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High-Fat and Cholesterol Intake Affects Brain Homeostasis and Could Accelerate the Development of Dementia: A Systemic View

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Additional information is available at the end of the chapter

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Abstract

Alzheimer's disease is the most common type of dementia in occidental countries. The majority of the cases develop the disease for no genetic reasons; therefore, it is crucial to establish which environmental factors trigger the development of the disease. It has been proposed that nutritional habits, especially main components of Western countries' diet such as saturated fat or cholesterol, increase the risk for development of Alzheimer's disease (AD) and/or accelerate the onset of the disease, which is a big concern in countries where obesity is a public health problem. It is crucial to understand the links between alimentary habits and the development of AD and other types of dementia. A possible mechanism is the disruption of blood–brain barrier (BBB), which is the protection of the brain from circulating blood. Such disruptions can result from consuming high-fat diet (HFD) or high-cholesterol diet (HCD) and inflammation produced by alteration in brain vasculature resulted for chronic consumption of such type of diets. What has named a "Systemic view" comprises the idea that; what happens outside of the brain environment does affect brain functioning and the modifications experienced in the brain environment resulted from the influence of external factors will affect the entire body. In the current chapter, we will review the state of the art in the studies of the impact of a diet rich in fat or cholesterol on the brain and how the alterations induced in other organs can impact brain functioning increasing the susceptibility of development of dementia.

Keywords: high-fat diet, high-cholesterol diet, Alzheimer's disease, blood–brain barrier, brain plasticity, cognition

1. Introduction

In the recent decades, the population in the industrialized Western countries has become remarkable sedentary and have had a considerable increase in the intake of what has been called "fast food," meals that are rich in fat and carbohydrates and contain elevated levels of cholesterol as well. The elevated consumption of fast food has had a strong impact on public health, which has important repercussions in several levels including an economic impact due to the elevated cost of a chronic use of specialized health services and a detrimental effect in both, life quality and expectancy for the patients. Among the adverse health effects of this type of diet, we can mention obesity, vascular diseases, and metabolic syndrome, and it has been recently proposed that it can increase the risk of developing Alzheimer's disease (AD), which is the most common type of dementia in elderly people. It is considered that a particular type of diet could accelerate the progress of the disease for a not yet well-known mechanism [1]. It is a revolutionary idea, since we have had for several years the conception that brain is actually protected by the blood-brain barrier (BBB); however, experimental evidence suggests that the consumption of diets rich in fat can disrupt the permeability of BBB, making it vulnerable to systemic molecules that could trigger degenerative processes [1, 2].

In the current chapter, we will review the state of the art related to the impact of diets rich in fat or cholesterol on the brain, and how the alterations induced in other organs can impact brain functioning and could increase the susceptibility to develop dementia. The bibliographic revision was carried out running an exhaustive search on the research articles related to the topic employing the database of the US National Library of Medicine, National Institutes of Health, PubMed.gov. Firstly, reviewing the most recent papers and those with the most relevant information. Thereafter, we carefully followed the references cited by the reviewed articles in order to study the grounding data on the subject and which direction it followed until our days in order to document the accuracy and evolution of the data.

2. Findings on amyloid- β production induced by saturated fat diet in noncerebral tissue

One of the histopathological hallmarks of AD is the extracellular deposition of amyloid- β peptide ($A\beta$) in the brain. It is widely accepted that $A\beta$ deposition occurs when the neuronal synthesis of the peptide exceeds the clearance capacity [3, 4]. However, some decades ago, the idea was proposed that $A\beta$ generated systemically could pass the BBB and be deposited in the brain, since $A\beta$ was detected in noncerebral biological fluids. Such idea raised from grounding data of Seubert et al. [5], who demonstrated that $A\beta$ fragment comprising the amino acids 13–28 can be detected in cerebrospinal fluid and plasma of several species including human as well as in conditioned media from human brain cell cultures. It originated the idea that cerebral $A\beta$ deposits could be generated systemically and for unknown mechanism, accumulate in the brain where they affect the capacity, to be clear, increasing the amount of the peptide and eventually form the extracellular deposits. A good amount of data has focused on this idea

since then. An interesting line of study has focus on the production of A β by noncerebral tissue induced by consumption of diets rich in fat. One of the physiological functions of A β is relate to lipids metabolism and many A β transport proteins have been associated with lipids *in vivo* [6]. The association of the A β soluble fraction with high-density lipoproteins from healthy human plasma and cerebrospinal fluid was reported as well [7, 8]. The association between lipids and A β was demonstrated in a very elegant study where A β activity was followed labeling it with radioactivity, and it was found that the peptide is expressed in tissues rich in fat, such as spleen, marrow, liver, adipose tissue, brain, kidney, lung, and skeletal muscle. It was shown that the expression of A β is associated with postprandial lipoproteins such as chylomicrons, lipoproteins that are in charge to move dietary fat from intestine to the target organs. These associations remain during lipolysis and tissue uptaking processes [9]. Therefore, it can be proposed that an increased plasmatic amount of such proteins containing A β could produce an imbalance and could even be delivered in brain contributing to cerebral amyloidosis, one of the responsible events related to Alzheimer's disease [9, 10]. The natural question is: how can we increase the amount of A β associated to postprandial lipids? One answer is the intake of diets rich in fat or cholesterol because they could break the balance of lipids content, but by which way? An interesting direction has been to study the expression of A β in organs rich in lipids and if such expression is regulated by fat or cholesterol diets.

Koudinov et al. [11] reported that hepatocytes secrete amyloid- β as a lipoprotein complex. Another organ where it has been documented that A β is produced is the small intestine. Given the evidence that A β is associated to postprandial lipoproteins, chylomicrons, Galloway et al. [10] followed this line of evidence and studied small intestinal epithelial cells (where the chylomicrons are produced). They fed wild-type mice with low- or high-fat diet. After six months of treatment they determinate by immunohistochemistry, the expression of the amyloid precursor protein in absorptive cells in the small intestine and observed a greater expression of this molecule in small intestinal epithelial cells of high-fat fed animals, whereas animals fasting 65 h did not show any expression. There is another study where the group of John CL Mamo evaluated the expression of A β in enterocytes after a low- or high-fat diet with 1% cholesterol in apolipoprotein E (apo E) (-/-) knockout mice. Apolipoprotein E is a lipoprotein that modulates A β biogenesis [12–14]. After six months of dietary treatment, the small intestine of apo E (-/-) KO mice fed with low-fat diet showed the same levels of expression of A β as the wild-type animals detected by immunohistochemistry. On the other hand, both groups of animals, wild-type and apo E (-/-) KO mice fed with high-fat diet, showed an increased expression of A β in enterocytes being higher in the KO animals. Also in these study, the group evaluates villi length between the groups treated, finding that the high-fat diet did not affect villi length in apo E (-/-) KO mice, but interestingly there is an increase in villi length of KO mice treated with low-fat diet when compared with wild-type mice under the same dietary conditions [15]. These groups also carried out a very elegant study to corroborate the association of A β production with recently generated lipoproteins, employing three-dimensional immunofluorescence microscopy and determinated that A β produced by enterocytes certainly has a clear colocalization with chylomicrons in small intestine enterocyte after three months of dietary treatment (free of cholesterol). They found that the amount of A β colocalizing with chylomicrons reaches the double [16]. These data together confirms the presence of A β in

lipoproteins generated in small intestine and that a diet rich in fat could increase the production of transport lipoproteins. However, the open question stills remains: how this A β produced systemically reaches the brain? (**Figure 1**). Further studies are necessary to establish if indeed an imbalance in lipids production induced by diet can promote the delivery of these systemic A β to brain and induce cerebral amyloidosis.

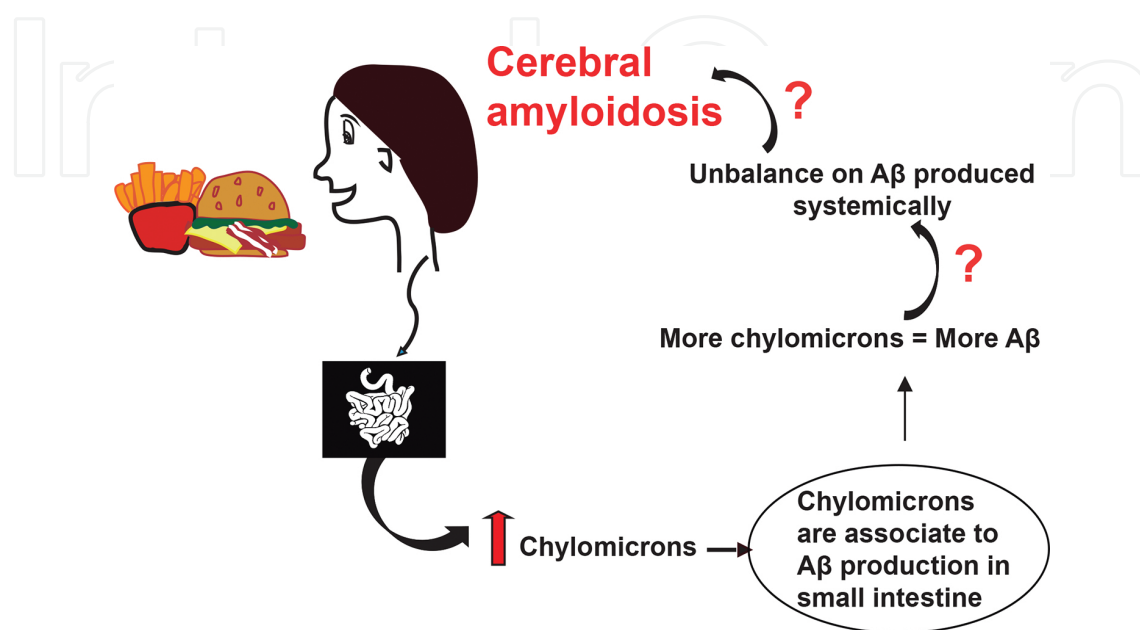


Figure 1. The ingestion of food rich on fat and cholesterol can increase the amount of postprandial lipoproteins chylomicrons. An increased production of chylomicrons can lead to an overproduction of A β and potentially produce an unbalance on A β processing and lead to cerebral amyloidosis.

3. Effect on vascularity and BBB integrity

The brain is a very well-protected organ with two barrier systems. One is a highly specialized microvascular endothelial system known as blood brain barrier (BBB), its function is to protect the brain from the entry of damaging substances and at the same time, allows the entry of nutrients as well as endocrine signals by means of an active transport and a passive diffusion system. The second is the choroid plexus, whose function is to prevent the entry of blood in the cerebrospinal circulation [17]. An unbalance in such systems could lead to disease conditions regarding the entrance of damaging molecules or disrupting the entrance of proper nutrients or endocrine signals. A good body of data has focused in study; how dietary habits can trigger BBB disruption? A longitudinal study, carried out in Sweden, evaluated the integrity of BBB *in vivo* in 81 women with a wide range of body size, who acceded to receive a lumbar puncture in order to obtain cerebrospinal fluid and compared the index of albumin content. Albumin is a constitutive protein that is absent in the brain, since its access is stopped by the BBB; therefore its presence in cerebrospinal fluid is a sign of disruption of the protection systems. Among these large group studied, the obese and overweight women between 70 and

84 years had the highest amount of albumin reported as the ratio of albumin in cerebrospinal fluid/Serum albumin (CSF/S albumin). Interestingly, they found a correlation between low levels of sex hormone binding globulin (SHBG) in the same group of women when they were younger [18]. It is known that SHBG decreases with overweight in both, male and female [19–21]. In the Swedish longitudinal study, SHBG was employed as measure of endocrine signal in the same group of females when they were in their middle forties, and decades later when they were analyzed for several parameters besides the CSF/S albumin ratio, such measures included behavioral evaluations finding that they had cognitive alterations [18]. It strongly suggests that since youth, these group of obese and overweighting women had less content of SHBG accompanied in elderly years by BBB disruption and cognitive decline. These data suggest that an unbalance between the selective entrance and exit of molecules and signaling driven by a failed BBB filtering can lead to development of dementia, but more experimental data is needed in order to elucidate the mechanism behind this effect. One way to explain the cognitive detriment found in these patients could be the diminishment of factors that have been shown to be protective for the brain, such as SHBG. High levels of SHBG have been associated with neuroprotection in stroke, vascular and cardiovascular diseases, diabetes [21–25], and an increased amount of molecules potentially damaging for the brain, such as A β [26–28]. Such idea can be supported by the fact that it was found in the obese and overweight women, a higher ratio of CSF/S albumin has been observed in subjects with AD as well [29, 30]. In this study, the CSF/S albumin content was measured in 118 patients diagnosed with AD and clinical data of vascular alterations was registered as well. The AD subjects were compared with individuals without dementia of the same age, finding a higher albumin ratio in those with both AD and vascular factors. There was not significant BBB disruption in the patients without vascular alterations; additionally, there is no correlation with BBB disturbances and age in the control group, which strongly suggests a relationship with the vascular alterations, BBB disruption, and AD [29]. Controversially in a study, albumin content as well as IgG in serum and cerebrospinal fluid in several groups of patients with different dementias such as early-progression familial AD, the senile dementia of Alzheimer type (Late Onset Alzheimer's Disease LOAD), and two types of vascular dementia: a group diagnosed with vascular dementia and others with multiinfarct, were measured. The multiinfarct group was reported with the highest significant alteration of the BBB but not in AD group. All these data supports the idea that vascular factors associated to BBB disruption are in relationship with the development of many dementia syndromes and are not restricted to AD [31]. That controversial information can be clarified with animal experimental data, where several variables can be controlled. The very first experimental evidence that the A β peptide can actually cross BBB and be deposited in the brain parenchyma was done in 1993 by Zlokovic et al. [32]. The researchers injected synthetic forms of A β peptide: 1–28 and 1–40, which were labeled with a radioactive marker in order to follow it after carrying out an injection in the neck vessel of the guinea pigs. The research group found a specific deposition of both synthetic peptides in the BBB microvasculature, initiating in the luminal side and transcellular transport into the brain parenchyma. This study strongly supports the idea that the A β produced systemically can cross the BBB. However, the mechanism remains unclear so far.

Although there is evidence that BBB can be disrupted in patients with dementia, it is possible that the development on AD can be due to systemically produced A β that can cross the BBB and form the deposits in the brain, but how does this happen? As we reviewed, obese patients apparently have a disrupted BBB permeability, although, what triggers that? Are the intake habits involved in such phenomenon? There is experimental evidence that suggest that components of Western diet, such as cholesterol and saturated fat, can contribute to that phenomenon. Studies with rabbits fed with a diet containing 2% cholesterol for 8 weeks, have demonstrated that such type of diet disrupts BBB permeability, alters vascularity, and induce vessels inflammation and A β peptide accumulation in parenchyma [26–28]; and this accumulation is similar to that observed in brains of AD patients [33]. This body of data, mainly generated by D.L. Sparks and collaborators, strongly supports the idea that high cholesterol consumption, importantly, contributes to the development of AD onset by the accumulation of A β , vascular alterations, as well as BBB selective permeability disruption.

The contribution of BBB disruption of a high energetic diet (HE) (approximately 40% Kcal of fat versus 13% of standard laboratory rodent diet) based on high saturated fat and glucose was evaluated in 60-days-old 32 male rats that were fed for 90 days with this type of diet. The researchers evaluated the BBB integrity, measuring by ELISA, the content of sodium fluorescein (NaFl) injected throughout the femoral artery in the prefrontal cortex, striatum, and hippocampus of the treated rats. They found a significant increased amount of NaFl in the hippocampus of the treated rats compared with the control but not in prefrontal cortex or in striatum. They also measured the mRNA expression of tight junction proteins by RT-PCR in choroid plexus and BBB capillaries. Tight junction proteins are critical components for maintenance of selective BBB permeability, its diminishment can alter the BBB function. They found a decrease expression of the tight junction proteins and alterations in behavioral task directly associated with hippocampal function [1]. A further study was carried out by Davidson et al. [34], where they fed 24 male rats with a high energy diet as well as high saturated fat and glucose and following for different time points (7, 14, 21 and 28 days), evaluated BBB integrity by injecting NaFl following the same procedure reported by Kanoski et al. [1]. They found that the hippocampus was the brain structure that exhibit the highest concentration of the dye compared with prefrontal cortex and striatum. In this study, the researchers evaluate the differences between those animals, under HE diet, that show what they called *obesity resistant* versus those that developed obesity. The obesity resistant group was the one that consumed the HE diet but gained the least weight and body fat. The animals included in the obesity group were those that gained the most bodyweight and fat. It was this last group that showed the major BBB permeability and had the highest deposit of NaFl in the hippocampus. Interestingly, they found that those animals, in the HE diet, had the lowest bodyweight and the lowest amount of fat, and did not show difference in the behavioral performance compared with the control group. However, those rats that developed obesity and had the higher deposit of dye in the hippocampus, showed alterations in the performance of the hippocampal-dependent tasks [34]. These evidences directly shows a relationship between diets rich in fat, obesity development, and hippocampal-related cognitive alterations. We will discuss in the next section, the relevance of the hippocampal structure, cognitive performance, and its detriment.

From the information reviewed in this section, we can conclude that BBB alteration is a feature that takes part of dementia onset in both, AD and vascular dementia. Obesity can contribute to this phenomenon and, although the mechanism is not well known, a particular factor that can participate in this process is the intake of diets rich in cholesterol or fat, as well as glucose, those known components of a typical Western diet (**Figure 2**).

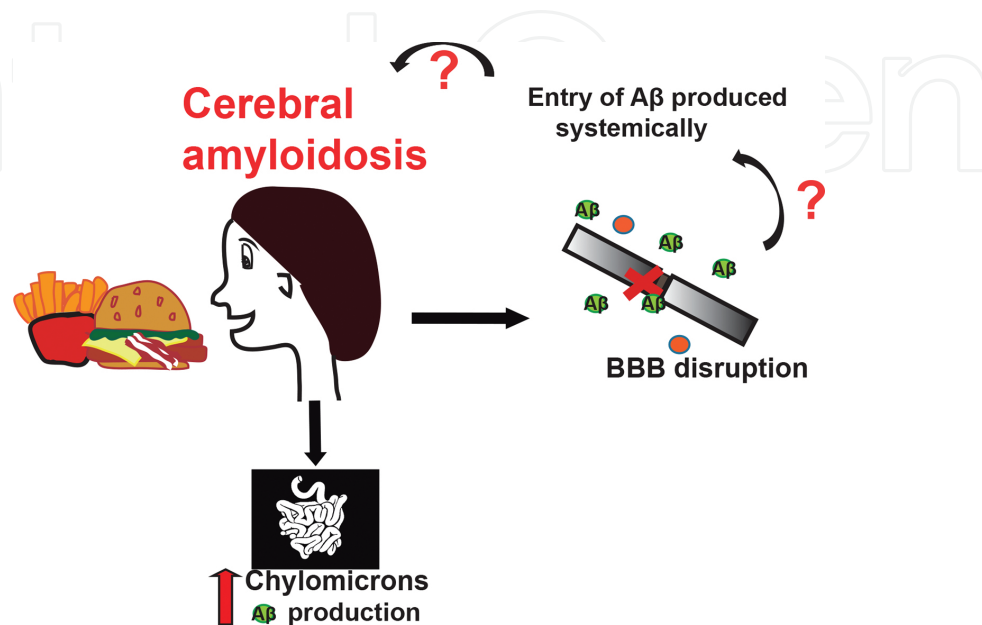


Figure 2. The overproduction of systemic $A\beta$, produced by consume diets rich on fat or cholesterol, can promote and alter the selective permeability of BBB, allowing the passage of molecules to the brain, such as systemic $A\beta$ that was not clear and lead to cerebral amyloidosis and brain inflammation.

4. Impact of a diet rich in cholesterol or fat on the development of AD onset

The hippocampus is a brain structure considered as a part of the allocortex, which is one of the oldest brain areas from the phylogenetical point of view. It has a high capacity of plasticity; it is directly involved in learning and memory process and, interestingly, is very susceptible to damage and has attracted the research focus for several years since it is one of the first brain structures that degenerate during the AD process [35]. As we reviewed in the last section, the hippocampus seems to be very susceptible to the effect of consumed diets rich in fat or cholesterol, but can this actually drive the brain into a degenerative process? Can it contribute to the development of dementia? We will discuss this idea in the current section. First, we will review how the diet high in cholesterol or fat can contribute to the development of features associated with AD, particularly with amyloidosis.

Diets rich in cholesterol, as we have reviewed, can induce vascular inflammation, BBB, and promotes $A\beta$ peptide accumulation in the brain parenchyma in an animal model of rabbit fed with high-cholesterol diet [26–28]. Supporting the association of elevated concentrations of cholesterol and AD detriment in a very recent *in vitro* study carried out by Avila-Muñoz and

Arias [36] in isolated astrocytes obtained from brain cortex of 1- to 3-day-old Wistar rats, they found astrocyte activation, An increase on the expression of amyloid precursor protein (APP), and promoted its amyloidogenic processing, and an increase in reactive species oxygen (ROS), a marker of oxidative stress, after treating the culture for 48 h with cholesterol concentrated at 25 or 50 μ M. All these parameters measured, including glia activation, resemble features that have been found in postmortem brain tissues obtained from AD patients [37–39], but how the consumption of a diet high in cholesterol can contribute to the development of AD? *In vivo* studies can answer this question. Transgenic mice Tg2576 (which express the human APP695 carrying the Swedish double mutation at codons 595 and 596, Hsiao et al. [40]), were fed with a 5% cholesterol diet for 6 weeks. They found an increase of the APP cytosolic fragment but apparently the hypocholesteremia induced by the diet does not deregulates A β metabolism (George et al, 2004).

In a further work, carried out by Refolo et al [41], with 5-months-old double-mutant for presenilin (PS) and amyloid precursor protein (PSAPP) mice, which express familial mutant PS1M146V and the APP695 mutations [42], evaluated the effect of a combined diet with 5% cholesterol and 10% fat for 7 weeks. They found that the dietary treatment induced elevated levels of cholesterol in both, plasma and brain, which is an important data since it showed that brain cholesterol is produced *in situ*, and this data demonstrates that brain cholesterol is increased by diet. This increase in brain cholesterol correlates with an increase of total A β in brain. In addition, there was an enhanced amount of A β , particularly not in A β 1–40 and 1–42, but in 1–30 and 1–34 as well. This was accompanied with an increase in the number of A β deposits as well as an increase in the plaque area in the hypercholesteremic transgenic mice. Interestingly, there were no changes found in presenilin 1 (PS1) processing. These data strongly supported the hypothesis that a diet high in fat and cholesterol can contribute to the development of amyloidosis, one of the main conditions to develop AD.

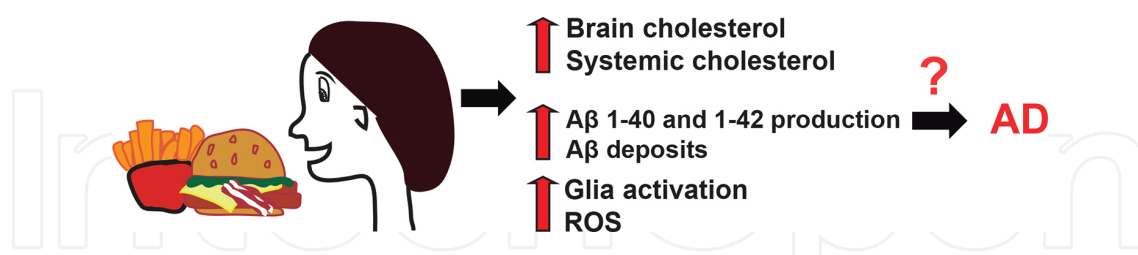


Figure 3. As result of consume diets high on fat and cholesterol there is an increase levels of brain cholesterol and systemic cholesterol. Also elevates A β production in brain and its deposit and increases as well the glia activation and production of ROS in brain. All these together can lead to AD onset.

All these data shows experimental evidence linking the consumption of diets rich in fat and/or cholesterol with the development of amyloidosis. Nevertheless, dementia is a more complex syndrome, comprised of many other features such as cognitive decline and neuronal lost. Particularly in the hippocampus, which is as we mentioned before, one of the first areas affected during the neurodegenerative process, its susceptibility to suffer alterations resulted from consuming diets high in fat or cholesterol appears crucial as one of the possible mecha-

nism involved in the development of AD (**Figure 3**). We will discuss that idea in the section below.

5. Impact on brain morphology, plasticity, and cognition

In the last sections, we have discussed how the consumption of diets rich in fat or cholesterol can contribute to the production of A β peptide in noncerebral tissue. The impact that this could have in the BBB selective permeability and its participation in brain amyloidosis conditions that can contribute to the dementia onset but, besides these alterations, one of the main conditions found in dementia patients is brain atrophy and behavioral alterations. Is brain functionality affected by the components typically found in the Western diet? Could diet composition affect brain architecture and plasticity? Moreover, is cognition affected the consumption of diets rich in fat or cholesterol? We will review such ideas in the current section.

A link between cognitive decline and dietary habits has been proposed. There is an epidemiological study carried out with Japanese men living in Hawaii compared with age-matched men living in Japan that evaluated the prevalence of dementia employing the Diagnostic and Statistical Manual of Mental Disorders. The results found that those subjects living in the USA have a higher prevalence of dementia: 9.3% for all type dementia, 5.4% for Alzheimer's disease, and 4.2% for vascular [43]. Continuing in this line of evidence, there is another study that was carried out with people from same ethnic background living in their natal land or in a foreign country (USA). They found in concordance with the study cited before, that those individual living in Indiana (where the study was carried out on) had a higher prevalence of dementia compared with age-matched individuals living in Nigeria or Ibadan [44]. This data strongly suggests that there are some stimuli in this Western country, which contribute to the development of several types of dementia, and the question is: what are these stimuli? A good candidate are the nutritional habits. In Western countries, especially countries such as the USA or Mexico, people consume food with high amounts of saturated fat and cholesterol and show the highest rates of obesity worldwide. The brain is an organ rich in lipids and essential fatty acids that are mainly obtained from food and have a crucial participation on brain functioning [45]. So, to think that lipids elevation induced by diet could be in detriment of the brain, which is a logical assumption, but what are the cellular mechanisms involved in the possible detrimental effect of food components such as fat and cholesterol? Well, experimental work has demonstrated evidence of the interplay between obesity, brain alteration, and cognitive decline, more especially with hippocampal-related cognitive processes. Seminal works in this area were carried out in the University of Toronto by Greenwood and Winocur [46]. They fed 1-month-old Long-Evans rats with two types of high-fat diets containing 40% of calories: a saturated fatty acids (lard-based) or a polyunsaturated fatty acids (soybean oil-based) and compared with a standard laboratory diet containing 4.5% of fat. They tested learning and memory abilities in the rats after 3 months of dietary treatment with the radial arm maze test, the variable-interval delayed alternation task, and the Hebb-Williams maze series. These tests evaluate spatial learning and memory performance and report failures in working or reference memories. They found that those animals fed with the lard-based diet showed impairment in

all the tests. Following this line of evidence, they analyzed further with different types of saturated fatty acid diets: monounsaturated (MUFA) and polyunsaturated (PUFA) fatty acids, finding a direct relationship between the 3 months consumption of saturated fatty acids and failures in basic alternation rule, and remembering trial-specific information over time in the variable-interval delayed alternation task. Interestingly, they found alterations in brain's phosphatidylcholine fatty acid profile. However, the changes in the membrane did not correlate with cognitive alterations [47]. It suggested there is another mechanism elucidating the cognitive impairment related to consumption of diets rich in fat; a good candidate is brain inflammation. Chronic inflammation is one of the principal altered events associated with AD [48], and it has been linked to obesity and has been reported that there is a correlation between both, obesity and AD [49, 50]. Middle-aged C57BL6 male mice were fed for 21 weeks with chow equivalent to Western diet containing 41% fat or a high-fat lard diet containing 60% fat for 16 weeks. They showed an alteration on learning acquisition measured by the Stone T-maze and it is accompanied by microglial activation, increase expression of cytokines like $\text{TNF}\alpha$, IL-6, and MCP-1, and a decrease on brain-derived neurotrophic factor (BDNF) [51]. Interestingly, there was not any detrimental effect observed in those animals that consumed the like-Western diet. These data agree with results from Greenwood and Winocur and propose a possible way underlying the effect diet, which is an inflammation process, and the decrease on neural factors crucial for learning processes. The results demonstrate that diet can interfere with learning abilities, but is it everything behind the diet effect on cognitive decline? There is a report with 344 white middle-aged male Fischer rats. The researchers evaluate the effect of a diet high in cholesterol and fat (diet containing 2% cholesterol and 10% hydrogenated coconut oil). The results showed a failure in working memory, here evaluated with the water radial arm maze as well as elevated lipids profile and reduce expression of Map-2 as an indicator of alteration of dendritic integrity, which correlates with memory mistakes measured in the test, and increase in inflammation markers such as microglia activation [52]. In a study carried out with Sprague-Dawley rats, which were fed for 7 days with high fat and fructose, several hippocampal alterations, such as decreased insulin signaling, were reported. In addition, they found that treated animals had a decrease in hippocampus total weight in addition with some other morphological alterations such as a diminishment on the number of dendritic spines and a reduction in the complexity of the hippocampal dendritic arborization. Moreover, there was a decrease in the expression of the microtubule-associated protein 2 (MAP-2) and in the content of synaptophysin in the CA1 region concomitant with an increased phosphorylation of tau protein, and in the presence of reactive astrocyte associated [53]. It directly demonstrates alterations in hippocampal cytoarchitecture that definitively have a strong impact on brain functionality, especially in hippocampal-related learning and memory processes.

Another feature which affected by consuming diets rich in fat is adult hippocampal neurogenesis (AHN). Adult neurogenesis is a highly specialized plasticity phenomenon that, under basal conditions, occurs in two restricted brain areas: a) the subventricular zone and b) the hippocampal dentate gyrus [54, 55]. Hippocampus is a crucial area for memory processes, since its decrease is associated to memory failures, especially in short-term memory, spatial memory, and learning flexibility [56–59]. The AHN is a complex process that comprises several devel-

opmental steps starting from the division of an endogenous neural precursor cell followed by its expansion, differentiation, and fully integration to the hippocampal network [60]. These steps are reported as number of proliferative cells measured by markers of cell division; cell fate decision with the marker of early differentiation, the cytoskeleton protein doublecortin (DCX) that is expressed in newly differentiated cells, and with NeuN, a nuclear marker of granular cells when the cell is fully differentiated. It has been recently documented that there are some food components which can regulate the neurogenic process (for a review [61]). The hippocampal neurogenesis has captured the attention since it was described in 1965 by Dass and Altman [62] due, as we already mentioned, the hippocampus is closely related to memory as well as neurodegenerative processes. Juvenile male and female Sprague-Dawley rats under a dietary regimen of high- (42% coconut butter and corn oil fat) or low-fat diet (10% fat by energy) or standard laboratory chow for 4 weeks, was found that males under high-fat diet show less cell proliferation than females and reported elevated levels of corticosterone, a stress hormone [63]. Differences in AHN were studied in mice susceptible to develop obesity (C57BL/6N) and obesity resistant (C3H/HeN). They were fed with high- and low-fat diet finding that those animals that developed obesity and consumed the high-fat diet had much lower number of proliferative cells and cells committed to neural lineage (DCX positive cells), which establish a clear link between obesity and AHN diminishment [64]. In our laboratory, we have observed that 8 weeks of diet rich in fat (60%) or high in cholesterol (1.4%) in 5-months-old male Wistar rats has an impact on AHN in both, cell proliferation and more especially in the morphology of DCX cells. These cell populations have less processes and a poor complexity than animals under normal laboratory diet, and we found alterations in short-term memory (Leal-Galicia and Meraz-Ríos data *not yet published*). All these data together strongly suggest a detrimental effect on diets rich in fat or cholesterol in cognitive components such as navigation memory, working memory, acquisition learning, and short-term memory suggesting as mediators, alterations in brain cytoarchitecture and AHN, and associates obesity with such cognitive alterations strongly supporting the hypothesis that obesity can lead to development of dementia (**Figure 4**).

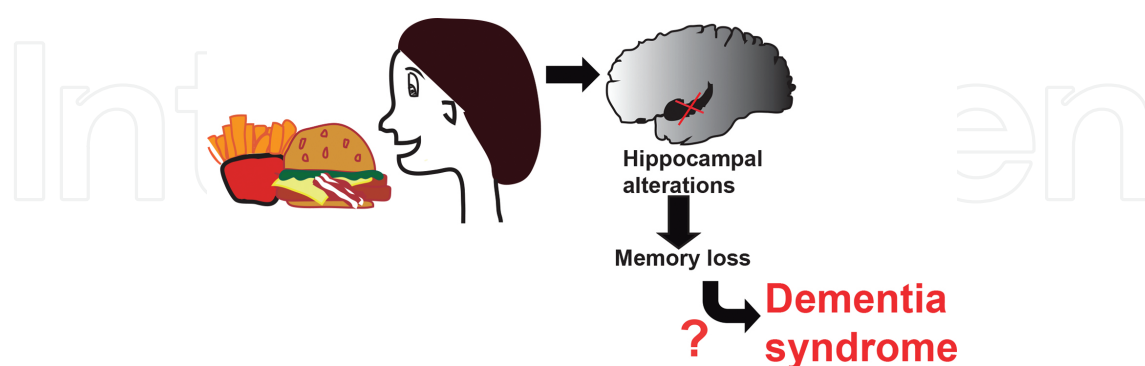


Figure 4. The intake of food with high amounts of fat or cholesterol produces alteration in the hippocampus such as: reduced expression of Map-2, reduction on the number of dendritic spines and in the complexity of the dendritic tree and a decrease on neurogenesis. Consume diets with these components has also a functional impact in short-term memory, working memory and learning flexibility, that could contribute to the detriment observed in the dementia syndrome.

6. Conclusion

The consumption of diets rich in cholesterol, fat, as well as another components (carbohydrates) of the so called “Western diet” can contribute to increase the production of the peptide A β . This could contribute to brain amyloidosis by means of alteration of the selective permeability of the BBB, since BBB alterations are induced for these type of diets. In addition, it has been shown in the brain of transgenic animals that the amyloidosis can be accelerated by the intake of fat or cholesterol, which can lead to accumulation of A β in the brain. Besides that, the intake of fat or cholesterol can induce alterations in brain morphology and plasticity accompanied by a detrimental in cognitive abilities in animal models that resemble those alterations in cognitive abilities reported in AD patients, such as short-term memory, working memory, and learning flexibility. These evidences strongly suggest an association with the dietary habits and the possible development of AD in both cases, Early Onset Alzheimer’s Disease or Late Onset Alzheimer’s Disease, and a connection with systemic disruptions and brain functions (**Figure 5**).

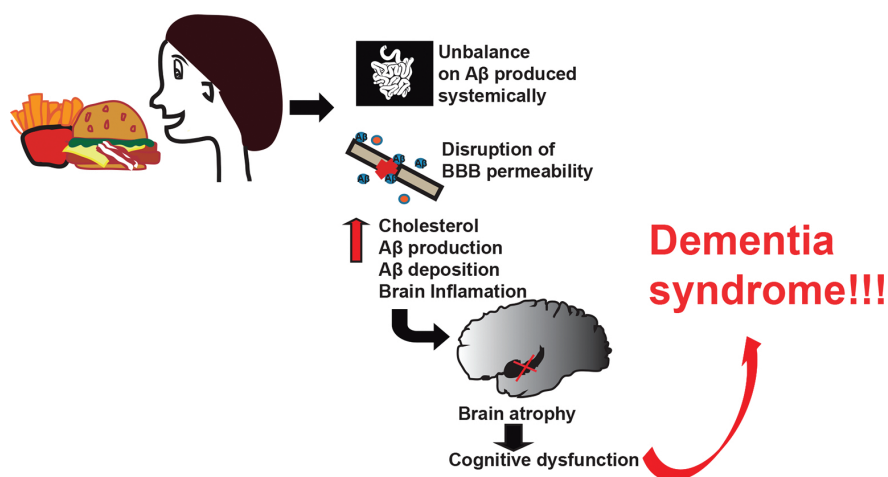


Figure 5. Diets rich on fat or cholesterol that are widely consume in Western countries can lead to develop dementia onset for several ways. One is the overproduction of systemic A β that can reach the brain due the chronic consume of these food components can affect the selective permeability of BBB. It can facilitate the pass of systemic A β as well as another molecules producing brain inflammation and A β deposits. It is accompanied for alterations in hippocampal plasticity and its cytoarchitecture. That can have an impact on brain functionality observed as memory failures. All these together can contribute to the development of dementia.

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References

- [1] Kanoski SE, Zhang Y, Zheng W, Davidson TL. The effects of a high-energy diet on hippocampal function and blood-brain barrier integrity in the rat. *J Alzheimers Dis.* 2010;21:207–219. DOI: 10.3233/JAD-2010-091414
- [2] Hsu TM, Kanoski SE. Blood-brain barrier disruption: mechanistic links between Western diet consumption and dementia. *Front Aging Neurosci.* 2014;9(6):88. DOI: 10.3389/fnagi.2014.00088
- [3] Goldgaber D, Schwarzman AI, Bhasin R, Gregori L, Schmechel D, Saunders AM, et al. Sequestration of amyloid beta-peptide. *Ann N Y Acad Sci.* 1993;695:139–143.
- [4] Wisniewski T, Ghiso J, Frangione B. Alzheimer's disease and soluble A beta. *Neurobiol Aging.* 1994;15:143–152.
- [5] Seubert P, Vigo-Pelfrey C, Esch F, Lee M, Dovey H, Davis D, et al. Isolation and quantification of soluble Alzheimer's beta-peptide from biological fluids. *Nature.* 1992;359:325–327.
- [6] Biere AL, Ostaszewski B, Stimson ER, Hyman BT, Maggio JE, Selkoe DJ. Amyloid beta-peptide is transported on lipoproteins and albumin in human plasma. *J Biol Chem.* 1996;271:32916–32922.
- [7] Koudinov A, Matsubara E, Frangione B, Ghiso J. The soluble form of Alzheimer's amyloid beta protein is complexed to high density lipoprotein and very high density lipoprotein in normal human plasma. *Biochem Biophys Res Commun.* 1994;205:1164–1171.
- [8] Koudinov AR, Berezov TT, Kumar A, Koudinova NV. Alzheimer's amyloid b interaction with normal human plasma high density lipoprotein: association with apolipoprotein and lipids. *Clin Chim Acta.* 1998;23:75–84.
- [9] James AP, Pal S, Gennat HC, Vine DF, Mamo JC. The incorporation and metabolism of amyloid-beta into chylomicron-like lipid emulsions. *J Alzheimer's Dis.* 2003;5:179–188.
- [10] Galloway S, Jian L, Johnsen R, Chew S, Mamo JC. Beta-amyloid or its precursor protein is found in epithelial cells of the small intestine and is stimulated by high-fat feeding. *J Nutr Biochem.* 2007;18:279–284.
- [11] Koudinov AR, Koudinova NV. Alzheimer's soluble amyloid beta protein is secreted by HepG2 cells as an apolipoprotein. *Cell Biol Int.* 1997;21:265–271.
- [12] Strittmatter WJ, Weisgraber KH, Huang DY, Dong LM, Salvesen GS, Pericak-Vance M, Schmechel D, Saunders AM, Goldgaber D, Roses AD. Binding of human apolipoprotein E to synthetic amyloid beta peptide: isoform-specific effects and implications for late-onset Alzheimer disease. *Proc Natl Acad Sci U S A.* 1993;90:8098–8102.

- [13] LaDu MJ, Lukens JR, Reardon CA, Getz GS. Association of human, rat, and rabbit apolipoprotein E with beta-amyloid. *J Neurosci Res.* 1997;49:9–18.
- [14] Ye S, Huang Y, Mullendorff K, Dong L, Giedt G, Meng EC, Cohen FE, Kuntz ID, Weisgraber KH, Mahley RW. Apolipoprotein (apo) E4 enhances amyloid beta peptide production in cultured neuronal cells: apoE structure as a potential therapeutic target. *Proc Natl Acad Sci U S A.* 2005;102:18700–18705.
- [15] Galloway S, Pallegage-Gamarallage MM, Takechi R, Jian L, Johnsen RD, Dhaliwal SS, Mamo JC. Synergistic effects of high fat feeding and apolipoprotein E deletion on enterocytic amyloid-beta abundance. *Lipids Health Dis.* 2008;22:15. DOI: 10.1186/1476-511X-7-15
- [16] Galloway S, Takechi R, Pallegage-Gamarallage MM, Dhaliwal SS, Mamo JC. Amyloid-beta co-localizes with apolipoprotein B in absorptive cells of the small intestine. *Lipids Health Dis.* 2009;22:8–46. DOI: 10.1186/1476-511X-8-46
- [17] Saunders NR, Habgood MD, Møllgård K, Dziegielewska KM. The biological significance of brain barrier mechanisms: help or hindrance in drug delivery to the central nervous system? *F1000Research* 2016, 5(F1000 Faculty Rev):313. DOI: 10.12688/f1000research.7378.1
- [18] Gustafson DR, Karlsson C, Skoog I, Rosengren L, Lissner L, Blennow K. Mid-life adiposity factors relate to blood-brain barrier integrity in late life. *J Intern Med.* 2007;262:643–650.
- [19] Heiss CJ, Sanborn CF, Nichols DL, Bonnick SL, Alford BB. Associations of body fat distribution, circulating sex hormones, and bone density in postmenopausal women. *J Clin Endocrinol Metab.* 1995;80:1591–1596.
- [20] Tchernof A, Després JP, Bélanger A, Dupont A, Prud'homme D, Moorjani S, Lupien PJ, Labrie F. Reduced testosterone and adrenal C19 steroid levels in obese men. *Metabolism.* 1995;44:513–519.
- [21] Kalish GM, Barrett-Connor E, Laughlin GA, Gulanski BI. Association of endogenous sex hormones and insulin resistance among postmenopausal women: results from the postmenopausal estrogen/progestin intervention trial. *J Clin Endocrinol Metab.* 2003;88:1646–1652.
- [22] Henderson VW, St John JA, Hodis HN, McCleary CA, Stanczyk FZ, Karim R, Shoupe D, Kono N, Dustin L, Allayee H, Mack WJ. Cognition, mood, and physiological concentrations of sex hormones in the early and late postmenopause. *Proc Natl Acad Sci U S A.* 2013;110:20290–20295. DOI: 10.1073/pnas.1312353110
- [23] Ding EL, Song Y, Malik VS, Liu S. Sex differences of endogenous sex hormones and risk of type 2 diabetes: a systematic review and meta-analysis. *JAMA.* 2006;295:1288–1299.
- [24] Lindstedt G, Lundberg PA, Lapidus L, Lundgren H, Bengtsson C, Bjorntorp P. Low sex-hormone-binding globulin concentration as independent risk factor for develop-

ment of NIDDM. 12-yr follow-up of population study of women in Gothenburg, Sweden. *Diabetes*. 1991;40:123–128.

- [25] Lapidus L, Lindstedt G, Lundberg PA, Bengtsson C, Gredmark T. Concentrations of sex-hormone binding globulin and corticosteroid binding globulin in serum in relation to cardiovascular risk factors and to 12-year incidence of cardiovascular disease and overall mortality in postmenopausal women. *Clin Chem*. 1986;32:146–152.
- [26] Sparks DL, Scheff SW, Hunsaker JC 3rd, Liu H, Landers T, Gross DR. Induction of Alzheimer-like β -amyloid immunoreactivity in the brains of rabbits with dietary cholesterol. *Exp Neurol*. 1994;126:88–94.
- [27] Sparks, DL. Dietary cholesterol induces Alzheimer-like β -amyloid immunoreactivity in rabbit brain. *Nutr Metab Cardiovasc*. 1997;7:255–266.
- [28] Sparks DL, Kuo YM, Roher A, Martin T, Lukas RJ. Alterations of Alzheimer's disease in the cholesterol-fed rabbit, including vascular inflammation. Preliminary observations. *Ann N Y Acad Sci*. 2000;903:335–344.
- [29] Blennow K, Wallin A, Fredman P, Karlsson I, Gottfries CG, Svennerholm L. Blood–brain barrier disturbance in patients with Alzheimer's disease is related to vascular factors. *Acta Neurol Scand*. 1990;81:323–326.
- [30] Skoog I, Wallin A, Fredman P, Hesse C, Aevansson O, Karlsson I, Gottfries CG, Blennow K. A population study on blood–brain barrier function in 85-year-olds: relation to Alzheimer's disease and vascular dementia. *Neurology*. 1998;50:966–971.
- [31] Mecocci P, Parnetti L, Reboldi GP, Santucci C, Gaiti A, Ferri C, Gernini I, Romagnoli M, Cadini D, Senin U. Blood-brain-barrier in a geriatric population: barrier function in degenerative and vascular dementias. *Acta Neurol Scand*. 1991;84:210–213.
- [32] Zlokovic BV, Ghiso J, Mackic JB, McComb JG, Weiss MH, Frangione B. Blood-brain barrier transport of amyloid beta peptides in efflux pump knock-out animals evaluated by in vivo optical imaging. *Biochem Biophys Res Commun*. 1993;30:1034–1040.
- [33] Sparks DL. Neuropathologic links between Alzheimer's disease and vascular disease. In: Iqbal K, Swaab DF, Winblad B, Wisniewski HM, editors. *Alzheimer's Disease and Related Disorders*. New York: John Wiley & Sons Ltd.; 1999, Vol 6, pp. 153–163.
- [34] Davidson TL, Monnot A, Neal AU, Martin AA, Horton JJ, Zheng W. The effects of a high-energy diet on hippocampal-dependent discrimination performance and blood–brain barrier integrity differ for diet-induced obese and diet-resistant rats. *Physiol Behav*. 2012;20:26–33. DOI: 10.1016/j.physbeh.2012.05.015
- [35] Arendt T. Alzheimer's disease as a loss of differentiation control in a subset of neurons that retain immature features in the adult brain. *Neurobiol Aging*. 2000;21:783–796.

- [36] Avila-Muñoz E, Arias C. Cholesterol-induced astrocyte activation is associated with increased amyloid precursor protein expression and processing. *GLIA* 2015;63:2010–2022. DOI: 10.1002/glia.22874.
- [37] Sidoryk-Wegrzynowicz M, Wegrzynowicz M, Lee E, Bowman AB, Aschner M. Role of astrocytes in brain function and disease. *Toxicol Pathol.* 2011;39:115–123.
- [38] Wharton SB, O'Callaghan JP, Savva GM, Nicoll JA, Matthews F, Simpson JE, Forster G, Shaw PJ, Brayne C, Ince PG; MRC Cognitive Function and Ageing Neuropathology Study Group. 2009. Population variation in glial fibrillary acidic protein levels in brain ageing: relationship to Alzheimer type pathology and dementia. *Dement Geriatr Cogn Disord.* 2009;27:465–473.
- [39] George AJ, Holsinger RM, McLean CA, Laughton KM, Beyreuther K, Evin G, Masters CL, Li QX. APP intracellular domain is increased and soluble AB is reduced with diet-induced hypercholesterolemia in a transgenic mouse model of Alzheimer disease. *Neurobiol Dis.* 2004;16:124–132.
- [40] Hsiao K, Chapman P, Nilsen S, Eckman C, Harigaya Y, Younkin S, Yang F, Cole G. Correlative memory deficits, Abeta elevation, and amyloid plaques in transgenic mice. *Science.* 1996;274:99–102.
- [41] Refolo LM, Malester B, LaFrancois J, Bryant-Thomas T, Wang R, Tint GS, Sambamurti K, Duff K, Pappolla MA. Hypercholesterolemia accelerates the Alzheimer's amyloid pathology in a transgenic mouse model. *Neurobiol Dis.* 2000;7:321–331. DOI: 10.1006/nbdi.2000.0304
- [42] McGowan E, Sanders S, Iwatsubo T, Takeuchi A, Saido T, Zehr C, Yu X, Uljon S, Wang R, Mann D, Dickson D, Duff K. Amyloid phenotype characterization of transgenic mice overexpressing both mutant amyloid precursor protein and mutant presenilin 1 transgenes. *Neurobiol Dis.* 1999;6:231–244.
- [43] White L, Petrovitch H, Ross GW, Masaki KH, Abbott RD, Teng EL, Rodriguez BL, Blanchette PL, Havlik RJ, Wergowske G, Chiu D, Foley DJ, Murdaugh C, Curb JD. Prevalence of dementia in older Japanese-American men in Hawaii. *JAMA.* 1996;276:955–960.
- [44] Hendrie HC, Osuntokun BO, Hall KS, Ogunniyi AO, Hui SL, Unverzagt FW, Gureje O, Rodenberg CA, Baiyewu O, Musick BS. Prevalence of Alzheimer's disease and dementia in two communities: Nigerian Africans and African Americans. *Am J Psychiatry.* 1995;152:1485–1492.
- [45] Vance JE, Karten B, Hayashi H. Lipid dynamics in neurons. *Biochem Soc Trans.* 2006;34:399–403.
- [46] Greenwood CE, Winocur G. Learning and memory impairment in rats fed a high saturated fat diet. *Behav Neural Biol.* 1990;53:74–87.

- [47] Greenwood CE, Winocur G. Cognitive impairment in rats fed high-fat diets: a specific effect of saturated fatty-acid intake. *Behav Neurosci.* 1996;110:451–459. DOI: 10.1037/0735-7044.110.3.451
- [48] Combs CK. Inflammation and microglia actions in Alzheimer's disease. *J Neuroimmune Pharmacol.* 2009;4:380–388.
- [49] Chandalia M, Abate N. Metabolic complications of obesity: inflated or inflamed? *J Diabetes Complicat.* 2007;21:128–138.
- [50] Rader DJ. Inflammatory markers of coronary risk. *N Engl J Med.* 2000;343:1179–1182.
- [51] Pistell PJ, Morrison CD, Gupta S, Knight AG, Keller JN, Ingram DK, Bruce-Keller AJ. Cognitive impairment following high fat diet consumption is associated with brain inflammation. *J Neuroimmunol.* 2010;219:25–32. DOI: 10.1016/j.jneuroim.2009.11.010
- [52] Granholm AC, Bimonte-Nelson HA, Moore AB, Nelson ME, Freeman LR, Sambamurti K. Effects of a saturated fat and high cholesterol diet on memory and hippocampal morphology in the middle-aged rat. *J Alzheimer's Dis.* 2008;14:133–145.
- [53] Calvo-Ochoa E, Hernández-Ortega K, Ferrera P, Morimoto S, Arias C. Short-term high-fat-and-fructose feeding produces insulin signaling alterations accompanied by neurite and synaptic reduction and astroglial activation in the rat hippocampus. *J Cereb Blood Flow Metab.* 2014;34:1001–1008. DOI: 10.1038/jcbfm
- [54] Alvarez-Buylla A, Seri B, Doetsch F. Identification of neural stem cells in the adult vertebrate brain. *Brain Res Bull.* 2002;57:751–758.
- [55] Kempermann G. Why new neurons? Possible functions for adult hippocampal neurogenesis. *J Neurosci.* 2002;22:635–638.
- [56] Kempermann G, Kuhn HG, Gage FH. More hippocampal neurons in adult mice living in an enriched environment. *Nature.* 1997;3:493–495.
- [57] Leal-Galicia P, Castañeda-Bueno M, Quiroz-Baez R, Arias C. Long-term exposure to environmental enrichment since youth prevents recognition memory decline and increases synaptic plasticity markers in aging. *Neurobiol Learn Mem.* 2008;90:511–518. DOI: 10.1016/j.nlm.2008.07.005
- [58] Garthe A, Huang Z, Kaczmarek L, Filipkowski RK, Kempermann G. Not all water mazes are created equal: cyclin D2 knockout mice with constitutively suppressed adult hippocampal neurogenesis do show specific spatial learning deficits. *Genes Brain Behav.* 2014;13:357–364. DOI: 10.1111/gbb.12130
- [59] Garthe A, Roeder I, Kempermann G. Mice in an enriched environment learn more flexibly because of adult hippocampal neurogenesis. *Hippocampus.* 2016;26:261–271. DOI: 10.1002/hipo.22520

- [60] Kempermann G, Jessberger S, Steiner B, Kronenberg G. Milestones of neuronal development in the adult hippocampus. *Trends Neurosci.* 2004;27:447–452.
- [61] Zainuddin MS, Thuret S. Nutrition, adult hippocampal neurogenesis and mental health. *Br Med Bull.* 2012;103:89–114. DOI: 10.1093/bmb/lds021
- [62] Altman J, Das GD. Autoradiographic and histological evidence of postnatal hippocampal neurogenesis in rats. *J Comp Neurol.* 1965;124:319–335.
- [63] Lindqvist A, Mohapel P, Bouter B, Frielingsdorf H, Pizzo D, Brundin P, Erlanson-Albertsson C. High-fat diet impairs hippocampal neurogenesis in male rats. *Eur J Neurol.* 2006;13:1385–1388.
- [64] Hwang IK, Kim IY, Kim DW, Yoo KY, Kim YN, Yi SS, Won MH, Lee IS, Yoon YS, Seong JK. Strain-specific differences in cell proliferation and differentiation in the dentate gyrus of C57BL/6N and C3H/HeN mice fed a high fat diet. *Brain Res.* 2008;19:1–6. DOI: 10.1016/j.brainres