Title
Glia in brain energy metabolism: A perspective.

Journal
Glia, 66(6)

Authors
Barros, L
Brown, Angus
Swanson, Raymond

Publication Date
2018-06-01

DOI
10.1002/glia.23316

Peer reviewed

HHS Public Access

Author manuscript

Glia. Author manuscript; available in PMC 2019 June 01.

Published in final edited form as:

Glia. 2018 June ; 66(6): 1134–1137. doi:10.1002/glia.23316.

Glia in brain energy metabolism: a perspective

L. Felipe Barros[1], **Angus Brown**[2], and **Raymond A. Swanson**[3]

[1]Center for Scientific Studies, Valdivia 5110466, Chile

[2]School of Life Sciences, University of Nottingham, Nottingham, NG7 2UH

[3]Dept. of Neurology, University of California San Francisco; and San Francisco Veterans Affairs Medical Center, San Francisco, CA 94121 USA

Abstract

Early views of glia as relatively inert, housekeeping cells have evolved, and glia are now recognized as dynamic cells that not only respond to neuronal activity but also sense metabolic changes and regulate neuronal metabolism. This evolution has been aided in part by technical advances permitting progressively better spatial and temporal resolution. Recent advances in cell-type specific genetic manipulation and sub-cellular metabolic probes promise to further this evolution by enabling study of metabolic interactions between intertwined fine neuronal and glial processes *in vivo*. Views of glia in disease processes have also evolved. Long considered purely reactive, glia and particularly microglia are now seen to play active roles in both promoting and limiting brain injury. At the same time, established concepts of glial energetics are now being linked to areas such as learning and neural network function, topics previously considered far removed from glial biology.

Keywords

axon; glucose; glutamate; glycogen; lactate; nitric oxide; superoxide

Prevailing views of glial energetics have been repeatedly revised. Glia are now recognized to both support and influence neuronal energy metabolism. Recent advances highlight influences of glial energetics on cognitive function and disease processes.

Energy metabolism in the central nervous system (CNS) differs from other tissues with respect to its relatively high resting rate and local, activity-dependent fluctuations. These features have been successfully exploited using fluorodeoxyglucose positron emission tomography (2DG PET), functional magnetic resonance imaging (fMRI), and other methods to detail the neuroanatomical substrates and connectivity that underlie brain function. It has only more recently been recognized how CNS glial cells – astrocytes, oligodendrocytes, and microglia – regulate, respond to, and contribute to these unique features. Untangling these bidirectional relationships between glia and neurons will be essential for a more complete

Corresponding Author: Raymond A. Swanson, MD, (127) Neurology VAMC, 4150 Clement St., San Francisco, CA 94121, raymond.swanson@ucsf.edu, (415) 750-2011.

ORCID: 0000-0002-3664-5359

understanding of brain energetics and function. The perspective presented here aims to highlight key milestones in this area to date, and identify areas of future interest.

Initial recognition that glia dynamically contribute to brain energy expenditure

The recognition that brain energy metabolism differs in key respects from other tissues is based on two landmark observations. The first was that brain metabolic rate is exceedingly high, accounting for roughly 20% of total body basal energy expenditure in adult humans while comprising less than 2% of body weight (Kety 1957). Subsequent studies established that the primary source of this energy demand was plasma membrane ion pumps and the activation of post-synaptic receptors. The second landmark observation was that local brain activity produced local increases in brain glucose utilization (Sokoloff et al. 1977). The 2-deoxyglucose tracer method developed for these studies further revealed that basal rates of glucose metabolism varied between brain regions, and between white matter and gray matter structures.

Neither of these two fundamental observations directly indicated any particular role for glial cells in brain energy metabolism. Although glial cells actively maintain plasma membrane ion gradients, they do not generate action potentials, and were consequently long considered metabolically inert relative to neurons. That view was overturned by the finding that astrocytes respond to neurotransmitters with membrane depolarization (Kettenmann et al. 1984). The immediate implication of this finding was that astrocytes could participate in brain information processing, but a corollary aspect was that astrocytes must similarly expend energy in processing these neurotransmitter induced responses. Later work showed that neurotransmitter-induced responses in astrocytes activate a variety of secondary signal transduction pathways, including G-protein-mediated signaling, intracellular calcium elevations, intracellular sodium elevations, and others that require ATP consumption (Rose and Karus 2013); and that microglia and oligodendrocytes likewise respond to extracellular signaling molecules with changes in membrane potential and second messenger responses. Extracellular K^+ elevations caused by neuronal activity also drive astrocyte energy consumption, by triggering active K^+ uptake. The external cation site of astrocyte (but not neuronal) Na^+/K^+ ATPase is stimulated by small very increases in extracellular $[K^+]$ (Amedee et al. 1997; Silver and Erecinska 1997).

A second indication that glia play a key role in CNS energy metabolism came from studies of brain glycogen, which in adult mammalian brain is localized primarily to astrocytes (Brown and Ransom 2007). Studies using cultured astrocytes showed that glycogen turnover was influenced by a variety of neurotransmitters and peptides (Magistretti et al. 1983). Using a modification of the 2-deoxyglucose method to label glycogen in the intact brain, it was subsequently shown that sensory stimuli that induce local neuronal activity also induce local astrocyte glycogen turnover, (Swanson et al. 1992). There is a net energy cost to cycling glucose into and out of glycogen polymers, and it remains uncertain what advantage is gained in utilizing glycogen over available glucose. An advantage may stem from the fact that glycogen can be mobilized extremely quickly, and without the initial ATP consumption

required for glucose phosphorylation. Alternatively, astrocyte glycogen consumption may serve to spare interstitial glucose for direct neuronal uptake, particularly when neuronal activity outstrips local glucose supply, or to generate lactate as a substrate for oxidative neuronal metabolism (Dringen et al. 1993). Intriguingly, observations from several recent studies suggest that learning and memory consolidation require astrocyte glycogen metabolism (Hertz and Chen 2017).

Glutamate as a nexus between neuronal activity and glial energy metabolism

It is surprising that glutamate was not recognized as a neurotransmitter until the 1980s, decades after the identification of acetylcholine, norepinephrine, and serotonin. Resistance to this idea can be attributed to the fact that glutamate is ubiquitous and abundant in brain (> 1mM), and had established functions as an energy intermediate and protein building block. Pharmacological dissection of glutamate receptors eventually resolved this issue, and glutamate is now recognized as the dominant excitatory neurotransmitter in mammalian brain. The eventual acceptance of glutamate as an excitatory neurotransmitter led to the first mechanistic understanding of how brain signaling both influences and depends upon astrocyte energy metabolism. Unlike most other neurotransmitters, amino acid neurotransmitters like glutamate are removed from extracellular space by cellular uptake rather than by cleavage. The normal extracellular to intracellular gradient for glutamate is approximately 1:10,000, and the energetic cost for glutamate uptake is accordingly high; approximately 1.5 ATP per molecule transported. Perhaps for this reason, the majority of glutamate uptake is performed by astrocytes, relieving the metabolic burden on neurons (Danbolt et al. 2016). Glutamate uptake is also electrogenic. Uptake by astrocytes may thus also serve to prevent neuronal membrane depolarization that would occur with neuronal glutamate uptake. Once in astrocytes, glutamate can be metabolized to glutamine, at the cost of an additional ATP, for shuttling back to neurons. Alternatively, glutamate can itself be oxidatively metabolized by astrocytes to generate ATP (McKenna et al. 1996). More recently, other metabolites such as adenosine and lactate have been identified as having signaling functions, and the gradual acceptance of their signaling functions may be recapitulating the glutamate history (Barros 2013). The dual roles for glutamate, lactate, and adenosine suggest a broad integration between neurons and glia in brain energy metabolism and information processing.

Trafficking of energy metabolites between glia and neurons

The recognition that astrocytes are primarily responsible for the clearance of glutamate released during synaptic activity was followed by the observation that glutamate can stimulate glucose uptake and lactate production by astrocytes, and led to the concept that neurons may be fueled “on demand” by astrocyte-derived lactate. By this model, astrocytes metabolize glucose to lactate (aerobic glycolysis) in a manner stimulated by glutamate uptake, with the lactate then released to be used by neurons for oxidative ATP production (Pellerin et al. 2007). There is substantial experimental support for the transfer of lactate from astrocytes (and possibly from oligodendrocytes) to neurons, but the quantitative and

functional significance lactate versus glucose as neuronal energy substrates remains to be clarified (Dienel 2012; Nehlig and Coles 2007).

A special case of glial-neuronal metabolite shuttling is presented by myelinated axons. In these axons the vast majority of surface area is isolated from extracellular space by ensheathing oligodendrocytes, and consequently the oligodendrocytes can control the passage of energy substrates and other molecules to the neuronal axons. In the isolated optic nerve (which contains neuronal axons, myelinating oligodendrocytes, and astrocytes), the capacity of axons to maintain high frequency electrical conduction varies with the initial concentration of astrocyte glycogen. Blocking glycogen metabolism induces conduction failure, as does blocking lactate transport (Brown et al. 2003). Importantly, metabolite flux through oligodendrocytes can in turn be regulated by axonal activity: glutamate activation of NMDA receptors on oligodendrocytes increases their glucose uptake, which may then be metabolized to lactate and released to axons for oxidative ATP production (Saab et al. 2016).

Energy metabolism in glial subcellular domains and metabolic sensing

Methodological advances have now refined our view of glia in brain energy metabolism to encompass not only intercellular communication and trafficking, but also subcellular compartmentation. Mitochondrial distribution in astrocytes is not random, and has been shown to be influenced by glutamate transport activity (Jackson et al. 2014). Moreover, astrocytes have extraordinarily complex shapes, each expressing hundreds of thin membranous processes that wrap around synapses and other cellular elements. These processes act independently of one another, exhibiting local fluctuations in Ca^{2+} during local synaptic activity, and are thus termed microdomains (Grosche et al. 1999). How activity is fueled in these astrocyte microdomains remains uncertain, as only a minority of them contain mitochondria.

The concept that glia, particularly astrocytes, can function as metabolic sensors has gained support at multiple levels in recent years. Astrocytes express regional differences in their capacity to detect and respond to metabolic signals such as pO_2, pCO_2, and pH, and play an essential role in the activity induced local blood flow changes mediated by these signals (Attwell et al. 2010; Gordon et al. 2007). Astrocyte responses to these and other metabolic signals likewise influence whole organism responses to their changes, such as respiratory rate (Gourine et al. 2010) and blood pressure.

Glial energy metabolism in disease and inflammation

Brain energy metabolism is altered in many neurological disorders. In some, such as ischemia and severe hypoglycemia, energy failure is a direct cause of brain injury. Ischemia also causes injury through spreading depression, a process in which astrocytes are both mediators and regulators (Seidel et al. 2016). Glycogen is the primary energy reserve in brain, and this reserve is small; equivalent to only a few minutes of brain glucose consumption under physiological conditions. Nevertheless, this astrocyte energy store has significant effects on the capacity of neurons to function and survive during hypoglycemia (Suh et al. 2007), in part because metabolic rate is suppressed during periods of insufficient

glucose supply (Hochachka 1999). Other disorders may be exacerbated by, if not directly caused by disordered energy metabolism. For example, subtle alterations in either mitochondrial function or mitochondrial quality control in Parkinson's disease can lead to death of the dopaminergic neurons that are preferentially affected in this disease. In Alzheimer's disease, decreases in brain glucose utilization precede symptom onset by decades, and is accompanied by a shift to more ketogenic metabolism (Ding et al. 2013). The contributions of astrocytes and oligodendrocytes to these changes remain to be established.

Microglia are now recognized to have diverse effects in neurological disorders. Though grouped with astrocytes and oligodendrocytes as "glia", microglia are more akin to circulating macrophages and the resident dendritic cells found in non-CNS tissues. Microglia shift to more glycolytic energy production and secrete lactate when stimulated by infection or tissue damage (Voloboueva et al. 2013). Activated microglia also release cytotoxic proteases and reactive oxygen species. While this response is likely adaptive to infection, it may have a net deleterious effect in non-infectious conditions such as stroke and neurodegenerative disorders. Glucose availability can be rate-limiting for the production of superoxide (Decoursey and Ligeti 2005), and probably also nitric oxide, thus linking blood glucose levels to pro-inflammatory microglial function. Glucose levels also influence pro-inflammatory gene expression in microglia, including expression of inducible nitric oxide synthase (Shen et al. 2017). Interestingly nitric oxide in turn affects energy metabolism by displacing oxygen from both hemoglobin and mitochondrial cytochrome C oxidase, and in astrocytes increases lactate release (San Martin et al. 2017). The functional implications of these complex interactions between inflammation and brain energy metabolism are only beginning to be appreciated.

Future directions

Effects of neuronal activity on glial metabolism are well-established, and our understanding of the signaling mechanisms mediating these interactions continues to expand. We can expect that studies of these interactions will be particularly facilitated by advances in cell-type specific gene editing techniques. Genetically-encoded fluorescent metabolite nanosensors are now available with exquisite spatial sensitivity, and these may pave the way for untangling the most intractable aspects of subcellular glial and neuronal energy metabolism, particularly as they are targeted to mitochondria and peri-synaptic fine processes *in vivo*. Both of these approaches are also likely shed further light on the changes that occur in glia under disease conditions, and help to resolve which of these are reactive and which may be contributory factors. Perhaps most excitingly, established concepts of glial energetics are now being applied to fundamental questions in systems neuroscience involving mechanisms of learning and memory. We seem to be entering a "golden era" for integrating glial energetics with broader brain functions, and can look forward with anticipation to future advances in these areas.

Acknowledgments

This work was supported by the NIH (RO1 NS081149); by the Dept. of Veterans Affairs (1IO1 BX003249); by Fondecyt 1160317 and Conicyt PB-01; by the University of Nottingham.

References

Amedee T, Robert A, Coles JA. Potassium homeostasis and glial energy metabolism. Glia. 1997; 21:46–55. [PubMed: 9298846]

Attwell D, Buchan AM, Charpak S, Lauritzen M, Macvicar BA, Newman EA. Glial and neuronal control of brain blood flow. Nature. 2010; 468:232–43. [PubMed: 21068832]

Barros LF. Metabolic signaling by lactate in the brain. Trends Neurosci. 2013; 36:396–404. [PubMed: 23639382]

Brown AM, Ransom BR. Astrocyte glycogen and brain energy metabolism. Glia. 2007; 55:1263–71. [PubMed: 17659525]

Brown AM, Tekkok SB, Ransom BR. Glycogen regulation and functional role in mouse white matter. J Physiol. 2003; 549:501–12. [PubMed: 12679378]

Danbolt NC, Furness DN, Zhou Y. Neuronal vs glial glutamate uptake: Resolving the conundrum. Neurochem Int. 2016; 98:29–45. [PubMed: 27235987]

Decoursey TE, Ligeti E. Regulation and termination of NADPH oxidase activity. Cell Mol Life Sci. 2005; 62:2173–93. [PubMed: 16132232]

Dienel GA. Brain lactate metabolism: the discoveries and the controversies. J Cereb Blood Flow Metab. 2012; 32:1107–38. [PubMed: 22186669]

Ding F, Yao J, Rettberg JR, Chen S, Brinton RD. Early decline in glucose transport and metabolism precedes shift to ketogenic system in female aging and Alzheimer's mouse brain: implication for bioenergetic intervention. PLoS One. 2013; 8:e79977. [PubMed: 24244584]

Dringen R, Gebhardt R, Hamprecht B. Glycogen in astrocytes: possible function as lactate supply for neighboring cells. Brain Res. 1993; 623:208–14. [PubMed: 8221102]

Gordon GR, Mulligan SJ, MacVicar BA. Astrocyte control of the cerebrovasculature. Glia. 2007; 55:1214–21. [PubMed: 17659528]

Gourine AV, Kasymov V, Marina N, Tang F, Figueiredo MF, Lane S, Teschemacher AG, Spyer KM, Deisseroth K, Kasparov S. Astrocytes control breathing through pH-dependent release of ATP. Science. 2010; 329:571–5. [PubMed: 20647426]

Grosche J, Matyash V, Moller T, Verkhratsky A, Reichenbach A, Kettenmann H. Microdomains for neuron-glia interaction: parallel fiber signaling to Bergmann glial cells. Nat Neurosci. 1999; 2:139–43. [PubMed: 10195197]

Hertz L, Chen Y. Glycogenolysis, an astrocyte-specific reaction, is essential for both astrocytic and neuronal activities involved in learning. Neuroscience. 2017 (in press).

Hochachka PW. Cross-species studies of glycolytic function. Adv Exp Med Biol. 1999; 474:219–29. [PubMed: 10635004]

Jackson JG, O'Donnell JC, Takano H, Coulter DA, Robinson MB. Neuronal activity and glutamate uptake decrease mitochondrial mobility in astrocytes and position mitochondria near glutamate transporters. J Neurosci. 2014; 34:1613–24. [PubMed: 24478345]

Kettenmann H, Backus KH, Schachner M. Aspartate, glutamate and gamma-aminobutyric acid depolarize cultured astrocytes. Neurosci Lett. 1984; 52:25–9. [PubMed: 6152041]

Kety, SS. The genral metabolism of the brain in vivo. In: Richter, D., editor. Metabolism of the nervous system. London: Peramon; 1957. p. 221-237.

Magistretti PJ, Manthorpe M, Bloom FE, Varon S. Functional receptors for vasoactive intestinal polypeptide in cultured astroglia from neonatal rat brain. Regul Pept. 1983; 6:71–80. [PubMed: 6306734]

McKenna MC, Sonnewald U, Huang X, Stevenson J, Zielke HR. Exogenous glutamate concentration regulates the metabolic fate of glutamate in astrocytes. J Neurochem. 1996; 66:386–93. [PubMed: 8522979]

Nehlig A, Coles JA. Cellular pathways of energy metabolism in the brain: is glucose used by neurons or astrocytes? Glia. 2007; 55:1238–50. [PubMed: 17659529]

Pellerin L, Bouzier-Sore AK, Aubert A, Serres S, Merle M, Costalat R, Magistretti PJ. Activity-dependent regulation of energy metabolism by astrocytes: an update. Glia. 2007; 55:1251–62. [PubMed: 17659524]

Rose CR, Karus C. Two sides of the same coin: sodium homeostasis and signaling in astrocytes under physiological and pathophysiological conditions. Glia. 2013; 61:1191–205. [PubMed: 23553639]

Saab AS, Tzvetavona ID, Trevisiol A, Baltan S, Dibaj P, Kusch K, Mobius W, Goetze B, Jahn HM, Huang W, et al. Oligodendroglial NMDA receptors regulate glucose import and axonal energy metabolism. Neuron. 2016; 91:119–32. [PubMed: 27292539]

San Martin A, Arce-Molina R, Galaz A, Perez-Guerra G, Barros LF. Nanomolar nitric oxide concentrations quickly and reversibly modulate astrocytic energy metabolism. J Biol Chem. 2017; 292:9432–9438. [PubMed: 28341740]

Seidel JL, Escartin C, Ayata C, Bonvento G, Shuttleworth CW. Multifaceted roles for astrocytes in spreading depolarization: A target for limiting spreading depolarization in acute brain injury? Glia. 2016; 64:5–20. [PubMed: 26301517]

Shen Y, Kapfhamer D, Minnella AM, Kim JE, Won SJ, Chen Y, Huang Y, Low LH, Massa SM, Swanson RA. Bioenergetic state regulates innate inflammatory responses through the transcriptional co-repressor CtBP. Nat Commun. 2017; 8:624. [PubMed: 28935892]

Silver IA, Erecinska M. Energetic demands of the Na+/K+ ATPase in mammalian astrocytes. Glia. 1997; 21:35–45. [PubMed: 9298845]

Sokoloff L, Reivich M, Kennedy C, Des Rosiers MH, Patlak CS, Pettigrew KD, Sakurada O, Shinohara M. The [14C]deoxyglucose method for the measurement of local cerebral glucose utilization: theory, procedure, and normal values in the conscious and anesthetized albino rat. J Neurochem. 1977; 28:897–916. [PubMed: 864466]

Suh SW, Bergher JP, Anderson CM, Treadway JL, Fosgerau K, Swanson RA. Astrocyte glycogen sustains neuronal activity during hypoglycemia: studies with the glycogen phosphorylase inhibitor CP-316,819 ([R-R*,S*]-5-chloro-N-[2-hydroxy-3-(methoxymethylamino)-3-oxo-1-(phenylmethyl)propyl]-1H-indole-2-carboxamide). J Pharmacol Exp Ther. 2007; 321:45–50. [PubMed: 17251391]

Swanson RA, Morton MM, Sagar SM, Sharp FR. Sensory stimulation induces local cerebral glycogenolysis: demonstration by autoradiography. Neuroscience. 1992; 51:451–61. [PubMed: 1465204]

Volobouéva LA, Emery JF, Sun X, Giffard RG. Inflammatory response of microglial BV-2 cells includes a glycolytic shift and is modulated by mitochondrial glucose-regulated protein 75/mortalin. FEBS Lett. 2013; 587:756–62. [PubMed: 23395614]