

Review

Autophagy in Astrocytes: Importance for Metabolism

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Abstract: Autophagy is an essential mechanism to maintain cellular homeostasis. Besides its role in controlling the quality of cytoplasmic components, it participates in nutrient obtaining and lipid mobilization under stressful conditions. Furthermore, autophagy is involved in the regulation of systemic metabolic, a function mainly performed by neuronal populations of the arcuate nucleus of the hypothalamus. Several studies have shown that blockade of autophagy in these neurons can affect central regulation of metabolism and impact body energy balance. Moreover, hypothalamic autophagy can be altered during obesity. However, neurons are not the only cell type involved in the central regulation of metabolism. Astrocytes, essential cells for brain homeostasis, are key metabolic regulators. They can sense metabolic signals in the hypothalamus and modulate systemic functions as glucose homeostasis and feeding response. Moreover, the response of astrocytes to obesity has been widely studied. Astrocytes are important mediators of brain inflammation and can be affected by increased levels of saturated fatty acids associated to obesity. Although autophagy plays important roles for astrocyte homeostasis and functioning, the contribution of astrocyte autophagy to systemic metabolism has not been analysed. Furthermore, how obesity can impact astrocyte autophagy is poorly understood. More studies are needed in order to understand the contribution of astrocyte autophagy to metabolism.

Keywords: astrocytes; autophagy; hypothalamus; metabolism; obesity.

1. Central regulation of metabolism

The central nervous system (CNS) plays an essential role in the control of body metabolism due to its capacity to detect peripheral signals which inform about energy status. Among these signals, nutrient availability (for instance levels of free fatty acids), and the hormones leptin and insulin are the major players. Leptin and insulin represent adiposity signals as their circulating levels are directly proportional to the amount of stored fat in the organism [1]. When nutrient availability and/or the levels of leptin and insulin are high, the brain inhibits caloric intake and glucose production. At the same time, energy expenditure and fat stores are increased. On the contrary, reduced levels of these circulating signals promote increased food intake and reduced energy expenditure in order to re-establish the energy balance [2].

The hypothalamus is one of the most important brain regions which govern feeding and energy expenditure. Among the diverse hypothalamic nuclei, the arcuate nucleus represents a key regulator of metabolic control due to its location. The arcuate nucleus is located on the ventral floor of the mediobasal hypothalamus and near the median eminence, a region rich in fenestrated capillaries which allow passive diffusion of metabolites from the blood. This strategic location facilitates the transport of circulating hormones and nutrients, and its detection by the neurons of the arcuate nucleus. As a consequence, the arcuate nucleus can

integrate peripheral metabolic signals and neuronal inputs, generating a coordinate response which allows the regulation of body metabolism [3,4].

In the arcuate nucleus, two neuronal populations with antagonistic functions can be distinguished: NPY/AgRP neurons and POMC neurons. The first group co-expresses the orexigenic peptides neuropeptide Y (NPY) and agouti-related protein (AgRP). Fasting favours the activation of this neuronal population, promoting feeding and reducing energy expenditure. POMC neurons express proopiomelanocortin precursor (POMC), from which α melanocyte-stimulating hormone (α -MSH) is synthesized. Both peptides have inhibitory effects on appetite (anorexigenic). POMC neurons are activated after feeding, favouring satiety feeling and promoting energy expenditure [4,5].

Despite the importance of the arcuate nucleus in the central control of metabolism, other hypothalamic regions as well as several brainstem nuclei and components of mesolimbic system participate in it. The signals coming from all these regions are finally integrated with inputs from the decision-making centres, achieving a coordinated response for feeding, glucose metabolism and energy expenditure [3,5].

2. Astrocyte functions and their importance in systemic metabolism

Astrocytes are one of the most abundant cell types in the CNS. They were initially considered only physical and metabolic supporters of neurons. Nowadays, they have been involved in a wide range of functions, becoming essential for brain homeostasis and activity.

Astrocytes participate in the formation and maintenance of the blood-brain barrier (BBB). They are closely associated with brain capillaries through specialized processes, known as perivascular endfeet, which reach brain microvessels [6]. Due to this characteristic, astrocytes are privileged located to sense metabolic and endocrine signals from the blood. Simultaneously, astrocytic processes associate to neurons, mediating the transport of nutrients and establishing a close metabolic cooperation with this cell type [7,8]. Furthermore, astrocytes can regulate blood flow in response to changes in neuronal activity, a phenomenon known as neurovascular coupling [9]. Moreover, astrocytes are the brain cell type which predominantly stores glycogen, an energy reserve which can help to sustain neuronal activity during adverse conditions [10,11].

Astrocytes control ion and water homeostasis in the CNS, an essential function for neural excitability and several signalling processes [12]. Furthermore, although astrocytes are not electrically excitable cells, they represent important regulators of synaptic activity. Astrocytic processes reach the synaptic cleft, where they modulate ion and neurotransmitter concentrations through the presence of specific ion channels and neurotransmitter receptors. Moreover, astrocytes can release gliotransmitters in response to neuronal activity, modulating synaptic activity and strength. The important participation of astrocytes in synapses was coined as tripartite synapse, a concept which has broadened to multipartite synapse due the discover of microglia involvement in it [13–15].

Another important function of astrocytes is their antioxidant role in the CNS. Astrocytes express a wide variety of antioxidant enzymes and store high amounts of glutathione and ascorbic acid, important antioxidant molecules. In addition, they release glutathione precursors which can be used by neurons to produce their own glutathione. Through all these mechanisms, astrocytes collaborate in scavenging reactive oxygen species (ROS) produced by neurons during oxidative phosphorylation [16–18]. Together with their antioxidant function, astrocytes participate in the response against CNS injuries in order to repair brain tissue [19,20].

In addition to their essential roles for brain homeostasis, astrocytes can also modulate body metabolism. Although hypothalamic neuronal circuits involved in this function are characterized in detail, the role of astrocytes has emerged during the last decades. Astrocytes contain glucose transporters GLUT-1 and GLUT-2, which allow the participation of this cell type in hypothalamic and systemic sensing of glucose [21–23]. Furthermore, communication between hypothalamic astrocytes through gap-junctions is also necessary for correct glucose

sensing in this region [24]. Together with glucose regulation, astrocytes are the main lipid metabolizers in the brain [25,26]. Moreover, production of ketone bodies by astrocytes in the hypothalamus can impact food intake [27]. In addition to their capacity to detect nutrients, astrocytes express receptors for hormones that regulate body metabolism such as leptin and insulin [28,29]. The exposure to these hormones modulates astrocytic function, regulating glucose and glutamate uptake together with ATP release [28,30,31]. Furthermore, specific elimination of leptin and insulin receptors in astrocytes is associated with systemic repercussions. Leptin receptor deletion in astrocytes modifies hypothalamic neuronal circuits and food intake patterns [32]. When insulin receptor is eliminated in this cell type, hypothalamic glucose sensing and systemic metabolism of glucose are impaired [33]. All these results show the importance of astrocyte in the control of systemic metabolism.

3. Astrocyte role in obesity

Obesity represents an alteration in energy balance and arises when caloric intake exceeds energy expenditure. This positive energy balance induces an abnormal or excessive accumulation of fat which negatively impacts health. Obesity has become a global epidemic during last decades. Between 1975 and 2016, its worldwide prevalence has triple and nowadays represents an important problem for public health [34,35]. Obesity is associated with reduced life expectancy and increased risk of cardiovascular diseases, diabetes, stroke, muscular disorders and some types of cancer [36]. Furthermore, obesity can impact brain function and has become a risk factor for neurodegenerative diseases like Alzheimer's disease [37–40].

Due to the variety of genetic and environmental factors which affects obesity, animal models of obesity have been developed to facilitate the study of obesity impact on the brain [41]. The use of these models has helped to understand that inflammation is one of the main pathophysiological mechanisms of obesity. First, increased expression of tumour necrosis factor α (TNF- α) was reported in the adipose tissue of obese mice and humans [42]. Some years later, inflammatory induction was described in the hypothalamus of mice after high fat diet (HFD) consumption and in obese humans [43,44].

Astrocytes play an essential role in the inflammatory response associated with obesity. Increased expression of glial fibrillary acidic protein (GFAP), an astrocyte marker, is seen in the hypothalamus after HFD consumption. Moreover, the morphology of astrocytes acquires a reactive phenotype [44]. These morphological changes observed in astrocytes are linked to alterations in the hypothalamic neuronal circuits. HFD intake increases the glial coverage of NPY and POMC neurons, decreasing the synaptic inputs received by these neurons [45].

Increased expression of proinflammatory cytokines and GFAP is observed only one day after HFD consumption. This early proinflammatory response is attenuated seven days after HFD onset, but reappears if HFD intake is prolonged [44]. Recent studies have shown that this initial activation of astrocytes could be a protective mechanism to adapt to the new metabolic situation. Morphological changes are described in astrocytes between fasting and fed status in mice [46]. Furthermore, inactivation of the inflammatory response of astrocytes before HFD consumption increases food intake of mice [47]. On the contrary, blockade of inflammatory signalling in astrocytes after HFD onset protects mice from metabolic alterations [48]. Therefore, initial activation of astrocytes could play a protective role while its chronic activation is responsible of metabolic alterations associated with HFD.

4. Autophagy importance in metabolism

Autophagy is a catabolic process which allows the degradation of cytoplasmic material through lysosomal action in mammals. Three different types of autophagy are distinguished by the mechanism used to deliver cytoplasmic components to lysosomes: macroautophagy, chaperone-mediated autophagy and microautophagy. Macroautophagy (autophagy hereafter) is characterized by the sequestration of cytoplasmic components into double-membrane

vesicles, known as autophagosomes, which finally fuse with lysosomes. In chaperone-mediated autophagy, proteins which contain a specific sequence of amino acids (KFERQ motif) are directly targeted to lysosomes. KFERQ motif allows protein recognition by cytoplasmic chaperones which interact with lysosome-associated membrane protein 2A (LAMP-2A). Due to this interaction, targeted proteins can translocate into the lysosomal lumen for degradation. Finally, microautophagy consists on direct sequestration of cytoplasmic material by lysosomes through invagination of lysosomal membrane. In mammals, microautophagy is carried out by late endosomes instead of lysosomes [49–51].

Autophagy is constitutively active at low levels and acts as a mechanism of quality control for cytoplasmic components. Through basal autophagy, proteins and organelles which are unnecessary or damaged can be eliminated. Furthermore, autophagy is induced in presence of several stressors such as nutrient deprivation, oxidative stress, pathogen infection and hypoxia. Under these conditions, autophagy enables metabolic adaptation and promotes cell survival. Among the stressors mentioned above, nutrient deprivation is the most potent activator of autophagy in cells. During starvation, autophagy allows the production of amino acids which can be used as an energy source and to synthesize essential proteins for cell survival [52–54]. Together with amino acid supply during starvation, autophagy can provide free fatty acids. This process, known as lipophagy, mobilizes lipids from lipid droplets through autophagic machinery. Deletion of essential genes for autophagy (*Atg5* and *Atg7*) causes lipid accumulation in hepatocytes due to reduced lipolysis *in vitro* and *in vivo* [55,56]. Lipophagy has been also described in fibroblasts, macrophage foam cells, T cells, neurons and glial cells [55,57–59]; suggesting its importance as a general mechanism to mobilize lipids independently of cell type.

Apart from autophagy importance in cell metabolism, several studies have shown its participation in the central regulation of metabolism and energy balance. Autophagy is active in the arcuate nucleus in basal conditions [60,61] and plays important functions in AgRP and POMC neurons. In AgRP neurons, autophagy allows the mobilization of neuronal lipids and production of AgRP peptide under starvation conditions. When autophagy is inhibited in AgRP neurons, AgRP production in response to fasting is blunted. Furthermore, POMC and α -MSH levels are increased independently of the nutritional status of mice, which contributes to reduced fat mass and body weight of these animals [62]. In comparison with the previous study, inhibition of autophagy in POMC neurons increases adiposity and body weight [61,63,64]. These changes in phenotype are associated with a reduced production of α -MSH and lipid mobilization in adipose tissue after fasting [63]. Furthermore, glucose regulation and leptin sensitivity are altered [61,63,64]. Moreover, axonal projections of POMC neurons to other hypothalamic nuclei are diminished, showing the importance of autophagy for the normal development of this neuronal population [61]. These studies manifest the relevance of autophagy for the correct functioning of AgRP and POMC neurons, essential players in central control of metabolism. In addition, hypothalamic autophagy can control lipophagy in the periphery. Stimulation of hypothalamic autophagy promotes lipid mobilization in brown adipose tissue and liver through lipophagy [65].

In relation to obesity, autophagy alterations have been described in the hypothalamus. Chronic HFD consumption downregulates the levels of autophagy markers in the hypothalamus of rodents [60,66,67]. Furthermore, an accumulation of the autophagy substrate p62 and ubiquitin is described, suggesting a blockade of autophagy in the hypothalamus after HFD consumption [66,67]. Together with a reduction in general activity of autophagy, obesity can affect selective forms of autophagy. Reduced autophagy of mitochondria and lipids is described in the hypothalamus after HFD intake [68]. Furthermore, additional blockade of autophagy by *Atg7* deletion in POMC neurons exacerbates HFD impact on mice, increasing body weight and impairing glucose homeostasis under these conditions [63,64]. Finally, maternal obesity can impact hypothalamic autophagy in the offspring. HFD administration during pregnancy reduces the incorporation of microtubule-associated protein 1A/1B light

chain 3B (LC3) to autophagosomes and accumulates p62 in the offspring hypothalamus at weaning. Moreover, this early exposure to HFD affects hypothalamic autophagy in response to HFD reexposure during adulthood [69].

5. Autophagy in astrocytes

As previously mentioned, adaptation to starvation is the most conserved function of autophagy. In the case of astrocytes, autophagy represents an essential mechanism to face the lack of nutrients. Several studies have shown that amino acids deprivation or ATP depletion activates autophagy in cultured astrocytes [70,71]. Furthermore, autophagy activation is maintained in case of prolonged nutrient deprivation, as it has been described in a cell line of human glioma [72]. The blockade of autophagy using chloroquine (a drug that impairs autophagosome fusion with lysosomes) exacerbates astrocyte cell death after nutrient deprivation [73]. These studies reveal that autophagy is activated during starvation to promote cell survival in astrocytes.

Apart from its role during starvation, autophagy represents a quality control mechanism to avoid protein aggregation. Accumulation of cytoplasmic protein inclusions is a common feature of neurodegenerative diseases. Astrocytes, which contribute to the development of these disorders, also show protein inclusions in their cytoplasm [74]. Initial studies described that autophagy deficits in CNS caused an accumulation of protein aggregates only in neurons, inducing neurodegeneration in mice [75,76]. However, astrocytes can modulate their autophagic response to prevent the formation of these inclusions. For instance, impairment of proteasome activity generates an accumulation of protein aggregates in the cytoplasm of astrocytes. Through autophagy activation, astrocytes achieve to reduce protein accumulation and promote cell viability [77]. Autophagy is also modulated in astrocytes affected by Alexander's disease, a disorder caused by mutations in *GFAP* gene. Under these conditions, astrocytes activate their autophagy to degrade GFAP and avoid its accumulation [78]. Another neurodegenerative disease characterized by the presence of cytoplasmic inclusions is Parkinson's disease. α -synuclein inclusions do not only accumulate in the cytoplasm of dopaminergic neurons, but also in astrocytes [79]. Some studies have shown that autophagy modulation in astrocytes can affect α -synuclein accumulation in the brain. When autophagy is inhibited by α B-crystallin (a small heat shock protein implicated in protein aggregation), the clearance of α -synuclein pre-formed fibrils is reduced in astrocytic cytoplasm. Furthermore, specific overexpression of α B-crystallin in astrocytes and its consequent inhibitory effect on autophagy generate a greater accumulation of α -synuclein in the brain of a Parkinson's disease mouse model [80]. Familiar forms of Parkinson's disease are linked to mutations in leucine-rich repeat kinase 2 (*LRRK2*), a gene involved in autophagy among several other functions [81]. Astrocytes derived from induced pluripotent stem cells of patients with mutations in *LRRK2* show α -synuclein accumulation in their cytoplasm. This accumulation is associated with impaired macroautophagy and chaperone-mediated autophagy, and can be prevented by using inducers of chaperone-mediated autophagy [82]. Together with the importance of autophagy for protein degradation in the cytoplasm of astrocytes, it participates in the elimination of extracellular amyloid plaques in Alzheimer's disease. Astrocytes which carry the ϵ 4 allele of apolipoprotein E (APOE), an allele associated with higher risk of Alzheimer's disease, have a reduced autophagic flux and impaired capacity to clear amyloid plaques in a mouse model of the disease. Moreover, induction of autophagy by rapamycin promotes A β plaques clearance, highlighting the role of autophagy in this astrocytic function [70]. All these studies manifest the relevance of astrocytic autophagy in the regulation of protein degradation and its important implications for neurodegeneration.

Autophagy is also involved in astrocyte differentiation during cortex development in mice. Atg5 knockdown reduces the differentiation of neural progenitor cells into astrocytes both *in vitro* and *in vivo*. On the contrary, increased number of astrocytes is found when this protein is

overexpressed, showing the importance of Atg5 in astrocyte differentiation [83]. Furthermore, autophagy is implicated in the differentiation of adult hippocampal neural stem cells into astrocytes. This differentiation process is associated with increased autophagic flux *in vitro*. Furthermore, genetic or pharmacological inhibition of autophagy affects astrocyte differentiation, reducing the number of GFAP-positive cells [84]. Finally, autophagy can affect astrocyte transformation into gliomas. Unc-51 like autophagy activating kinase 2 (ULK2), an inducer of autophagy, is hypermethylated and its expression is reduced in glioma. Ectopic expression of ULK2 reduces Ras-induced transformation of astrocytes, showing an inhibitory role of autophagy in glioma transformation [85].

Astrocytes can adapt their metabolic function to provide energy in presence of CNS insults. During inflammatory response, changes in the metabolic profile of reactive astrocytes have been described [7,86]. Furthermore, a rearrangement of mitochondrial networks occurs in astrocytes under these circumstances. After being exposed to an inflammatory stimulus, astrocyte mitochondria become fragmented. However, this response is transient as mitochondria finally recover their tubular morphology. During mitochondrial rearrangement, autophagy is activated and fragmented mitochondria are engulfed by autophagosomes. Lack of autophagy avoids the recovery of tubular mitochondria, favouring ROS production and affecting cell viability [87].

Together with its participation in mitochondrial remodelling, autophagy contributes to astrocyte activation and death after brain lesions such as cerebral ischemia and traumatic brain injury. Autophagy is induced in cortical astrocytes after permanent middle cerebral artery occlusion [88]. Furthermore, autophagy activation is also described in cultured astrocytes exposed to oxygen-glucose deprivation, a model which mimics ischemic conditions *in vitro*. Increased levels of Beclin-1, LC3-II/LC3-I ratio and autophagic vesicles are found in astrocytes exposed to this type of deprivation. Inhibition of autophagy using 3-methyladenine (3-MA) or bafilomycin reduces autophagy activation and counteracts cell death [88]. Furthermore, astrocyte activation is reduced after autophagy inhibition by 3-MA in this *in vitro* model [89]. Autophagy activation is also described in astrocytes exposed to glutamate, an *in vitro* model which imitates glutamate excitotoxicity seen in traumatic brain injury. Induction of autophagy is accompanied by astrocyte death under these conditions. Autophagy inhibition by 3-MA reduces astrocyte death, showing that autophagy contributes to cytotoxicity caused by glutamate [90].

Viral infection can also modulate autophagy in astrocytes and one example of it is human immunodeficiency virus (HIV). Astrocytes are a target for HIV in the CNS, maintaining a latent infection and acting as a possible reservoir of this virus [91,92]. Astrocytes can modulate their autophagic activity as a protective mechanism to avoid HIV-induced cell death. Productive HIV infection promotes an activation of mitophagy in human astrocytes, favouring selective elimination of damaged mitochondria by autophagy. Through this mechanism, production of mitochondrial ROS is reduced and mitochondrial membrane potential is maintained, which promotes astrocyte survival [93]. Furthermore, the use of autophagy inducers (rapamycin) and inhibitors (3-MA and leupeptin) reduces or promotes human astrocyte cytotoxicity, respectively [94].

Several compounds with protective effects for the brain act through the modulation of autophagy in astrocytes. For instance, progesterone exerts antiinflammatory effects on astrocytes exposed to β -amyloid through autophagy activation. When autophagy is inhibited by 3-MA, the protective effect of progesterone is lost and the transcription of proinflammatory cytokines is increased in astrocytes [95]. In the case of resveratrol, it can counteract autophagy alterations after glutamate exposure and promote astrocyte viability [90]. In addition, the antidepressant fluoxetine protects cultured astrocytes from the deleterious effect of corticosterone through the induction of autophagic flux. Fluoxetine concretely increases

mitophagy, which allows the elimination of damaged mitochondria and alleviates ROS production induced by corticosterone in astrocytes [96].

Finally, astrocyte autophagy also affects neuronal survival. Autophagy blockade caused by lysosomal dysfunction in astrocytes induces degeneration of cortical neurons *in vivo* [97]. Furthermore, autophagy modulation in astrocytes can regulate neuronal viability after harmful stimuli. In a model of oxygen and glucose deprivation followed by reoxygenation, autophagy induction by rapamycin in astrocytes reduces neuronal death. By contrast, autophagy inhibition in astrocytes increases neuronal death in this *in vitro* model [98]. Furthermore, the specific upregulation of autophagy in astrocytes reduces infarct volume and neuronal loss in an *in vivo* model of middle cerebral artery occlusion with later reperfusion [98].

All these studies show the involvement of autophagy in a wide variety of functions in astrocytes, ranging from their development to their homeostasis and survival. For this reason, autophagy represents an essential mechanism for the correct function of astrocytes. Furthermore, due to the essential role of astrocytes in maintaining brain homeostasis and functions, astrocyte autophagy can affect brain activity and deserves special attention.

6. Involvement of astrocyte autophagy in systemic metabolism

Although autophagy has been identified as an essential mechanism for the central regulation of metabolism, all the studies have only explored the role of neuronal autophagy [60,61,63,64]. Astrocytes are key players in metabolic control and their autophagy exerts important roles for brain functioning. However, the contribution of astrocyte autophagy to the regulation of systemic metabolism has not been explored yet.

It is important to take into consideration that autophagy can be differentially regulated in neurons and astrocytes. For instance, activation of autophagy after starvation is more pronounced in cultured astrocytes than neurons [99]. Moreover, acute ethanol exposure enhances autophagy in cultured astrocytes. This induction of autophagy represents a protective mechanism which tries to avoid astrocyte inflammation and cell death under these conditions. However, ethanol downregulates autophagy in neuronal cultures, making neurons more sensitive to ethanol toxicity [100]. Furthermore, autophagy and lysosomal biogenesis could differ between glia and CA1 neurons in the brain of Alzheimer's disease patients. This is due to increased nuclear translocation of transcription factor EB (TFEB), a master regulator of these processes, in glial cells compared to neurons [101]. The existence of all these differences shows the complexity of autophagy regulation in the brain and highlights the necessity of studying the contribution of autophagy to systemic metabolism in each cell type.

Apart from determining how astrocyte autophagy can impact metabolic regulation, it would be interesting to determine its contribution to obesity pathophysiology. As we have described above, hypothalamic obesity is altered during obesity. In particular, these studies only collected data from hypothalamus in general [60,66,67] or analysed the effect of HFD after autophagy inhibition in POMC neurons [63,64]. However, the impact of HFD intake on autophagy has not been widely examined in astrocytes. The only available data is the description of increased LC3-II levels in hippocampal astrocytes after chronic HFD [102]. Higher LC3-II levels correlate with increased number of autophagosomes in the cytoplasm [103]. Nevertheless, autophagy is a very dynamic process and elevated number of autophagosomes can be associated with increased autophagosome formation or reduced degradation. For this reason, measuring only LC3-II levels is not enough to determine the status of autophagy in astrocytes after HFD consumption [104].

Together with hypothalamic inflammation, obesity is characterized by alterations in lipid content of the brain. HFD consumption causes an abnormal accumulation of saturated fatty acids like palmitic acid (PA) in the brain of mice [105,106]. Moreover, metabolic syndrome patients show higher incorporation of free fatty acids in the brain [107]. To study the impact of saturated fatty acids on the brain, an *in vitro* model consisting on treating the different brain cell

types with PA has been developed. In the case of astrocytes, PA decreases glucose uptake and lactate release [108]. Furthermore, it increases the production of proinflammatory cytokines [105,109] and ROS in astrocytes [110,111]. As a consequence of these alterations, PA induces apoptosis and decreases cell viability of astrocytes [110,112].

Using this *in vitro* model, the impact of saturated fatty acids on astrocyte autophagy has been analysed. PA exposure can modulate autophagy in astrocytes, but autophagy blockade and induction has been described [102,113]. PA simultaneously increases LC3-II and p62 levels in cultured astrocytes [113]. The existence of high levels of LC3-II and accumulation of p62 suggested a reduction in autophagic activity. To confirm the blockade of autophagy, autophagic flux was measured using hydroxychloroquine, a lysosomal inhibitor which avoids autophagosome fusion with lysosomes. LC3-II accumulation caused by hydroxychloroquine was reduced after PA treatment, which confirms the blockade of autophagy in astrocytes [113]. A reduction in autophagic activity has been also described in hypothalamic neurons exposed to PA [114]. On the contrary, autophagy induction by PA has been also reported in cultured astrocytes [102]. In this study, increased levels of LC3-II and autophagosome accumulation were described in astrocytes after PA exposure. Although autophagy flux and levels of autophagic substrates were not quantified, the inhibition of autophagosome formation by 3-MA avoided the changes induced by PA [102]. These results suggest that autophagy is induced by PA in astrocytes, an opposite result compared to the blockade of autophagy found by Ortiz-Rodriguez et al. [113]. The differences between these two studies could be caused by the use of astrocytes from different brain regions, as the response of cortical [113] and hippocampal [102] astrocytes was analysed. For instance, differences in the response to PA between hypothalamic and cortical astrocytes have been reported [115], which could explain the differences found in astrocyte autophagy.

As it can be seen, few studies have explored how astrocyte autophagy can be modulated during obesity. Furthermore, contradictory results have been reported in the *in vitro* model of PA treatment. For all these reasons, more studies are needed in order to understand the role of autophagy for astrocyte contribution to obesity. Furthermore, dissecting the implication of astrocyte autophagy in metabolic regulation and its alterations could help to find new therapeutic targets to develop new anti-obesity drugs.

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Abbreviations

3-MA	3-methyladenine
α -MSH	α melanocyte-stimulating hormone
AgRP	Agouti-related protein
APOE	Apolipoprotein E
BBB	Blood-brain barrier
CNS	Central nervous system
GFAP	Glial fibrillary acidic protein
HFD	High fat diet
HIV	Human immunodeficiency virus
LAMP-2A	Lysosome-associated membrane protein 2A
LC3	Microtubule-associated protein 1A/1B light chain 3B
LRRK2	Leucine-rich repeat kinase 2

NPY	Neuropeptide Y
PA	Palmitic acid
POMC	Proopiomelanocortin
ROS	Reactive oxygen species
TFEB	Transcription factor EB
TNF- α	Tumour necrosis factor α
ULK2	Unc-51 like autophagy activating kinase 2

References

1. Seeley, R.J.; Woods, S.C. Monitoring of stored and available fuel by the CNS: implications for obesity. *Nat. Rev. Neurosci.* **2003**, *4*, 901–909; DOI:10.1038/nrn1245.
2. Schwartz, M.W.; Porte, D. Diabetes, obesity, and the brain. *Science (80-.)*. **2005**, *307*, 375–379; DOI:10.1126/science.1104344.
3. Timper, K.; Brüning, J.C. Hypothalamic circuits regulating appetite and energy homeostasis: pathways to obesity. *Dis. Model. Mech.* **2017**, *10*, 679–689; DOI:10.1242/dmm.026609.
4. García-Cáceres, C.; Bolland, E.; Prevot, V.; Luquet, S.; Woods, S.C.; Koch, M.; Horvath, T.L.; Yi, C.X.; Chowen, J.A.; Verkhratsky, A.; et al. Role of astrocytes, microglia, and tanocytes in brain control of systemic metabolism. *Nat. Neurosci.* **2019**, *22*, 7–14; DOI:10.1038/s41593-018-0286-y.
5. Waterson, M.J.; Horvath, T.L. Neuronal regulation of energy homeostasis: beyond the hypothalamus and feeding. *Cell Metab.* **2015**, *22*, 962–970; DOI:10.1016/j.cmet.2015.09.026.
6. Abbott, N.J.; Rönnbäck, L.; Hansson, E. Astrocyte-endothelial interactions at the blood-brain barrier. *Nat. Rev. Neurosci.* **2006**, *7*, 41–53; DOI:10.1038/nrn1824.
7. Bélanger, M.; Allaman, I.; Magistretti, P.J. Brain energy metabolism: focus on astrocyte-neuron metabolic cooperation. *Cell Metab.* **2011**, *14*, 724–738; DOI:10.1016/j.cmet.2011.08.016.
8. Marina, N.; Turovsky, E.; Christie, I.N.; Hosford, P.S.; Hadjihambi, A.; Korsak, A.; Ang, R.; Mastitskaya, S.; Sheikhabaei, S.; Theparambil, S.M.; et al. Brain metabolic sensing and metabolic signaling at the level of an astrocyte. *Glia* **2018**, *66*, 1185–1199; DOI:10.1002/glia.23283.
9. Petzold, G.C.; Murthy, V.N. Role of astrocytes in neurovascular coupling. *Neuron* **2011**, *71*, 782–797; DOI:10.1016/j.neuron.2011.08.009.
10. Cataldo, A.M.; Broadwell, R.D. Cytochemical identification of cerebral glycogen and glucose-6-phosphatase activity under normal and experimental conditions: I. Neurons and glia. *J. Electron Microsc. Tech.* **1986**, *3*, 413–437.
11. Brown, A.M.; Ransom, B.R. Astrocyte glycogen and brain energy metabolism. *Glia* **2007**, *55*, 1263–1271; DOI:10.1002/glia.20557.
12. Verkhratsky, A.; Nedergaard, M. Physiology of astroglia. *Physiol. Rev.* **2018**, *98*, 239–389; DOI:10.1152/physrev.00042.2016.
13. Araque, A.; Parpura, V.; Sanzgiri, R.P.; Haydon, P.G. Tripartite synapses: glia, the unacknowledged partner. *Trends Neurosci.* **1999**, *22*, 208–215; DOI:10.1016/s0166-2236(98)01349-6.
14. Kettenmann, H.; Kirchhoff, F.; Verkhratsky, A. Microglia: new roles for the synaptic stripper. *Neuron* **2013**, *77*, 10–18; DOI:10.1016/j.neuron.2012.12.023.
15. Mederos, S.; González-Arias, C.; Perea, G. Astrocyte–neuron networks: a multilane highway of signaling for homeostatic brain function. *Front. Synaptic Neurosci.* **2018**, *10*, 45;

DOI:10.3389/fnsyn.2018.00045.

16. Fernandez-Fernandez, S.; Almeida, A.; Bolaños, J.P. Antioxidant and bioenergetic coupling between neurons and astrocytes. *Biochem. J.* **2012**, *443*, 3–11; DOI:10.1042/BJ20111943.
17. Baxter, P.S.; Hardingham, G.E. Adaptive regulation of the brain's antioxidant defences by neurons and astrocytes. *Free Radic. Biol. Med.* **2016**, *100*, 147–152; DOI:10.1016/j.freeradbiomed.2016.06.027.
18. Makar, T.K.; Nedergaard, M.; Preuss, A.; Gelbard, A.S.; Perumal, A.S.; Cooper, A.J. Vitamin E, ascorbate, glutathione, glutathione disulfide, and enzymes of glutathione metabolism in cultures of chick astrocytes and neurons: evidence that astrocytes play an important role in antioxidative processes in the brain. *J. Neurochem.* **1994**, *62*, 45–53; DOI:10.1046/j.1471-4159.1994.62010045.x.
19. Liddelow, S.A.; Barres, B.A. Reactive astrocytes: production, function, and therapeutic potential. *Immunity* **2017**, *46*, 957–967; DOI:10.1016/j.immuni.2017.06.006.
20. Burda, J.E.; Sofroniew, M. V. Reactive gliosis and the multicellular response to CNS damage and disease. *Neuron* **2014**, *81*, 229–248; DOI:10.1016/j.neuron.2013.12.034.
21. Chari, M.; Yang, C.S.; Lam, C.K.; Lee, K.; Mighiu, P.; Kokorovic, A.; Cheung, G.W.; Lai, T.Y.; Wang, P.Y.; Lam, T.K. Glucose transporter-1 in the hypothalamic glial cells mediates glucose sensing to regulate glucose production in vivo. *Diabetes* **2011**, *60*, 1901–1906; DOI:10.2337/db11-0120.
22. Marty, N.; Dallaporta, M.; Foretz, M.; Emery, M.; Tarussio, D.; Bady, I.; Binnert, C.; Beermann, F.; Thorens, B. Regulation of glucagon secretion by glucose transporter type 2 (glut2) and astrocyte-dependent glucose sensors. *J. Clin. Invest.* **2005**, *115*, 3545–3553; DOI:10.1172/JCI26309.
23. Young, J.K.; McKenzie, J.C. GLUT2 immunoreactivity in Gomori-positive astrocytes of the hypothalamus. *J. Histochem. Cytochem.* **2004**, *52*, 1519–1524; DOI:10.1369/jhc.4A6375.2004.
24. Allard, C.; Carneiro, L.; Grall, S.; Cline, B.H.; Fioramonti, X.; Chrétien, C.; Baba-Aissa, F.; Giaume, C.; Pénicaud, L.; Leloup, C. Hypothalamic astroglial connexins are required for brain glucose sensing-induced insulin secretion. *J. Cereb. Blood Flow Metab.* **2014**, *34*, 339–346; DOI:10.1038/jcbfm.2013.206.
25. Edmond, J.; Robbins, R.A.; Bergstrom, J.D.; Cole, R.A.; de Vellis, J. Capacity for substrate utilization in oxidative metabolism by neurons, astrocytes, and oligodendrocytes from developing brain in primary culture. *J. Neurosci. Res.* **1987**, *18*, 551–561; DOI:10.1002/jnr.490180407.
26. Blázquez, C.; Galve-Roperh, I.; Guzmán, M. De novo-synthesized ceramide signals apoptosis in astrocytes via extracellular signal-regulated kinase. *FASEB J.* **2000**, *14*, 2315–2322; DOI:10.1096/fj.00-0122com.
27. Le Foll, C.; Dunn-Meynell, A.A.; Mizioro, H.M.; Levin, B.E. Regulation of hypothalamic neuronal sensing and food intake by ketone bodies and fatty acids. *Diabetes* **2014**, *63*, 1259–1269; DOI:10.2337/db13-1090.
28. Hernandez-Garzón, E.; Fernandez, A.M.; Perez-Alvarez, A.; Genis, L.; Bascuñana, P.; Fernandez de la Rosa, R.; Delgado, M.; Angel Pozo, M.; Moreno, E.; McCormick, P.J.; et al. The insulin-like growth factor I receptor regulates glucose transport by astrocytes. *Glia* **2016**, *64*, 1962–1971; DOI:10.1002/glia.23035.
29. Diano, S.; Kalra, S.P.; Horvath, T.L. Leptin receptor immunoreactivity is associated with the Golgi apparatus of hypothalamic neurons and glial cells. *J. Neuroendocrinol.* **1998**, *10*, 647–650; DOI:10.1046/j.1365-2826.1998.00261.x.
30. Fuente-Martín, E.; García-Cáceres, C.; Granado, M.; de Ceballos, M.L.; Sánchez-Garrido, M.Á. Sarman, B.; Liu, Z.W.; Dietrich, M.O.; Tena-Sempere, M.; Argente-Arizón, P.; Díaz, F.; et al. Leptin

- regulates glutamate and glucose transporters in hypothalamic astrocytes. *J. Clin. Invest.* **2012**, *122*, 3900–3913; DOI:10.1172/JCI64102.
31. Cai, W.; Xue, C.; Sakaguchi, M.; Konishi, M.; Shirazian, A.; Ferris, H.A.; Li, M.E.; Yu, R.; Kleinridders, A.; Pothos, E.N.; et al. Insulin regulates astrocyte gliotransmission and modulates behavior. *J. Clin. Invest.* **2018**, *128*, 2914–2926; DOI:10.1172/JCI99366.
 32. Kim, J.G.; Suyama, S.; Koch, M.; Jin, S.; Argente-Arizon, P.; Argente, J.; Liu, Z.W.; Zimmer, M.R.; Jeong, J.K.; Szigeti-Buck, K.; et al. Leptin signaling in astrocytes regulates hypothalamic neuronal circuits and feeding. *Nat. Neurosci.* **2014**, *17*, 908–910; DOI:10.1038/nn.3725.
 33. García-Cáceres, C.; Quarta, C.; Varela, L.; Gao, Y.; Gruber, T.; Legutko, B.; Jastroch, M.; Johansson, P.; Ninkovic, J.; Yi, C.X.; et al. Astrocytic insulin signaling couples brain glucose uptake with nutrient availability. *Cell* **2016**, *166*, 867–880; DOI:10.1016/j.cell.2016.07.028.
 34. World Health Organization. Obesity and overweight. Available online: <https://www.who.int/en/news-room/fact-sheets/detail/obesity-and-overweight> (accessed on Feb 20, 2020).
 35. Hruby, A.; Hu, F.B. The epidemiology of obesity: a big picture. *Pharmacoeconomics.* **2015**, *33*, 673–689; DOI:10.1007/s40273-014-0243-x.
 36. Fruh, S.M. Obesity: risk factors, complications, and strategies for sustainable long-term weight management. *J. Am. Assoc. Nurse Pract.* **2017**, *29*, S3–S14; DOI:10.1002/2327-6924.12510.
 37. Gunstad, J.; Paul, R.H.; Cohen, R.A.; Tate, D.F.; Spitznagel, M.B.; Gordon, E. Elevated body mass index is associated with executive dysfunction in otherwise healthy adults. *Compr. Psychiatry* **2007**, *48*, 57–61; DOI: 10.1016/j.comppsy.2006.05.001.
 38. Cheke, L.G.; Bonnici, H.M.; Clayton, N.S.; Simons, J.S. Obesity and insulin resistance are associated with reduced activity in core memory regions of the brain. *Neuropsychologia* **2017**, *96*, 137–149; DOI:10.1016/j.neuropsychologia.2017.01.013.
 39. Profenno, L.A.; Porsteinsson, A.P.; Faraone, S.V. Meta-analysis of Alzheimer’s disease risk with obesity, diabetes, and related disorders. *Biol. Psychiatry* **2010**, *67*, 505–512; DOI: 10.1016/j.biopsych.2009.02.013.
 40. Kivipelto, M.; Ngandu, T.; Fratiglioni, L.; Viitanen, M.; Kåreholt, I.; Winblad, B.; Helkala, E.L.; Tuomilehto, J.; Soininen, H.; Nissinen, A. Obesity and vascular risk factors at midlife and the risk of dementia and Alzheimer disease. *Arch. Neurol.* **2005**, *62*, 1556–1560; DOI:10.1001/archneur.62.10.1556.
 41. Lutz, T.A.; Woods, S.C. Overview of animal models of obesity. *Curr. Protoc. Pharmacol.* **2012**, *Chapter 5*, Unit5.61; DOI:10.1002/0471141755.ph0561s58.
 42. Hotamisligil, G.S.; Arner, P.; Caro, J.F.; Atkinson, R.L.; Spiegelman, B.M. Increased adipose tissue expression of tumor necrosis factor-alpha in human obesity and insulin resistance. *J. Clin. Invest.* **1995**, *95*, 2409–2415; DOI:10.1172/JCI117936.
 43. De Souza, C.T.; Araujo, E.P.; Bordin, S.; Ashimine, R.; Zollner, R.L.; Boschero, A.C.; Saad, M.J.; Velloso, L.A. Consumption of a fat-rich diet activates a proinflammatory response and induces insulin resistance in the hypothalamus. *Endocrinology* **2005**, *146*, 4192–4199; DOI:10.1210/en.2004-1520.
 44. Thaler, J.P.; Yi, C.X.; Schur, E.A.; Guyenet, S.J.; Hwang, B.H.; Dietrich, M.O.; Zhao, X.; Sarruf, D.A.; Izgur, V.; Maravilla, K.R.; et al. Obesity is associated with hypothalamic injury in rodents and humans. *J. Clin. Invest.* **2012**, *122*, 153–162; DOI:10.1172/JCI59660.
 45. Horvath, T.L.; Sarman, B.; García-Cáceres, C.; Enriori, P.J.; Sotonyi, P.; Shanabrough, M.; Borok, E.;

- Argente, J.; Chowen, J.A.; Perez-Tilve, D.; et al. Synaptic input organization of the melanocortin system predicts diet-induced hypothalamic reactive gliosis and obesity. *Proc. Natl. Acad. Sci.* **2010**, *107*, 14875–14880; DOI:10.1073/pnas.1004282107.
46. Zhang, Y.; Reichel, J.M.; Han, C.; Zuniga-Hertz, J.P.; Cai, D. Astrocytic process plasticity and IKK β /NF- κ B in central control of blood glucose, blood pressure, and body weight. *Cell Metab.* **2017**, *25*, 1091–1102; DOI: 10.1016/j.cmet.2017.04.002.
47. Buckman, L.B.; Thompson, M.M.; Lippert, R.N.; Blackwell, T.S.; Yull, F.E.; Ellacott, K.L. Evidence for a novel functional role of astrocytes in the acute homeostatic response to high-fat diet intake in mice. *Mol. Metab.* **2015**, *4*, 58–63; DOI:10.1016/j.molmet.2014.10.001.
48. Douglass, J.D.; Dorfman, M.D.; Fasnacht, R.; Shaffer, L.D.; Thaler, J.P. Astrocyte IKK β /NF- κ B signaling is required for diet-induced obesity and hypothalamic inflammation. *Mol. Metab.* **2017**, *6*, 366–373; DOI:10.1016/j.molmet.2017.01.010.
49. Boya, P.; Reggiori, F.; Codogno, P. Emerging regulation and functions of autophagy. *Nat. Cell Biol.* **2013**, *15*, 713–20; DOI:10.1038/ncb2788.
50. Galluzzi, L.; Baehrecke, E.H.; Ballabio, A.; Boya, P.; Bravo-San Pedro, J.M.; Cecconi, F.; Choi, A.M.; Chu, C.T.; Codogno, P.; Colombo, M.I.; et al. Molecular definitions of autophagy and related processes. *EMBO J.* **2017**, *36*, 1811–1836; DOI:10.15252/embj.201796697.
51. Mizushima, N. A brief history of autophagy from cell biology to physiology and disease. *Nat. Cell Biol.* **2018**, *20*, 521–527; DOI:10.1038/s41556-018-0092-5.
52. Kroemer, G.; Mariño, G.; Levine, B. Autophagy and the integrated stress response. *Mol. Cell* **2010**, *40*, 280–293; DOI:10.1016/j.molcel.2010.09.023.
53. Murrow, L.; Debnath, J. Autophagy as a stress-response and quality-control mechanism: implications for cell injury and human disease. *Annu. Rev. Pathol.* **2013**, *8*, 105–137; DOI:10.1146/annurev-pathol-020712-163918.
54. Mizushima, N. Autophagy: process and function. *Genes Dev.* **2007**, *21*, 2861–2873; DOI:10.1101/gad.1599207.
55. Singh, R.; Kaushik, S.; Wang, Y.; Xiang, Y.; Novak, I.; Komatsu, M.; Tanaka, K.; Cuervo, A.M.; Czaja, M.J. Autophagy regulates lipid metabolism. *Nature* **2009**, *458*, 1131–1135; DOI:10.1038/nature07976.
56. Singh, R.; Cuervo, A.M. Lipophagy: connecting autophagy and lipid metabolism. *Int. J. Cell Biol.* **2012**, *2012*, 282041; DOI:10.1155/2012/282041.
57. Martinez-Vicente, M.; Tallozy, Z.; Wong, E.; Tang, G.; Koga, H.; Kaushik, S.; De Vries, R.; Arias, E.; Harris, S.; Sulzer, D.; et al. Cargo recognition failure is responsible for inefficient autophagy in Huntington's disease. *Nat. Neurosci.* **2010**, *13*, 567–576; DOI:10.1038/nn.2528.
58. Ouimet, M.; Franklin, V.; Mak, E.; Liao, X.; Tabas, I.; Marcel, Y.L. Autophagy regulates cholesterol efflux from macrophage foam cells via lysosomal acid lipase. *Cell Metab.* **2011**, *13*, 655–667; DOI:10.1016/j.cmet.2011.03.023.
59. Hubbard, V.M.; Valdor, R.; Patel, B.; Singh, R.; Cuervo, A.M.; Macian, F. Macroautophagy regulates energy metabolism during effector T cell activation. *J. Immunol.* **2010**, *185*, 7349–7357; DOI:10.4049/jimmunol.1000576.
60. Meng, Q.; Cai, D. Defective hypothalamic autophagy directs the central pathogenesis of obesity via the I κ B kinase β (IKK β)/NF- κ B pathway. *J. Biol. Chem.* **2011**, *286*, 32324–32332; DOI:10.1074/jbc.M111.254417.

61. Coupé, B.; Ishii, Y.; Dietrich, M.O.; Komatsu, M.; Horvath, T.L.; Bouret, S.G. Loss of autophagy in pro-opiomelanocortin neurons perturbs axon growth and causes metabolic dysregulation. *Cell Metab.* **2012**, *15*, 247–255; DOI:10.1016/j.cmet.2011.12.016.
62. Kaushik, S.; Rodriguez-Navarro, J.A.; Arias, E.; Kiffin, R.; Sahu, S.; Schwartz, G.J.; Cuervo, A.M.; Singh, R. Autophagy in hypothalamic AgRP neurons regulates food intake and energy balance. *Cell Metab.* **2011**, *14*, 173–183; DOI:10.1016/j.cmet.2011.06.008.
63. Kaushik, S.; Arias, E.; Kwon, H.; Lopez, N.M.; Athonvarangkul, D.; Sahu, S.; Schwartz, G.J.; Pessin, J.E.; Singh, R. Loss of autophagy in hypothalamic POMC neurons impairs lipolysis. *EMBO Rep.* **2012**, *13*, 258–265; DOI:10.1038/embor.2011.260.
64. Quan, W.; Kim, H.K.; Moon, E.Y.; Kim, S.S.; Choi, C.S.; Komatsu, M.; Jeong, Y.T.; Lee, M.K.; Kim, K.W.; Kim, M.S.; et al. Role of hypothalamic proopiomelanocortin neuron autophagy in the control of appetite and leptin response. *Endocrinology* **2012**, *153*, 1817–1826; DOI:10.1210/en.2011-1882.
65. Martinez-Lopez, N.; Garcia-Macia, M.; Sahu, S.; Athonvarangkul, D.; Liebling, E.; Merlo, P.; Cecconi, F.; Schwartz, G.J.; Singh, R. Autophagy in the CNS and periphery coordinate lipophagy and lipolysis in the brown adipose tissue and liver. *Cell Metab.* **2016**, *23*, 113–127; DOI:10.1016/j.cmet.2015.10.008.
66. Ignacio-Souza, L.M.; Bombassaro, B.; Pascoal, L.B.; Portovedo, M.A.; Razolli, D.S.; Coope, A.; Victorio, S.C.; De Moura, R.F.; Nascimento, L.F.; Arruda, A.P.; et al. Defective regulation of the ubiquitin/proteasome system in the hypothalamus of obese male mice. *Endocrinology* **2014**, *155*, 2831–2844; DOI: 10.1210/en.2014-1090.
67. Portovedo, M.; Ignacio-Souza, L.M.; Bombassaro, B.; Coope, A.; Reginato, A.; Razolli, D.S.; Torsoni, M.A.; Torsoni, A.S.; Leal, R.F.; Velloso, L.A.; et al. Saturated fatty acids modulate autophagy's proteins in the hypothalamus. *PLoS One* **2015**, *10*, e0119850; DOI:10.1371/journal.pone.0119850.
68. Morselli, E.; Criollo, A.; Rodriguez-Navas, C.; Clegg, D.J. Chronic high fat diet consumption impairs metabolic health of male mice. *Inflamm. Cell Signal.* **2014**, *1*, e561; DOI:10.14800/ics.561.
69. Reginato, A.; de Fante, T.; Portovedo, M.; da Costa, N.F.; Payolla, T.B.; Miyamoto, J.É.; Simino, L.A.; Ignácio-Souza, L. M. Torsoni, M.A.; Torsoni, A.S.; Milanski, M. Autophagy proteins are modulated in the liver and hypothalamus of the offspring of mice with diet-induced obesity. *J. Nutr. Biochem.* **2016**, *34*, 30–41; DOI:10.1016/j.jnutbio.2016.04.002.
70. Simonovitch, S.; Schmukler, E.; Bepalko, A.; Iram, T.; Frenkel, D.; Holtzman, D.M.; Masliah, E.; Michaelson, D.M.; Pinkas-Kramarski, R. Impaired autophagy in APOE4 astrocytes. *J. Alzheimer's Dis.* **2016**, *51*, 915–927; DOI:10.3233/JAD-151101.
71. Pamerter, M.E.; Perkins, G.A.; McGinness, A.K.; Gu, X.Q.; Ellisman, M.H.; Haddad, G.G. Autophagy and apoptosis are differentially induced in neurons and astrocytes treated with an in vitro mimic of the ischemic penumbra. *PLoS One* **2012**, *7*, e51469; DOI:10.1371/journal.pone.0051469.
72. Catalano, M.; D'Alessandro, G.; Lepore, F.; Corazzari, M.; Caldarella, S.; Valacca, C.; Faienza, F.; Esposito, V.; Limatola, C.; Cecconi, F.; et al. Autophagy induction impairs migration and invasion by reversing EMT in glioblastoma cells. *Mol. Oncol.* **2015**, *9*, 1612–1625; DOI:10.1016/j.molonc.2015.04.016.
73. Korenić, A.; Andjus, P.; Radenović, L.; Spasojević, I. The role of autophagy and lipolysis in survival of astrocytes under nutrient deprivation. *Neurosci. Lett.* **2015**, *595*, 128–133; DOI:10.1016/j.neulet.2015.04.020.
74. Kovacs, G.G.; Lee, V.M.; Trojanowski, J.Q. Protein astroglialopathies (PAG) in human neurodegenerative diseases and aging. *Brain Pathol.* **2017**, *27*, 675–690; DOI:10.1111/bpa.12536.

75. Hara, T.; Nakamura, K.; Matsui, M.; Yamamoto, A.; Nakahara, Y.; Suzuki-Migishima, R.; Yokoyama, M.; Mishima, K.; Saito, I.; Okano, H.; et al. Suppression of basal autophagy in neural cells causes neurodegenerative disease in mice. *Nature* **2006**, *441*, 885–889; DOI:10.1038/nature04724.
76. Komatsu, M.; Waguri, S.; Chiba, T.; Murata, S.; Iwata, J.I.; Tanida, I.; Ueno, T.; Koike, M.; Uchiyama, Y.; Kominami, E.; et al. Loss of autophagy in the central nervous system causes neurodegeneration in mice. *Nature* **2006**, *441*, 880–884; DOI:10.1038/nature04723.
77. Jänen, S.B.; Chaachouay, H.; Richter-Landsberg, C. Autophagy is activated by proteasomal inhibition and involved in aggresome clearance in cultured astrocytes. *Glia* **2010**, *58*, 1766–1774; DOI:10.1002/glia.21047.
78. Tang, G.; Yue, Z.; Talloczy, Z.; Hagemann, T.; Cho, W.; Messing, A.; Sulzer, D.I.; Goldman, J.E. Autophagy induced by Alexander disease-mutant GFAP accumulation is regulated by p38/MAPK and mTOR signaling pathways. *Hum. Mol. Genet.* **2008**, *17*, 1540–1555; DOI:10.1093/hmg/ddn042.
79. Booth, H.D.E.; Hirst, W.D.; Wade-Martins, R. The role of astrocyte dysfunction in Parkinson's disease pathogenesis. *Trends Neurosci.* **2017**, *40*, 358–370; DOI:10.1016/j.tins.2017.04.001.
80. Lu, S.Z.; Guo, Y.S.; Liang, P.Z.; Zhang, S.Z.; Yin, S.; Yin, Y.Q.; Wang, X.M.; Ding, F.; Gu, X.S.; Zhou, J.W. Suppression of astrocytic autophagy by α B-crystallin contributes to α -synuclein inclusion formation. *Transl. Neurodegener.* **2019**, *8*, 3; DOI:10.1186/s40035-018-0143-7.
81. Manzoni, C. The LRRK2-macroautophagy axis and its relevance to Parkinson's disease. *Biochem. Soc. Trans.* **2017**, *45*, 155–162; DOI:10.1042/BST20160265.
82. di Domenico, A.; Carola, G.; Calatayud, C.; Pons-Espinal, M.; Muñoz, J.P.; Richaud-Patin, Y.; Fernandez-Carasa, I.; Gut, M.; Faella, A.; Parameswaran, J.; et al. Patient-specific iPSC-derived astrocytes contribute to non-cell-autonomous neurodegeneration in Parkinson's disease. *Stem Cell Reports* **2019**, *12*, 213–229; DOI:10.1016/j.stemcr.2018.12.011.
83. Wang, S.; Li, B.; Qiao, H.; Lv, X.; Liang, Q.; Shi, Z.; Xia, W.; Ji, F.; Jiao, J. Autophagy-related gene Atg5 is essential for astrocyte differentiation in the developing mouse cortex. *EMBO Rep.* **2014**, *15*, 1053–1061; DOI:10.15252/embr.201338343.
84. Ha, S.; Jeong, S.H.; Yi, K.; Chu, J.J.M.; Kim, S.; Kim, E.K.; Yu, S.W. Autophagy mediates astrogenesis in adult hippocampal neural stem cells. *Exp. Neurobiol.* **2019**, *28*, 229–246; DOI:10.5607/en.2019.28.2.229.
85. Shukla, S.; Patric, I.R.; Patil, V.; Shwetha, S.D.; Hegde, A.S.; Chandramouli, B.A.; Arivazhagan, A.; Santosh, V.; Somasundaram, K. Methylation silencing of ULK2, an autophagy gene, is essential for astrocyte transformation and tumor growth. *J. Biol. Chem.* **2014**, *289*, 22306–22318; DOI:10.1074/jbc.M114.567032.
86. Morita, M.; Ikeshima-Kataoka, H.; Kreft, M.; Vardjan, N.; Zorec, R.; Noda, M. Metabolic plasticity of astrocytes and aging of the brain. *Int. J. Mol. Sci.* **2019**, *20*, E941; DOI:10.3390/ijms20040941.
87. Motori, E.; Puyal, J.; Toni, N.; Ghanem, A.; Angeloni, C.; Malaguti, M.; Cantelli-Forti, G.; Berninger, B.; Conzelmann, K.K.; Götz, M.; et al. Inflammation-induced alteration of astrocyte mitochondrial dynamics requires autophagy for mitochondrial network maintenance. *Cell Metab.* **2013**, *18*, 844–859; DOI:10.1016/j.cmet.2013.11.005.
88. Qin, A.P.; Liu, C.F.; Qin, Y.Y.; Hong, L.Z.; Xu, M.; Yang, L.; Liu, J.; Qin, Z.H.; Zhang, H.L. Autophagy was activated in injured astrocytes and mildly decreased cell survival following glucose and oxygen deprivation and focal cerebral ischemia. *Autophagy* **2010**, *6*, 738–753; DOI:10.4161/auto.6.6.12573.
89. Han, B.; Zhang, Y.; Zhang, Y.; Bai, Y.; Chen, X.; Huang, R.; Wu, F.; Leng, S.; Chao, J.; Zhang, J.H.; et

- al. Novel insight into circular RNA HECTD1 in astrocyte activation via autophagy by targeting MIR142-TIPARP: implications for cerebral ischemic stroke. *Autophagy* **2018**, *14*, 1164–1184; DOI:10.1080/15548627.2018.1458173.
90. Lin, C.J.; Chen, T.H.; Yang, L.Y.; Shih, C.M. Resveratrol protects astrocytes against traumatic brain injury through inhibiting apoptotic and autophagic cell death. *Cell Death Dis.* **2014**, *5*, e1147; DOI:10.1038/cddis.2014.123.
91. Gray, L.R.; Roche, M.; Flynn, J.K.; Wesselingh, S.L.; Gorry, P.R.; Churchill, M.J. Is the central nervous system a reservoir of HIV-1? *Curr. Opin. HIV AIDS* **2014**, *9*, 552–558; DOI:10.1097/COH.000000000000108.
92. Li, G.H.; Henderson, L.; Nath, A. Astrocytes as an HIV reservoir: mechanism of HIV infection. *Curr. HIV Res.* **2016**, *14*, 373–381; DOI:10.2174/1570162x14666161006121455.
93. Ojeda, D.S.; Grasso, D.; Urquiza, J.; Till, A.; Vaccaro, M.I.; Quarleri, J. Cell death is counteracted by mitophagy in HIV-productively infected astrocytes but is promoted by inflammasome activation among non-productively infected cells. *Front. Immunol.* **2018**, *9*, 2633; DOI:10.3389/fimmu.2018.02633.
94. Mehla, R.; Chauhan, A. HIV-1 differentially modulates autophagy in neurons and astrocytes. *J. Neuroimmunol.* **2015**, *285*, 106–118; DOI:10.1016/j.jneuroim.2015.06.001.
95. Hong, Y.; Liu, Y.; Zhang, G.; Wu, H.; Hou, Y. Progesterone suppresses A β 42-induced neuroinflammation by enhancing autophagy in astrocytes. *Int. Immunopharmacol.* **2018**, *54*, 336–343; DOI:10.1016/j.intimp.2017.11.044.
96. Shu, X.; Sun, Y.; Sun, X.; Zhou, Y.; Bian, Y.; Shu, Z.; Ding, J.; Lu, M.; Hu, G. The effect of fluoxetine on astrocyte autophagy flux and injured mitochondria clearance in a mouse model of depression. *Cell Death Dis.* **2019**, *10*, 577; DOI:10.1038/s41419-019-1813-9.
97. Di Malta, C.; Fryer, J.D.; Settembre, C.; Ballabio, A. Astrocyte dysfunction triggers neurodegeneration in a lysosomal storage disorder. *Proc. Natl. Acad. Sci.* **2012**, *109*, E2334–E2342; DOI:10.1073/pnas.1209577109.
98. Liu, X.; Tian, F.; Wang, S.; Wang, F.; Xiong, L. Astrocyte autophagy flux protects neurons against oxygen-glucose deprivation and ischemic/reperfusion injury. *Rejuvenation Res.* **2018**, *21*, 405–415; DOI:10.1089/rej.2017.1999.
99. Kulkarni, A.; Dong, A.; Kulkarni, V.V.; Chen, J.; Laxton, O.; Anand, A.; Maday, S. Differential regulation of autophagy during metabolic stress in astrocytes and neurons. *Autophagy* **2019**, 1–17; DOI:10.1080/15548627.2019.1703354.
100. Pla, A.; Pascual, M.; Guerri, C. Autophagy constitutes a protective mechanism against ethanol toxicity in mouse astrocytes and neurons. *PLoS One* **2016**, *11*, e0153097; DOI:10.1371/journal.pone.0153097.
101. Bordi, M.; Berg, M.J.; Mohan, P.S.; Peterhoff, C.M.; Alldred, M.J.; Che, S.; Ginsberg, S.D.; Nixon, R.A. Autophagy flux in CA1 neurons of Alzheimer hippocampus: increased induction overburdens failing lysosomes to propel neuritic dystrophy. *Autophagy* **2016**, *12*, 2467–2483; DOI:10.1080/15548627.2016.1239003.
102. Chen, Z.; Nie, S.D.; Qu, M.L.; Zhou, D.; Wu, L.Y.; Shi, X.J.; Ma, L.R.; Li, X.; Zhou, S.L.; Wang, S.; et al. The autophagic degradation of Cav-1 contributes to PA-induced apoptosis and inflammation of astrocytes. *Cell Death Dis.* **2018**, *9*, 771; DOI:10.1038/s41419-018-0795-3.
103. Kabeya, Y.; Mizushima, N.; Ueno, T.; Yamamoto, A.; Kirisako, T.; Noda, T.; Kominami, E.; Ohsumi, Y.; Yoshimori, T. LC3, a mammalian homologue of yeast Apg8p, is localized in autophagosome

membranes after processing. *EMBO J.* **2000**, *19*, 5720–5728; DOI:10.1093/emboj/19.21.5720.

104. Klionsky, D.J.; Abdelmohsen, K.; Abe, A.; Abedin, M.J.; Abeliovich, H.; Acevedo Arozena, A.; Adachi, H.; Adams, C.M.; Adams, P.D.; Adeli, K.; et al. Guidelines for the use and interpretation of assays for monitoring autophagy (3rd edition). *Autophagy* **2016**, *12*, 1–222; DOI:10.1080/15548627.2015.1100356.
105. Morselli, E.; Fuente-Martin, E.; Finan, B.; Kim, M.; Frank, A.; Garcia-Caceres, C.; Navas, C.R.; Gordillo, R.; Neinast, M.; Kalainayakan, S.P.; et al. Hypothalamic PGC-1 α protects against high-fat diet exposure by regulating ER α . *Cell Rep.* **2014**, *9*, 633–645; DOI:10.1016/j.celrep.2014.09.025.
106. Valdearcos, M.; Robblee, M.M.; Benjamin, D.I.; Nomura, D.K.; Xu, A.W.; Koliwad, S.K. Microglia dictate the impact of saturated fat consumption on hypothalamic inflammation and neuronal function. *Cell Rep.* **2014**, *9*, 2124–2138; DOI:10.1016/j.celrep.2014.11.018.
107. Karmi, A.; Iozzo, P.; Viljanen, A.; Hirvonen, J.; Fielding, B.A.; Virtanen, K.; Oikonen, V.; Kemppainen, J.; Viljanen, T.; Guiducci, L.; et al. Increased brain fatty acid uptake in metabolic syndrome. *Diabetes* **2010**, *59*, 2171–2177; DOI:10.2337/db09-0138.
108. Patil, S.; Melrose, J.; Chan, C. Involvement of astroglial ceramide in palmitic acid-induced Alzheimer-like changes in primary neurons. *Eur. J. Neurosci.* **2007**, *26*, 2131–2141; DOI:10.1111/j.1460-9568.2007.05797.x.
109. Gupta, S.; Knight, A.G.; Gupta, S.; Keller, J.N.; Bruce-Keller, A.J. Saturated long-chain fatty acids activate inflammatory signaling in astrocytes. *J. Neurochem.* **2012**, *120*, 1060–1071; DOI:10.1111/j.1471-4159.2012.07660.x.
110. Wong, K.L.; Wu, Y.R.; Cheng, K.S.; Chan, P.; Cheung, C.W.; Lu, D.Y.; Su, T.H.; Liu, Z.M.; Leung, Y.M. Palmitic acid-induced lipotoxicity and protection by (+)-catechin in rat cortical astrocytes. *Pharmacol. Reports* **2014**, *66*, 1106–1113; DOI:10.1016/j.pharep.2014.07.009.
111. González-Giraldo, Y.; Garcia-Segura, L.M.; Echeverria, V.; Barreto, G.E. Tibolone preserves mitochondrial functionality and cell morphology in astrocytic cells treated with palmitic acid. *Mol. Neurobiol.* **2018**, *55*, 4453–4462; DOI:10.1007/s12035-017-0667-3.
112. Wang, Z.; Liu, D.; Wang, J.; Liu, S.; Gao, M.; Ling, E.A.; Hao, A. Cytoprotective effects of melatonin on astroglial cells subjected to palmitic acid treatment in vitro. *J. Pineal Res.* **2012**, *52*, 253–264; DOI:10.1111/j.1600-079X.2011.00952.x.
113. Ortiz-Rodriguez, A.; Acáz-Fonseca, E.; Boya, P.; Arevalo, M.A.; Garcia-Segura, L.M. Lipotoxic effects of palmitic acid on astrocytes are associated with autophagy impairment. *Mol. Neurobiol.* **2019**, *56*, 1665–1680; DOI:10.1007/s12035-018-1183-9.
114. Hernández-Cáceres, M.P.; Toledo-Valenzuela, L.; Díaz-Castro, F.; Ávalos, Y.; Burgos, P.; Narro, C.; Peña-Oyarzun, D.; Espinoza-Cacedo, J.; Cifuentes-Araneda, F.; Navarro-Aguad, F.; et al. Palmitic acid reduces the autophagic flux and insulin sensitivity through the activation of the Free Fatty Acid Receptor 1 (FFAR1) in the hypothalamic neuronal cell line N43/5. *Front. Endocrinol. (Lausanne)*. **2019**, *10*, 176; DOI:10.3389/fendo.2019.00176.
115. Oliveira, A.A.B.; Melo, N.F.M.; Vieira, É.D.S.; Nogueira, P.A.S.; Coope, A.; Velloso, L.A.; Dezonne, R.S.; Ueira-Vieira, C.; Botelho, F.V.; Gomes, J.A.S.; et al. Palmitate treated-astrocyte conditioned medium contains increased glutathione and interferes in hypothalamic synaptic network in vitro. *Neurochem. Int.* **2018**, *120*, 140–148; DOI:10.1016/j.neuint.2018.08.010.