1629-1639 (1971)
4. Oldendorf W.H. & Szabo J.: Amino acid assignment to one of three blood-brain barrier amino acid carriers. *Am J Physiol.* 230(1), 94-98 (1976)
5. Pratt O.E.: The transport of metabolizable substances into the living brain. *Adv Exp Med Biol.* 69, 55-75 (1976)
6. Clarke D.D., Ronan E.J., Dicker E. & Tirri L.: Ethanol and its relation to amino acid metabolism in brain. In *Metabolic Compartmentation and Neurotransmission*. Eds: Berl S., Clarke D.D., Schneider D. Plenum Press, New York. 449-460 (1975)
7. Balazs R., Machiyama Y., Hammond B.J., Julian T. & Richter D.: The operation of the  $\gamma$ -aminobutyrate bypath of the tricarboxylic acid cycle in brain tissue *in vitro*. *Biochem. J.* 116, 445-467 (1970)
8. Machiyama Y., Balazs R., Hammond B.J., Julian T. & Richer D.: The metabolism of GABA and glucose in potassium stimulated brain tissue *in vitro*. *Biochem. J.*, 116, 469-482 (1970)
9. Norenberg M.D. & Martínez-Hernández A.: Fine structural localization of glutamine synthetase in astrocytes of rat brain. *Brain Res.*, 161, 303-310 (1979)
10. Berl S., Lajtha A. & Waelsch H.: Amino acid and protein metabolism. VI. Cerebral compartments of glutamic acid metabolism. *J. Neurochem.* 7, 186-197 (1961)
11. van den Berg C.J., Matheson D.F., Ronda G., Reijnierse G.L.A., Blokhuis G.G.D., Kroon M.C., Clarke D.D. & Garfinkel D.: A model of glutamate metabolism in brain: a biochemical analysis of a heterogenous structure. In *Metabolic Compartmentation and Neurotransmission*. Eds: Berl S., Clarke D.D., Schneider D. Plenum Press, New York. 709-723 (1975)
12. Tanabe Y., Masu M., Ishii T., Shigemoto R. & Nakanishi S.: A family of metabotropic glutamate receptors. *Neuron.* 8(1), 169-179 (1992)
13. Watkins J.C. & Collingridge G.L.: In *The NMDA receptor*. Oxford: Oxford Univ. Press. (1989)
14. Daw N.W., Stein P.S.G. & Fox K.: The role of NMDA receptors in information processing. *Annu. Rev. Neurosci.* 16, 207-222 (1993)
15. Thomas RJ: Excitatory amino acids in health and disease. *Journal of the American Geriatrics Society* 43(11), 1279-1289 (1995)
16. Muller W.E., Mutschler E. & Riederer P.: Noncompetitive NMDA receptor antagonists with fast open-channel blocking kinetics and strong voltage-dependency as potential therapeutic agents for Alzheimer's dementia. *Pharmacopsychiatry* 28(4), 113-124 (1995)
17. Coyle J.T.: An animal model for Huntington's disease. *Biological Psychiatry* 14(2),251-276 (1979)
18. McDonald J.W. & Johnston M.V.: Pharmacology of N-methyl-D-aspartate-induced brain injury in an *in vivo* perinatal rat model. *Synapse.* 6(2), 179-188 (1990)
19. Flatman J.A., Schwindt P.C. & Crill W.E.: The induction and modification of voltage-sensitive responses in cat neocortical neurons by N-methyl-D-aspartate. *Brain Res.* 363, 62-77 (1986)
20. Nowak L., Bregetowski P., Ascher P., Herbet A. & Prochiantz A.: Magnesium gates glutamate-activated channels in mouse central neurones. *Nature* 307, 462-465 (1984)
21. Mayer M.L., McDermott A.B., Westbrook G.L., Smith S.J. & Barker J.L.: Agonist- and voltage-gated calcium entry in cultured mouse spinal cord neurons under voltage clamp measured using arsenazo III. *J. Neurosci.* 7, 3230-3244 (1987)

## Excitatory Amino Acid Neurotransmission

22. Watanabe M.: Dynamic regulation of the NMDA receptor channel subunits in the central nervous system and their involvement in synaptic plasticity and development. *Kaibogaku Zasshi - Journal of Anatomy* 71(5),517-522 (1996)
23. Mayer M.L. & Westbrook G.L.: The physiology of excitatory amino acids in the vertebrate central nervous system. *Prog. Neurobiol.* 28, 197-276 (1987)
24. Murphy S.N., Thayer S.A. & Miller R.J.: The effects of excitatory amino acids on intracellular calcium in single mouse striatal neurons. *J. Neurosci.* 7, 4145-4158 (1987)
25. Iino M., Ozawa S. & Tsuzuki K.: Permeation of calcium through excitatory amino acid receptor channels in cultured rat hippocampal neurones. *J. Physiol. (London)* 424, 151-165 (1990)
26. Gilbertson T.A., Scobey R. & Wilson M.: Permeation of calcium ions through non-NMDA glutamate channels in retinal bipolar cells. *Science* 251, 1613-1615 (1991)
27. Sugiyama H., Ito I. & Hirono C.: A new type of glutamate receptor linked to inositol phospholipid metabolism. *Nature* 325, 531-533 (1987)
28. Schoepp D., Bockaert J. & Sladeczek F.: Pharmacological and functional characteristics of metabotropic excitatory amino acid receptor. *Trends Pharmacol. Sci.* 11, 508-515 (1990)
29. Sugiyama H., Ito I. & Watanabe S.: Glutamate receptor subtypes may be classified into two major categories: a study on *Xenopus* oocytes injected with rat brain mRNA. *Neuron* 3, 129-132 (1989)
30. Batchelor A.M., Madge D.J. & Garthwaite J.: Synaptic activation of metabotropic glutamate receptors in the parallel fibre-Purkinje cell pathway in rat cerebellar slices. *Neuroscience* 63(4), 911-915 (1994)
31. Fei Y.J., Kanai Y., Nussberger S., Ganapathy V., Leibach F.H., Romero M.F., Singh S.K., Boron W.F. & Hediger M.A.: Expression cloning of a mammalian proton-coupled oligopeptide transporter. *Nature* 368, 563-566 (1994)
32. Pines G, Danbolt N.C., Bjoras M., Zhang Y., Bendahan A., Eide L., Koepsell H., Storm-Mathisen J., Seeburg E. & Kanner B.I.: Cloning and expression of a rat brain L-glutamate transporter. *Nature* 360, 464-467 (1992)
33. Storck T, Schulte S., Hofmann K. & Stoffel W.: Structure, expression, and functional analysis of a Na(+)-dependent glutamate/aspartate transporter from rat brain. *Proceedings of the National Academy of Sciences of the United States of America* 89(22),10955-10959 (1992)
34. Fairman W.A., Vandenberg R.J., Arriza J.L., Kavanaugh M.P. & Amara S.G.: An excitatory amino-acid transporter with properties of a ligand-gated chloride channel. *Nature* 375, 599-603 (1995)
35. Arriza J.L., Eliasof S., Kavanaugh M.P. & Amara S.G.: Excitatory amino acid transporter 5, a retinal glutamate transporter coupled to a chloride conductance. *Proceedings of the National Academy of Sciences of the United States of America* 94(8),4155-4160 (1997)
36. Tolner B., Poolman B., Wallace B. & Konings W.N.: Revised nucleotide sequence of the gLTP gene which encodes the proton glutamate aspartate transport protein of *Escherichia-Coli* k-12. *Journal of Bacteriology* 174, 2391-2393 (1992)
37. Jiang J., Gu B., Albright L.M. & Nixon B.T.: Conservation between coding and regulatory elements of *Rhizobium-Meliloti* and *Rhizobium-leguminosarum* DCT genes. *Journal of Bacteriology* 171 (10), 5244-5253 (1989)
38. Deguchi Y., Yamato I. & Anraku Y.: Nucleotide sequence of gltS, the Na<sup>+</sup>/glutamate symport carrier gene of *Escherichia coli* B. *Journal of Biological Chemistry* 265(35), 21704-21708 (1990)
39. Kalman M., Gentry D.R. & Cashel M.: Characterization of the *Escherichia-Coli* k-12 GLT-S glutamate permease gene. *Molecular & General Genetics* 225 (3), 379-386 (1991)
40. Guastella J., Nelson N., Nelson H., Czyzyk L., Keynan S., Miedel M.C., Davidson N., Lester H.A. & Kanner B.I.: Cloning and expression of a rat brain GABA transporter. *Science* 249, 1303-1306 (1990)
41. Shimada S., Kitayama S., Lin C.L., Patel A., Nanthakumar E., Gregor P., Kuhar M. & Uhl G.: Cloning and expression of a cocaine-sensitive dopamine transporter complementary DNA. *Science* 254, 576-578 (1991)
42. Kloeckner U., Storck T., Conradt M. & Stoffel W.: Electrogenic L glutamate uptake in *Xenopus-laevis* oocytes expressing a rat brain L glutamate-L-aspartate transporter GLAST-1. *Journal of Biological Chemistry* 268 (20), 14594-14596 (1993)
43. Balcar V.J. & Johnston G.A.R.: The structural specificity of the high affinity uptake of L-glutamate and L-aspartate by rat brain slices. *Journal of Neurochemistry* 19, 2657-2666 (1972)
44. Mc Bean G.J. & Roberts P.J.: Neurotoxicity of L-glutamate and DL-threo-3-hydroxyaspartate in the rat striatum. *Journal of Neurochemistry* 44, 247-254 (1985)
45. Palmer A.M., Procter A.W., Stratmann G.C. & Bowen D.M.: Excitatory amino-acid-releasing and cholinergic neurons in Alzheimer's disease. *Neuroscience Letters* 66 (2),199-204 (1986)
46. Kanner B.I.: Glutamate transporters from brain: a novel neurotransmitter transporter family. *FEBS Lett.* 325, 95-99 (1993)
47. Keinänen K, Wisden W., Sommer B., Werner P., Herb A., Verdoorn T.A., Sakmann B. & Seeburg P.H.: A family

## Excitatory Amino Acid Neurotransmission

- of AMPA-selective glutamate receptors. *Science* 249, 556-560 (1990)
48. Lehre K.P., Levy L.M., Ottersen O.P., Storm-Mathisen J. & Danbolt N.C.: Differential expression of two glutamate transporters in rat brain: quantitative and immunocytochemical observations. *J. Neurosci.* 15:1835-1853 (1995)
49. Kanner B.I. & Schuldiner S.: Mechanism of transport and storage of neurotransmitters. *Critical Reviews in Biochemistry* 22 (1), 1-38 (1987)
50. Nicholls D. & Attwell D.: The release and uptake of excitatory amino acids. *Trends in Pharmacological Sciences* 11 (11), 462-468 (1990)
51. Pines G. & Kanner B.I.: Counterflow of L-glutamate in plasma membrane vesicles and reconstituted preparations from rat brain. *Biochemistry* 29 (5), 11209-11214 (1990)
52. Balcar V.J. & Johnston G.A.R.: Glutamate uptake by brain slices and its relation to the depolarization of neurones by acidic amino acids. *Journal of Neurobiology* 3, 295-301 (1972)
53. Kanner B.I. & Sharon I.: Active transport of L-glutamate by membrane vesicles isolated from rat brain. *Biochemistry* 17, 3949-3953 (1978)
54. Danbolt N.C., Pines G. & Kanner B.I.: Purification and reconstitution of the sodium and potassium-coupled glutamate transport glycoprotein from rat brain. *Biochemistry* 29 (28), 6734-6740 (1990)
55. Bridges R.J., Stanley M.S., Anderson M.W., Cotman C.W. & Chamberlin A.R.: Conformationally defined neurotransmitter analogues selective inhibition of glutamate uptake by one pyrrolidine-2,4-dicarboxylate diastereomer. *Journal of Medicinal Chemistry* 34 (2), 717-725 (1991)
56. Nagy D., Kato T. & Kushner P.D.: Reactive astrocytes are widespread in the cortical gray matter of amyotrophic lateral sclerosis. *J. Neurosci. Res.* 38, 336-347 (1994)
57. Bristol, L.A. & Rothstein, J.D.: Glutamate transporter gene expression in amyotrophic lateral sclerosis motor cortex. *Ann. Neurol.* 39:676-679 (1996)
58. Kanai Y. & Hediger M.A.: Primary structure and functional characterization of a high-affinity glutamate transporter. *Nature* 360, 467-471 (1992)
59. Blakely R.D., Berson H.E., Freneau R.T. Jr., Caron M.G., Peek M.M., Prince H.K. & Bradley C.C.: Cloning and expression of a functional serotonin transporter from rat brain. *Nature* 354, 66-70 (1991)
60. Bouvier M., Szatkowski M., Amato A. & Attwell D.: The glial cell glutamate uptake carrier countertransports pH-changing anions. *Nature* 360, 471-474 (1992)
61. Zaczek R., Arlis S., Markl A., Murphy T., Drucker H. & Coyle J.T.: Characteristics of chloride-dependent incorporation of glutamate into brain membranes argue against a receptor binding site. *Neuropharmacology* 20 (4), 281-288 (1987)
62. Pin J.P., Bockaert J. & Recasens M.: The calcium-chloride-dependent L-[3H]glutamate binding: a new receptor or a particular transport process?. *FEBS Letters* 175, 31-36 (1984)
63. Sheng M.: PDZs and receptor/channel clustering: rounding up the latest suspects. *Neuron* 17(4), 759-67 (1996)
64. Kanner B.I. & Schuldiner S.: Mechanism of transport and storage of neurotransmitters. *CRC Crit. Rev. Biochem.* 22, 1-38 (1987)
65. Johnson R.: Accumulation of biological amines in chromaffin granules: a model for hormone and neurotransmitter transport. *Physiol. Rev.* 68, 232-307 (1988)
66. Burger P.M., Mehl E., Cameron P.L., Maycox P.R., Baumert M., Lottspeich F., DeCamilli P. & Jahn R.: Synaptic vesicles immunisolated from rat cerebral cortex contain high levels of glutamate. *Neuron* 3:715-720 (1989)
67. Naito S. & Ueda T.: Adenosine triphosphatase-dependent uptake of glutamate into protein I-associated synaptic vesicles. *J. Biol. Chem.* 258, 696-699 (1983)
68. Hartiger J. & Jahn R.: An anion binding site that regulates the glutamate transporter of synaptic vesicles. *J. Biol. Chem.* 268(31), 23122-23127 (1993)
69. Moriyama Y. & Yamamoto A.: Microvesicles isolated from bovine pineal gland specifically accumulate L-glutamate. *FEBS Lett.* 367, 233-236 (1995)
70. Maycox P.R., Deckwerth T., Hell J.W. & Jahn R.: Glutamate uptake by brain synaptic vesicles. *J. Biol. Chem.* 263, 15423-15428 (1988)
71. Naito S. & Ueda T.: Characterization of glutamate uptake into synaptic vesicles. *J. Neurochem.* 44, 99-109 (1985)
72. Moriyama Y. & Yamamoto A.: Vesicular L-glutamate transporter in microvesicles from bovine pineal glands. Driving force, mechanism of chloride anion activation, and substrate specificity. *J. Biol. Chem.* 270(38), 22314-22320 (1995)
73. Sokoloff L., Takahashi S., Gotoh J., Driscoll B.F. & Law M.J.: Contribution of astroglia to functionally activated energy metabolism. *Dev. Neurosci.*, 18(5-6), 344-52 (1996)
74. McLennan H.: The autoradiographic localization of L-[3H]glutamate in rat brain tissue. *Brain Res.* 115, 139-144 (1976)

## Excitatory Amino Acid Neurotransmission

75. Hertz L. & Schousboe A.: Role of astrocytes in compartmentation of amino acid and energy metabolism. In *Astrocytes*. Eds: Federoff S., Vernadakis A. Academic Press, New York. Vol. 2, 179-208 (1986)
76. Hertz L. & Schousboe A.: Metabolism of glutamate and glutamine in neurons and astrocytes in primary cultures. In *Glutamine and glutamate in mammals*. Eds: Kvamme E. CRC Press, Boca Raton, Fla. Vol. 2, 39-55 (1988)
77. Hertz L., Yu A.C.H. & Schousboe A.: Uptake and metabolism of malate in cultured neurons and astrocytes. *J. Neurosci. Res.* 33, 289-396 (1992)
78. Hertz L., Peng L., Westergaard N., Yudkoff M. & Schousboe A.: Neuronal-astrocytes interactions in metabolism of transmitter amino acids of the glutamate family. In *Alfred Benzon Symposium*. No. 32: Drug research related to neuroactive amino acids. (Schousboe A. & Diemer N. eds.) Munksgaard, Copenhagen. (1992)
79. Yu A.C.H. & Hertz L.: Metabolic sources of energy in astrocytes. In *Glutamine, glutamate and GABA in the central nervous system*. (Hertz L., Kvamme E., McGeer E.G. & Schousboe A. eds.) Alan R. Liss, New York. (1983)
80. Tildon J.T. & Roeder L.M.: Glutamine oxidation by dissociated cells and homogenates of rat brain: kinetics and inhibitor studies. *J. Neurochem.* 42, 26-35 (1984)
81. Solokoff L.: The brain as a chemical machine. In *Neuronal-astrocytic interactions: their implications in normal and pathological brain function* (Yu A., Hertz L., Norenberg M.D., Sykova E. & Waxman S. eds.) *Prog. Brain Res.* 94 (1992)
82. Erecinska M., Nelson D. & Chance B.: Depolarization induced changes in cellular energy production. *Proc. Natl. Acad. Sci. USA* 88, 7600-7604 (1991)
83. Code W.E., White H.S. & Hertz L.: The effect of midazolam on calcium signaling in astrocytes. *Ann. N.Y. Acad. Sci.* 625, 430-432 (1991)
84. Tate S.S., Leu F.-Y. & Meister A.: Rat liver glutamine synthetase. Preparation, properties, and mechanism of inhibition by carbamyl phosphate. *J. Biol. Chem.*, 247 (17), 5312-5321 (1972)
85. Woolfolk C.A., Shapiro B. & Stadtman E.R.: Regulation of glutamine synthetase. I. Purification and properties of glutamine synthetase from *Escherichia coli*. *Arch. Biochem. Biophys.*, 116, 117-192 (1966)
86. Deuel T.F., Louie M. & Lerner A.: Glutamine synthetase from rat liver. Purification, properties, and preparation of specific antisera. *J. Biol. Chem.*, 253 (17), 6111-6118 (1978)
87. Wilk S., Meister A., Haschemeyer R.H.: Dissociation of native octameric brain glutamine synthetase to a tetramer by treatment with N-acetylimidazole. *Biochemistry* 9(10), 2039-2043 (1970)
88. Berl S.: Glutamine synthetase: determination of its distribution in brain development. *Biochemistry* 5, 916-922 (1966)
89. Cooper A.J.W., Veraga F. & Duffy T.E.: Cerebral glutamide synthetase. In *Glutamine, glutamate and GABA in the central nervous system*. Eds: Hertz L., Kvamme E., McGeer E.G., Schousboe A. New York: Liss. 77-93 (1983)
90. Weyne J., VanLeuven F., Kazemi H. and Leusen I. (1978) Selected brain amino acids and ammonium during chronic hypercapnia in conscious rats. *J. Appl. Physiol.* 44, 333-339 (1978)
91. Tatibana M. & Ito K.: Carbamyl phosphate synthetase of the hematopoietic mouse spleen and the control of pyrimidine biosynthesis. *Biochem-Biophys-Res-Commun.* 26(2), 221-227 (1967)
92. Hogstad S., Svenneby G., Torgner I. Aa., Kvamme E., Hertz L. & Schousboe A.: Glutaminase in neurons and astrocytes cultured from mouse brain: kinetic properties and effect of phosphate, glutamate and ammonia. *Neurochem. Res.* 13(4), 383-388 (1988)
93. Ward H.K. & Bradford H.F.: Relative activities of glutamine synthetase and glutaminase in mammalian synaptosomes. *J. Neurochem.*, 33, 339-342 (1979)
94. Kaneko T., Urade Y., Watanabe Y. & Mizuno N.: Production, characterization, and immunohistochemical application of monoclonal antibodies to glutaminase purified from rat brain. *J. Neurosci.* 7, 302-309 (1987)
95. Nimmo G.A. & Tipton K.F.: The distribution of soluble and membrane-bound forms of glutaminase in pig brain. *J. Neurochem.*, 33, 1089-1094 (1979)
96. Nimmo G.A. & Tipton K.F.: Purification of soluble glutaminase from pig brain. *Biochem. Pharmacol.* 29, 359-367 (1980)
97. Svenneby G., Torgner I.A. & Kvamme E.: Purification of phosphate-dependent pig brain glutaminase. *J. Neurochem.* 20, 1217-1224 (1973)
98. Kvamme E., Svenneby G. & Tveit B.: In *Molecular Basis of some aspects of mental activity*. Eds: Walaas O. Academic Press, New York 211-219 (1966)
99. Curthoys N.P., Kuhlenschmidt T., Godfrey S.S. & Weiss R.F.: Phosphate-dependent glutaminase from rat kidney. Cause of increased activity in response to acidosis and identity with glutaminase from other tissues. *Arch. Biochem. Biophys.* 172(1), 162-167 (1976)
100. Horowitz M.L. & Knox W.E.: A phosphate activated glutaminase in rat liver different from that in kidney and other tissues. *Enzymol. Biol. Clin. Basel.* 9(4), 241-255 (1968)

## Excitatory Amino Acid Neurotransmission

101. Nimmo G.A. & Tipton K.F.: Kinetic comparisons between soluble and membrane-bound glutaminase preparations from pig brain. *FEBS Letters*, 57-64 (1981)
102. Svenneby G.: Time and temperature dependent activation of pig brain glutaminase. *J. Neurochem.* 19, 165-174 (1972)
103. Kvamme E. & Torgner I. Aa.: The effect of acetyl-coenzyme A on phosphate-activated glutaminase from pig kidney and brain. *Biochem. J.* 137, 525-530 (1974)
104. Collins R.M. Jr., Zielke H.R. & Woody R.C.: Valproate increases glutaminase and decreases glutamine synthetase activities in primary cultures of rat brain astrocytes. *J. Neurochem.*, 62, 1137-1143 (1994)
105. Palmada M. & Centelles J.J.: The effect of pH on glutamate dehydrogenase from bovine brain mitochondria. Submitted (1998)
106. Grisolia S., Quijada C.L. & Fernandez M.: Glutamate dehydrogenase from yeast and from animal tissues. *Biochim. Biophys. Acta*, 81, 61 (1964)
107. Colon A., Plaitakis A., Perakis A., Berl S. and Clarke D.D.: Purification and characterization of a soluble and a particulate glutamate dehydrogenase from rat brain. *J. Neurochem.* 46, 1811-1819 (1986)
108. Plaitakis A., Berl S. & Yahr M.D. Neurological disorders associated with deficiency of glutamate dehydrogenase. *Ann. Neurol.* 15, 144-153 (1984)
109. Frieden C.: In "The role of nucleotides for the function and conformation of enzymes" (H.M. Kalckar *et al.*, eds.), p. 194. Munksgaard. Copenhagen (1969)
110. Moon K. & Smith E.L.: Sequence of bovine liver glutamate dehydrogenase. 8. Peptides produced by specific chemical cleavages; the complete sequence of the protein. *J. Biol. Chem.* 248(9), 3082-3088 (1973)
111. Dennis S.C. & Clark J.B.: The pathway of glutamate metabolism in rat brain mitochondria. *Biochem. J.* 168, 521-527 (1977)
112. Obaru K., Tsuzuki T., Shimada C. & Shimada K. (1986) Structural organization of the mouse aspartate aminotransferase isoenzyme genes. Introns antedate the divergence of cytosolic and mitochondrial isoenzyme genes. *J. Mol. Biol.* 200, 13-22 (1986)
113. Erecinska M. & Silver I.A.: Metabolism and role of glutamate in mammalian brain. *Prog. Neurobiol.* 35, 245-296 (1990)
114. García R.A.G. & Villegas J.: Aspartate aminotransferase and glutamate dehydrogenase activities in the squid giant nerve. *J. Neurochem.* 64, 437-442 (1995)
115. Homola A.D. & Dekker E.E.: Decarboxylation of gamma-hydroxyglutamate by glutamate decarboxylase of *Escherichia coli* (ATCC 11246) *Biochemistry* 6(8), 2626-2634 (1967)
116. Choi D.W., Maulucci-Gedde M. & Kriegstein A.R.: Glutamate neurotoxicity in cortical cell culture. *J. Neurosci.* 7(2), 357-368 (1987)
117. Pomara N., Singh R., Deptula D., Chou J.C.-Y., Schwartz M.B. & LeWitt P.A.: Glutamate and other CSF amino acids in Alzheimer's disease. *Am. J. Psychiatry* 149, 251-254 (1992)
118. Perry T.L. & Hansen S.: What excitotoxin kills striatal neurons in Huntington's disease? Clues from neurochemical studies. *Neurology* 40, 20-24 (1990)
119. Plaitakis AP, Constantakakis E. & Smith J.: The neuroexcitotoxic amino acids glutamate and aspartate are altered in the spinal cord and brain in amyotrophic lateral sclerosis. *Ann. Neurol.* 24, 446-449 (1988)
120. Rothstein J.D., Dykes-Hoberg M., Pardo C.A., Bristol L.A., Jin L., Kuncl R.W., Kanai Y., Hediger M.A., Wang Y., Schielke J.P. & Welty D.F.: Knockout of glutamate transporters reveals a major role for astroglial transport in excitotoxicity and clearance of glutamate. *Neuron* 16, 675-686 (1996)
121. Szatkowski M. & Attwell D.: Triggering and execution of neuronal death in brain ischaemia: two phases of glutamate release by different mechanisms. *Trends Neurosci.* 17(9), 359-365 (1994)
122. Cedarbaum J.M., Sheu K.-F.R., Harding B.J., Blass J.P., Javoy-Agid F. & Agid Y.: Deficiency of glutamate dehydrogenase in postmortem brain samples from parkinsonian putamen. *Annals Neurol.* 28(1), 111-112 (1990)
123. Rothstein, J.D., Van Kammen, M., Levey, A.I., Martin, L., Kunel, R.W. (1995) Selective loss of glial glutamate transporter GLT-1 in amyotrophic lateral sclerosis. *Ann. Neurol.* 38:73-84.
124. Marangos W.F., Greenamyre J.T., Penny J.B., Young A.B.: Glutamate dysfunction in Alzheimer's disease: an hypothesis. *Trends Neurosci.* 10, 65-68 (1987)
125. Arai H., Kobayashi K., Ichimiya Y., Kosaka K. & Iisuka R.: Free amino acids in post-mortem cerebral cortices from patients with Alzheimer-type dementia. *Neurosci. Res.* 2, 486-490 (1985)
126. Procter A.W., Palmer A.M., Francis P.T., Lowe S.L., Neary D., Murphy E., Doshi R. & Bowen D.M.: Evidence of glutamatergic denervation and possible abnormal metabolism in Alzheimer's disease. *J. Neurochem.* 50, 790-802 (1988)
127. Hyman B.T., VanHoeren G.W. & Damasio A.R.: Alzheimer's disease: glutamate depletion in the hippocampal perforant pathway zone. *Ann. Neurol.* 22, 37-38 (1987)
128. Reynolds G.P. & Pearson S.J.: Decreased glutamic

## Excitatory Amino Acid Neurotransmission

acid and increased 5-hydroxytryptamine in Huntington's disease brain. *Neurosci. Lett.* 78, 233-238 (1987)

129. Cross A.J., Slater P. & Reynolds G.P.: Reduced high affinity glutamate uptake sites in the brains of patients with Huntington's disease. *Neurosci. Lett.* 67, 198-202 (1986)

130. Schapira A.H., Cooper J.M., Dexter D., Jenner P., Clark J.B. & Marsden C.D.: Mitochondrial complex I deficiency in Parkinson's disease. *Lancet* 1, 1269 (1989)

131. Bindoff-L.A., Birch-Machin M., Cartledge N.E., Parker W.D. Jr. & Turnbull D.M.: Mitochondrial dysfunction in Parkinson's disease. *Lancet* 2, 49 (1989)

132. Clow D.W. & Jhamandas K.J.: Characterization of L-glutamate action on the release of endogenous dopamine from the rat caudate-putamen. *J. Pharmacol. Exp. Ther.* 248, 722-728 (1989)

133. Rothstein J.D., Jin L, Dykes-Hoberg M. & Kuncl R.W.: Chronic inhibition of glutamate uptake produces a model of slow neurotoxicity. *Proc. Natl. Acad. Sci. USA* 90, 6591-6595 (1993)

134. Trotti D., Rossi D., Gjesdal O., Levy L.M., Racagni G., Danbolt N.C. & Volterra A.: Peroxynitrite inhibits glutamate transporter subtypes. *J. Biol. Chem.* 271(11), 5976-5979 (1996)

135. Rosen D.R., Siddique T., Patterson D., Figlewicz D.A., Sapp P., Hentati A., Donaldson D., Goto J. & O'Regan J.P.: Mutations in Cu/Zn superoxide dismutase gene are associated with familial amyotrophic lateral sclerosis. *Nature* 1993 Jul 22;364(6435), 362 (1993)

136. Moreno J.J. & Pryor W.A.: Inactivation of alpha 1-proteinase inhibitor by peroxynitrite. *Chem. Res. Toxicol.* 5:425-431 (1992)

137. Nicholls D. & Attwell D.: The release and uptake of excitatory amino acids. *Trends Pharmacol Sci.* 11(11), 462-468 (1990)

138. Attwell D., Barbour B., Szatkowski M.: Nonvesicular release of neurotransmitter. *Neuron* 11:401-407 (1993)

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