



UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA

*Università degli Studi di Padova*

*Padua Research Archive - Institutional Repository*

Neuroepigenetics and Alzheimer's Disease: An Update

*Original Citation:*

*Availability:*

This version is available at: 11577/3272301 since: 2018-07-19T09:35:22Z

*Publisher:*

*Published version:*

DOI: 10.3233/JAD-180259

*Terms of use:*

Open Access

This article is made available under terms and conditions applicable to Open Access Guidelines, as described at <http://www.unipd.it/download/file/fid/55401> (Italian only)

(Article begins on next page)

**(TITLE PAGE)**

**Neuroepigenetics and Alzheimer Disease: An Update**

Authors / address

**Morena Zusso, Massimo Barbierato, Laura Facci, Stephen D. Skaper, Pietro Giusti**

Corresponding author address

**Prof. Pietro Giusti, MD, PhD**

**Dept of Pharmaceutical and Pharmacological Sciences**

**University of Padua**

**Largo Meneghetti, 2**

**35131 Padua (Italy)**

**pietro.giusti@unipd.it**

Running title: **Epigenetic and Alzheimer**

## **Abstract**

Epigenetics is the study of changes in gene expression which may be triggered by both genetic and environmental factors, and independent from changes to the underlying DNA sequence — a change in phenotype without a change in genotype — which in turn affects how cells read genes.

Epigenetic changes represent a regular and natural occurrence but can be influenced also by factors such as age, environment, and disease state. Epigenetic modifications can manifest themselves not only as the manner in which cells terminally differentiate, but can have also deleterious effects, resulting in diseases such as cancer. At least three systems including DNA methylation, histone modification and non-coding RNA (ncRNA)-associated gene silencing are thought to initiate and sustain epigenetic change. For example, in Alzheimer disease (AD), both genetic and non-genetic factors contribute to disease etiopathology. While over 250 gene mutations have been related to familial AD, less than 5% of AD cases are explained by known disease genes. More than likely non-genetic factors, probably triggered by environmental factors, are causative factors of late-onset AD. AD is associated with dysregulation of DNA methylation, histone modifications, and ncRNAs. Among the classes of ncRNA, microRNAs (miRNAs) have a well-established regulatory relevance. MicroRNAs are highly expressed in CNS neurons, where they play a major role in neuron differentiation, synaptogenesis, and plasticity. MicroRNAs impact higher cognitive functions, as their functional impairment is involved in the etiology of neurological diseases, including AD. Alterations in the miRNA network contribute to AD disease processes, e.g. in the regulation of amyloid peptides, tau, lipid metabolism, and neuroinflammation. MicroRNAs, both as biomarkers for AD and therapeutic targets, are in the early stages of exploration. In addition, emerging data suggest that altered transcription of long ncRNAs, endogenous, ncRNAs longer than 200 nucleotides, may be involved in an elevated risk for AD.

**Keywords:** Epigenetics, Alzheimer disease, DNA methylation, histone, phosphorylation, ubiquitylation, SUMOylation, amyloid, tau, neuroinflammation

What drives the development of an organism from embryo to adult? Although at one time debated between genetic determinism and a primary influence by interactions with the surrounding environment [1], the concept of nature and nurture as being mutually exclusive [2] has evolved into a more complex and less dichotomous vision, with most biologists believing that interactions between genes and the environment steer an organism's development. However, we have only recently begun to identify the mechanisms behind these interactions which form the basis of epigenetics [3].

Epigenetics involves changes in gene function triggered by both genetic and environmental factors, not caused by mutations in DNA sequence [4]. Such changes may relate to chromosomal ones that affect gene activity and expression, as well as heritable phenotypic changes that do not derive from genome modification. These effects on cellular and physiological phenotypic traits could be driven by external or environmental factors or be part of a normal developmental program.

Numerous central nervous system (CNS) physiological functions (neural stem cell fate determination, neural plasticity, and learning and memory, see [5]) have significant epigenetic components. This is the case also for neurodegenerative diseases. For example, in Alzheimer disease (AD), both genetic and non-genetic factors contribute to disease etiopathology. While over 250 gene mutations have been related to familial AD, especially those for amyloid precursor protein (APP), presenilin 1 (PSEN1) and presenilin 2 (PSEN2), even though less than 5% of all AD cases are explained by known disease genes [6]. It is thus likely that non-genetic factors, more than likely triggered by environmental cues, are causative factors of late-onset AD. Many CNS pathologies, including AD are associated with dysregulation of DNA methylation, histone modifications, and non-coding RNAs (ncRNAs) [7]. These changes may have a significant role in AD and other neurodegenerative disorders through a variety of pathways.

## **DNA METHYLATION**

Methylation of DNA cytosine residues at the 5<sup>o</sup> position (5mC) is the principal and most widely characterized epigenetic modification [8]. DNA methylation is the product of a family of DNA methyltransferases (DNMTs) that add methyl groups to gene promoters to repress gene expression and block the binding of transcriptional enzymes [9]. DNMTs, in particular the subtype m5C methyltransferases (C5 Mtase), methylate the C5 carbon of cytosine in DNA to yield C5-methylcytosine [10] (see Fig.1). C5 Mtase is particularly efficient in adding methyl groups to CpG sites, or cytosine residues in DNA directly followed by a guanidine residue on the 3' prime side of the same DNA strand. Regions with high numbers of CpG sites, spanning at least 200 bp with higher than 60% observed-to-expected CpG ratio, are designated CpG islands and mainly occur in the gene promoter upstream of the transcription start site. Methylation of CpG islands in a gene promoter stably inhibits transcription of that gene [11].

Ten-eleven translocation methylcytosine dioxygenase 1 (Tet1) initiates DNA demethylation by converting 5-mC to 5-hydroxymethylcytosine (5-hmC), 5-formylcytosine, and 5-carboxylcytosine at CpG-rich regions of genes [12]. Tet1 expression is high during early development and localizes to the nuclei of CNS neurons in adulthood. Studies with Tet1-knockout mice indicate its involvement in hippocampal neuronal functions, such as adult neurogenesis and memory formation and extinction [13-15]. While richly expressed in cortical and hippocampal neuron nuclei, there appears to be comparatively less Tet1 expression in glia and oligodendrocytes [13,15]. Some authors have speculated Tet1 as an essential element for adult hippocampal neural progenitor cell proliferation, with this key regulator also influencing a number of neuronal activity-related genes [13-15].

Mammalian cells, when young, display DNA hypermethylation throughout their genome. CpG islands within the promoters of expressed genes, however, are an exception. DNA repeats extensively methylated include long interspersed nuclear elements, short Interspersed Nuclear Elements, and long terminal repeat transposable elements. In this way they remain in a constitutive heterochromatin state. Aging is accompanied by a generalized genome DNA hypomethylation,

which leads to activation of normally silenced DNA sequences. It bears mentioning that DNA methylation levels of some CpGs are age-related allowing the estimation of DNA methylation age based on the cumulative assessment of CpGs [16]. DNA methylation may also increase in a non-stochastic manner over the CpG islands of certain genes, correlating with their heterochromatinization and silencing. In spite of conflicting results [17], the majority of global methylation studies employing antibody-specific immunohistochemistry on postmortem AD brain tissue show a reduction in DNA methylation in temporal neocortex [18], entorhinal cortex [19], and hippocampus [20]. A reduction in global DNA methylation could have a role in activation of microglia and astrocytes and output of pro-inflammatory cytokines during aging [21], with the potential for creating a vicious feedback cycle.

Epigenetic processes play a role in deregulation of gene expression that occurs in AD. Initially focusing on APP gene methylation, findings from these studies proved relatively conflicting and inconsistent, possibly due to different techniques, limited sample numbers, and the use of heterogeneous tissue. Other APP-related genes (apolipoprotein E, nicastrin and beta-site APP Cleaving Enzyme 1) were found to be unchanged in AD brain samples. However, Di Jager et al [22] functionally validated CpG associations significantly associated with the burden of AD pathology and identified the nearby genes whose RNA expression was altered in AD: ANK1, CDH23, DIP2A, RHBDF2, RPL13, SERPINF1 and SERPINF2. These authors suggest that such DNA methylation changes may have a role in the onset of AD, given that they were seen in pre-symptomatic subjects and that six of the validated genes connect to a known AD susceptibility gene network.

Alterations in DNA methylation are found in a number of genes not directly related to amyloid and tau. The methylation process occurs also in normal aging, with hyper- or hypo-methylation appearing to be faster in AD. Because methylation takes place mainly in CpG islands, and about 70% of promoters in man contain at least one CpG island [23]; the presence of multiple methylated

CpG sites in the promoters of these islands causes stable silencing of genes [24,25]. On the other hand, a decrease in methylation at CpG sites leads to gene activation [26] (**Table 1**).

## **HISTONE MODIFICATIONS**

Histones are nuclear proteins enwrapped by DNA to form a nucleosome. The five major families of histones are: H1/H5, H2A, H2B, H3, and H4. Histones H2A, H2B, H3 and H4 are considered core histones, with H1/H5 as linker histones. Histone protein tails have residues capable of being acetylated, methylated, phosphorylated, ubiquitylated, and sumoylated. Post-translational histone modifications, such as methylation and acetylation of lysine residues on histone tails affect gene expression, mainly by altering chromatin structure: euchromatin, a lightly packed form of chromatin enriched in genes allows gene transcription, whereas heterochromatin, a tightly packed form of chromatin, blocks it. Furthermore, there are enzymes that add modifications, such as histone methyltransferases, and others that remove these modifications, including histone demethylases. A complex interplay between activating and repressing histone modifications is a major regulatory pathway for gene expression. It should be noted that lysine methyltransferases have a broad spectrum of non-histone protein substrates [27].

### ***Methylation***

Methylation of histone tails results in either increased or reduced gene expression, depending on the amino acid methylated. For instance, H3K4 tri-methylation [28] is associated with increased transcription, whereas H3K9me3 results in transcription repression [29].

### ***Acetylation***

Unlike methylation of histone tails that either induces or represses gene transcription, acetylation of histone tails is solely associated with active gene expression. Histone acetylation is currently the most researched epigenetic mechanism in CNS dysfunction and neurodegenerative

diseases as it relates to astrocyte function. Conditioned medium from lipopolysaccharide (LPS)-stimulated microglia decreased total H3 and H4 acetylation in cultured astrocytes and increased astrocyte cell death from H<sub>2</sub>O<sub>2</sub> treatment, while decreasing expression of the anti-oxidant factor nuclear factor erythroid 2–related factor 2 [30]. Valproic acid, a histone deacetylase (HDAC) inhibitor, reportedly attenuates the detrimental effects of conditioned medium from LPS-treated microglia [31].

### ***Deacetylation***

Histone tail deacetylation antagonizes gene expression at loci throughout the genome [32]. Good evidence points to histone acetyltransferase and HDACs involvement in various cognitive processes, proposing that dynamic regulation of histone acetylation status is associated with synaptic plasticity and memory [33, 34]. Among histone-modifying enzymes, HDAC2 is a critical negative regulator of structural and functional plasticity in the mammalian nervous system [35]. HDAC2 localizes to the promoters of numerous synaptic-plasticity-associated genes, where it deacetylates histone substrates [36]. Loss of HDAC2 or treatment with HDAC inhibitors promotes synaptic gene expression, long-term synaptic plasticity, memory processes, and decreases disease progression both in AD subjects and in a transgenic mouse AD model [37], while HDAC2 over-expression has the opposite effects [36-39].

Modified HDAC function can contribute to numerous pathological states, including cancer, cardiovascular disease, and neurological diseases [40]. HDAC2 levels are elevated in AD brain and in mouse AD models [41]. HDAC2 up-regulation in the latter results from both transcriptional and post-transcriptional mechanisms and contributes to cognitive impairment; HDAC inhibitors and *HDAC2* knockdown result in striking recovery of impaired cognitive functions [36]. As such, HDAC2 is a promising target for treating the cognitive symptoms of AD and other neurological disorders.



Sp3 is a gene that encodes transcription factors which bind to consensus GC- and GT-box regulatory elements in target genes. Functional screening of potential co-regulators revealed that knockdown of *Sp3* was similar to *HDAC2* knockdown in terms of facilitating synaptic transmission. Consistent with a role in recruitment of HDAC2 to target genes, knockdown of *Sp3* reduced HDAC2 occupancy and increased histone acetylation of synaptic gene promoters, and facilitated synaptic gene expression. As with HDAC2, Sp3 expression was elevated in brain of a mouse AD model and in AD patients. Expression of an HDAC2 fragment containing the Sp3-binding domain counteracted the synaptic plasticity and memory defects found in a mouse AD model. Together, these findings indicate that HDAC2 and Sp3 cooperate to regulate neuronal plasticity genes and provide proof-of-principle that disruption of the HDAC2-Sp3 interaction is an effective strategy to disrupt the synaptic plasticity-suppressing functions of this complex [42].

### ***Phosphorylation, ubiquitylation and SUMOylation***

Histone phosphorylation is usually associated with DNA damage, with increased phosphorylation of histone H2AX around the sites of DNA damage in hippocampal and cortical astrocytes in AD patients [43]. Increased phosphorylation of H3 histone is found in frontal cortex of AD and bipolar disorder patient brains [44]. Furthermore, Ogawa et al. [45] described, in AD hippocampal neurons, co-localization between tangles and hyperphosphorylation of H3 Ser10. Unlike the case for actively dividing cells, phosphorylated histone H3 was restricted to the neuronal cell cytoplasm (and not nucleus) despite activation of the mitotic machinery. Therefore, the aberrant cytoplasmic localization of phosphorylated histone H3 may be a sign of mitotic disbalance that leads to neuronal cell dysfunction and neurodegeneration in AD. Histone phosphorylation appears to be part of a complex interplay between other epigenetic markers, such as histone acetylation and methylation, and DNA methylation. Indeed, histone phosphorylation has been demonstrated to increase pro-inflammatory gene activation [46,47].

Histone ubiquitylation is another consequence of DNA damage. H2A ubiquitylation usually leads to gene silencing, whereas H2B ubiquitylation has been linked to gene activation. Histone ubiquitylation is important for regulating stem cell maintenance and differentiation, including neural stem cells [48]. Little is known, however, role for histone ubiquitylation in neurodegenerative diseases.

Small Ubiquitin-like Modifier (SUMO) proteins are a family of small proteins capable of modifying the function of other proteins through covalent interactions. SUMOylation is a post-translational modification that participates in nuclear-cytosolic transport, transcriptional regulation, apoptosis, protein stability, stress response, and cell cycle progression [49]. SUMOylation involves an enzymatic cascade analogous to that in ubiquitination. Unlike the case for ubiquitin, SUMOylation does not tag proteins for degradation. Rather, it can repress gene transcription through the opposing actions of histone acetylation and ubiquitylation, and reduction of histone SUMOylation leads to higher levels of acetylation [50]. Although post-translational protein SUMOylation has been suggested to contribute to pathogenesis of several neurodegenerative diseases, such as AD, data are limited in these cases. A major finding concerning SUMOylation in neurodegeneration was reported by Tao et al. [51], who demonstrated that SUMOylation of HDAC1 was an endogenous protective mechanism against amyloid- $\beta$  ( $A\beta$ ) toxicity in a mouse AD model. These authors also reported that acute  $A\beta$  treatment in rats induced expression of a protein inhibitor of signal transducer and activator of transcription 1 (PIAS1), which is a SUMO E3 ligase [51].

A number of proteins involved in AD pathology (APP, tau,  $\beta$ -site amyloid precursor protein cleaving enzyme 1 (BACE1), glycogen synthase kinase-3 $\beta$  and c-Jun N-terminal kinase) are SUMO targets [52]. Furthermore, AD patients have altered levels of SUMOylation and SUMO-related protein expression. For example, SUMO3 labeling was increased in post-mortem AD hippocampus [53]. In confirmation of these results, genomic analysis of Korean patients affected by late-onset

AD showed mutations of the Ubc9 gene (UBE2I), suggesting a link with increased risk of developing AD for this population [54].

SUMO ligases, including SUMO-1 and PIAS1, are expressed in rat CNS, and decrease with age or exposure to LPS [55]. These authors also reported that SUMOylation of the transcription factor CCAAT/enhancer-binding protein regulates expression of the gene for inducible nitric oxide synthase; decreased SUMOylation led to increased inducible nitric oxide synthase expression in cultured astrocytes. Hoppe et al. [56] found that A $\beta$ <sub>1-42</sub>-treated mouse astrocytes contained reduced levels of SUMO-1-conjugated proteins, with over-expression of constitutively active SUMO-1 halting some of the morphological effects of A $\beta$ <sub>1-42</sub>. Similarly, SUMOylation of liver X receptors in cultured astrocytes, by the SUMO ligases PIAS1 and HDAC4, reduced interferon gamma-induced activation of signal transducer and activator of transcription 1 and subsequent inflammatory responses [57]. These results indicate that SUMOylation is involved in gene expression and that SUMOylation can reduce inflammation, which points to a potential role for SUMOylation in neurodegeneration [58, 59].

## **NON-CODING RNAs**

Non-coding DNA sequences are DNA components that do not encode protein sequences. Some non-coding DNA is transcribed into functional ncRNA species (transfer RNA, ribosomal RNA, and regulatory RNAs). Non-coding DNA also regulates the transcription and translation of protein-coding sequences, scaffold attachment regions, centromeres, and telomeres. The advent of RNA sequencing has led to the discovery of new classes of RNA [60]. While known ncRNAs number in the thousands, their roles in the regulation of gene expression and genomic organization remain in their infancy. Among the classes of ncRNA, microRNAs (miRNAs) and long non-coding RNAs (lncRNAs) have received the most attention. The former have with a well-established regulatory role [61, 62], while the latter appear to be involved in the development of a number of human

diseases [63-65]. The present discussion will be restricted to the role of miRNAs and lncRNAs in AD.

### ***miRNA***

MicroRNAs are small (20-24 nucleotide) ncRNAs that, although coding for proteins, are able to alter gene expression [66]. MicroRNAs prevent translation by binding to the 3' untranslated end of mRNA, resulting in mRNA degradation [67]. MicroRNAs thus represent another form of epigenetic regulation by altering translation. MicroRNAs, which are highly expressed in CNS neurons, play a major role in neuron differentiation, synaptogenesis, and plasticity. MicroRNAs profoundly impact higher cognitive functions, as evidenced by their functional impairment being involved in the etiology of neurological diseases, including AD [68]. A growing body of evidence points to alterations in the miRNA network as active contributors to AD disease processes [69; for a recent review see 70].

#### ***miRNA Regulation of A $\beta$***

AD pathology is associated with a number of altered features of APP: increased expression, polymorphisms in its promoter, abnormal processing, and altered A $\beta$  clearance [71]. MicroRNAs regulate expression of APP and other enzymes involved in A $\beta$  processing, in particular BACE1.

- *APP*: miR-20a, miR-19, and miR-106a/b (all miR-20a family members) [72] and miR-101, among others, directly regulate APP mRNA in cultured human cells [73]. miRNAs are also involved in regulating alternative splicing of APP. In AD patients, APP in neurons undergoes alternative splicing at exons 7, 8, and 15, with increased expression levels in exons 7 and/or 8 isoforms of APP [74]. In addition, abnormal splicing of APP in neurons was associated with heightened A $\beta$  production [75]. On the other hand, miR-124 was downregulated in AD brains [76].

- *BACE1*: Increased BACE1 expression and activity have been reported in sporadic AD brain [77]. The miR-29 family (*homo sapiens* (hsa)-miR-29a, hsa-miR-29b, and hsa-miR-29c) has received much attention in the context of BACE1, with several reports linking this family to

BACE1 regulation in vivo and in cultured cells. MicroR-29 family members show marked reductions in AD brain, and specifically so in relation to AD dementia. These reductions are associated with exceptionally high BACE1 protein, and loss of miR-29a/b-1 cluster suppressing activity in cultured human cells results in increased A $\beta$  production [78]. miR-339-5p, miR-195 [79], and miR-107 [80], among other miRNAs, are deregulated in AD brain and can directly target BACE1 in vitro.

### ***miRNA regulation of tau***

The microtubule-associated protein tau stabilizes microtubule structure and facilitates axonal transport. In AD, tau undergoes translocation to the somato-dendritic compartment, where it undergoes hyper-phosphorylation and misfolding to generate neurotoxic intracellular aggregates (neurofibrillary tangles) [81]. Tau pathology may be a consequence of an alteration in one or more processes regulating its metabolism, e.g. expression, localization, transcriptional/posttranslational modification, and clearance. Hyper-phosphorylation may follow from up-regulation and/or abnormal expression of tau kinases, down-regulation of phosphatases, mutation, and covalent modification of tau [82,83]. The following two sections discuss miRNA involvement in regulating tau metabolism in pathological conditions.

- *Tau mRNA expression and metabolism:* The miR-132/miR-212 cluster has been tied to the regulation of tau expression. Decreased levels of miR-132 levels are reported in advanced stage AD brain [57,84,85]. Other miRNAs involved in tau expression and metabolism include: miR-219, that represses tau synthesis post-transcriptionally and is down-regulated in autopsy brain tissue taken at autopsy from AD patients and subjects with severe primary age-related tauopathy [86]; miR-128a, that modulates BAG2 expression, a co-chaperone suggested to be involved in tau aggregation and degradation [87].

- *Tau phosphorylation:* Neurofibrillary tangles in AD brain are composed mainly of hyperphosphorylated microtubule-associated proteins, whose abnormal phosphorylation may

represent a key process leading to their aggregation [88]. The state of tau phosphorylation represents a fine balance between kinases and phosphatases, processes that may be regulated by miRNAs. Interestingly, hyperphosphorylation of tau at pathological sites was accompanied by increased phosphorylation of mitogen-activated protein kinase 3/extracellular signal-regulated kinase 1. In mouse neurons: extracellular signal-regulated 1 is down-regulated by members of the miR-15 family (including miR-15a), while this miRNA is reduced in AD brain [89]. Glycogen synthase kinase-3 $\beta$ , also known as tau protein kinase, occupies a key position in A $\beta$  production and neurofibrillary tangle formation and is regulated, at least in smooth muscle cells, by miR-26a [90,91]. Together with miR-26b, miR-26a appears critical for brain-derived neurotrophic factor expression [92]. Postmortem AD brain reportedly contains markedly raised miR-26b levels in the temporal gyrus of [93]. miR-922 is another miRNA that increases tau phosphorylation. In human cell lines, Cogswell et al. [94] showed that miR-922 heightening tau phosphorylation by down-regulating UCHL1, a deubiquitinating enzyme that is decreased in AD brain. Furthermore, UCHL1 levels were inversely proportional to tangle number [95]. Intriguingly, converging evidence suggests that psychotic AD (AD + P) [96] is associated with an acceleration of frontal degeneration, with tau pathology playing a primary role [97]. Within this context, a new study by Kwon et al. [98] shows that Tet1 over-expression leads to anxiety-like behavior and enhanced fear memories via the activation of calcium-dependent cascade through Egr1 expression in mice.

### ***miRNA regulation of lipid metabolism***

The apolipoprotein E gene  $\epsilon$ 4 allele is probably the strongest genetic risk factor known to-date for AD [99]. It is associated with modification in the metabolism of a number of lipids linked to AD [100]. Cholesterol metabolism is likely to be the main player, with dysregulation of genes involved in its biosynthesis/efflux being associated with AD evolution [101]. miR-33, by regulating lipid metabolism via inhibition of ABCA1, can influence AD. ABCA1 plays a direct role in AD by decreasing levels of A $\beta$  [102]. miR-33 directly regulates ABCA1 in human neuronal cell lines and

in mouse primary neurons and astroglia [103]. This has practical implications for AD: Kim et al. [104] demonstrated that miR-33, by down-regulating ABCA1, affects A $\beta$  levels. However, deregulation of miR-33 in AD brain remains to be proved. ABCA1 and cholesterol metabolism are regulated also by miR-758. It has been proposed that this miRNA is implicated in the regulation of AD development [105]. A number of other miRNAs (miR-137, miR-181c, miR-9, and miR29a/b) have been linked to impaired lipid metabolism in AD. For a recent review see Goedeke and Fernández-Hernando [99].

### ***miRNA regulation of neuroinflammation***

In AD, as with other neurodegenerative diseases, binding of misfolded/aggregated proteins to glial cell receptors triggers innate immune responses that contribute to disease progression. Genes that regulate glia clearance of misfolded proteins and provoke inflammatory reactions appear to increase one's risk for AD [106]. Nuclear factor-kappaB (NF- $\kappa$ B), an immune and stress-induced transcription factor, regulates transcription of several miRNAs linked to neuroinflammation. Under physiological conditions, NF- $\kappa$ B activity induced by inflammation is blocked by acetylcholine [107]. At the same time, production of acetylcholine is markedly compromised in AD [108]. Consequently, miR-34a, a miRNA controlled by NF- $\kappa$ B, is up-regulated in hippocampal CA1 region of AD brain [109]. These same authors showed that miR-34a regulates, in mouse microglia, triggering receptor expressed on myeloid cells-2, a critical factor for A $\beta$ <sub>1-42</sub> clearance that is down-regulated in AD brain CA1 region [110,111]. This link is strongly supported by the observation that rare heterozygous variants of triggering receptor expressed on myeloid cells-2 are associated with a significant increase in AD risk [112], miR-146a [113], miR-155 [114], and miR-181 family [115], also involved with the innate immune system, are known to be relevant to AD.

### **Long non-coding RNAs (lnc-RNAs)**

LncRNAs are endogenous, non-coding RNAs longer than 200 nucleotides [116]. Transcriptome assembly after next-generation RNA sequencing has revealed more than 50,000 lncRNAs in various human tissues. LncRNAs are transcribed from introns, exons of protein-coding genes, and from intergenic regions [117,118]. LncRNAs are transcribed as precursor transcripts, after which they are subject to splicing, maturation, exportation, and decay in analogy to mRNAs but, and unlike the latter, lncRNA genes are poorly conserved [119]. LncRNA binding to nucleic acid or protein regulates gene expression, cell metabolism, division, differentiation, survival, senescence, neurodegeneration, and aging [120-125]. LncRNAs present different structures, including mRNA-like forms and circular RNAs [117]. LncRNAs may comprise just 100 kilobase pairs [126], and possess fewer long exons, although these are shorter than mRNAs [119,127].

Altered lncRNA transcription may be involved in increasing the risk of AD. There is evidence for several specific lncRNAs being dysregulated in AD, including APP, and BACE1 [128]. Such altered expression is detectable not only in AD brain, but also in the plasma and CSF of these patients [128-131]. In particular, BACE1-AS lncRNA is an antisense RNA transcribed by RNA polymerase II from the complementary strand of BACE1 in the locus 11q 23.3 [132]; it is directly implicated in the increased abundance of A $\beta$ <sub>1-42</sub> in AD. BACE1-AS stabilizes BACE1 mRNA by forming an RNA duplex to mask the binding site [132], thereby preventing BACE1 degradation by MiR-485-5p [133]. Higher BACE1-AS levels can increase BACE1 protein and elevated levels of BACE1 inactivate the cAMP-protein kinase A-cyclic AMP response element binding protein pathway, leading to deficits in learning and memory, and to excessive production of A $\beta$ <sub>1-42</sub> and amyloid plaques [74].

A number of other lncRNAs have been identified in brain that are related to AD. 51A is an antisense RNA transcribed from intron 1 of the Sorl1 gene. Sorl1 is reduced in AD brain [134], and a loss of Sorl1 function disrupts APP cleavage and promotes an increase of neurotoxic A $\beta$  peptides [135]. Increased expression of 51A lncRNA leads to a strong decrease of the Sorl1 splice variant A mRNA and, resulting in increased amounts of A $\beta$ <sub>1-40</sub> and A $\beta$ <sub>1-42</sub>. BC200 is a small untranslated



RNA, transcribed by RNA polymerase III in the neuronal cell body where it is transported to dendrites as ribonucleoprotein particles. BC200 has been implicated in protein synthesis. Through its binding to the poly(A)-binding protein 1, BC200 takes part in regulating transcription initiation. Higher levels of BC200 in brain are associated with the severity of AD [136,137]. GDNFOS is a cis-antisense transcript from the glial cell line-derived neurotrophic factor (GDNF) gene containing four exons that can give rise to three splice variants (GDNFOS1, GDNFOS2, and GDNFOS3). The first two splice variants are non-coding RNAs, but GDNFOS3 possesses a potential open reading frame. While conceivable that GDNFOS3 may influence GDNF concentration in the brain, more evidence will be needed to confirm an interaction between GDNFOS and GDNF mRNA [136]. LncRNA 17A is an antisense lncRNA complementary to an intronic region of the GABBR2 gene, expressed in neuroblastoma, and leads to an increase in A $\beta$  secretion. Other lncRNAs implicated in AD are NAT-Rad18, Uchl1 RNA (an antisense lncRNA complementary to mouse ubiquitin carboxy-terminal hydrolase L1) [138], CDKN2B-AS (ANRIL, antisense non-coding RNA in the INK1 locus) [139], HARIF and HARIR located in the highly accelerated region 1 (HAR1) [140, 141], Sox2ot (a RNA that overlaps SOX2 gene), and Snhg3 (a lncRNA associated to ribosomal processing) [142]. In addition, reassessment of microarray data using a novel algorithm revealed about 100 brain-specific intergenic lncRNAs that showed changes greater than two-fold in AD [131,143].

## CONCLUSIONS

A rapidly growing body of data associates epigenetic alterations to the development of neuropathological and neurodevelopmental disorders [144]. Conceivably, disruption of gene expression due to epigenetic changes throughout the human lifespan could, over the long term, act as a 'seed' for development of disorders [145]. Collectively, the studies described here point to a role for epigenetic mechanisms in the complex etiology of AD. As such, understanding epigenetic

dysregulation in AD could contribute to our view of the origin and progression of AD and, possibly, the development of efficacious therapeutics. However, one caveat with epigenetic studies is the issue of causality. In other words, alterations in DNA modifications could be either causal to the disease process, or could themselves arise as a consequence of disease-associated pathological changes. One way to overcome such doubts would be to determine if a given epigenetic variation was present before the appearance of disease symptoms, preferably via longitudinal studies following the same cohort of individuals over a number of years (an approach that, in itself, is not only very costly but also requires a protracted time frame).

Could there be a disconnect between epigenetic variation which arises before disease onset and actual disease causation? For instance, while aging is accompanied by a generalized genome DNA hypomethylation, not all old people with DNA hypomethylation develop AD. Clearly, the question of cause and effect of aging and pathology awaits a conclusive answer. Given the potential reversibility of epigenetic changes, identifying disease-causative mechanisms may one day provide viable therapeutic targets.

Given the failure of AD clinical trials to date, focus is now shifting to diagnose AD at as early a stage as possible, even before onset of cognitive decline. Despite the inherent difficulties, timely disease detection offers a multitude of benefits, not the least of which are opportunities for early intervention, better management of symptoms, and cost savings [146]. miRNAs have emerged as potential candidates for reliable biomarkers of early-stage AD, being present in biofluids and displaying high stability in terms of storage/handling [147] Table 2 summarizes such studies in which receiver operating characteristic (ROC) curve analysis was applied to optimize biomarker validity. Recent attempts at using miRNAs in serum, plasma, and cerebrospinal fluid (CSF) as AD biomarkers have identified a number of differentially expressed miRNAs [cf. 148], although lack of consistency between studies was evident. miR-181c emerged as one of only a few miRNAs identified in multiple studies, being down-regulated in AD CSF and serum [80], along with miR-146a (involved in innate immune response) up-regulated in AD brain and CSF [149]. Moreover,

ncRNAs, miRNAs – and especially lncRNAs - as therapeutic targets are only beginning to be considered. Even so, these transcripts represent potential targets for two reasons: (i) lncRNA expression seems to be rather cell- and tissue-specific [150]; (ii) the sequence-specific function of lncRNA can be advantageous in designing specific therapies. As a closing, albeit speculative thought, is the possibility that epigenetic mutations exist that function to protect or promote recovery from the neuropathological sequelae of AD.

#### CONFLICT OF INTEREST/DISCLOSURE STATEMENT

The authors have no conflict of interest to report.

## REFERENCES

- [1] Esposito E, Grigorenko E, Sternberg R (2011) The Nature-Nurture Issue (an Illustration Using Behaviour-Genetic Research on Cognitive Development). In *An Introduction to Developmental Psychology: Second Edition*, Slater A and Bremner G, eds. BPS Blackwell United Kingdom, pp 79-114.
- [2] Galton F. Hereditary Genius. An inquiry into its laws and consequences. Macmillan and Co. London and New York 1892.
- [3] Sweatt JD (2013) The emerging field of neuroepigenetics. *Neuron* **80**, 624-632.
- [4] Dupont C, Armant DR, Brenner CA (2009) Epigenetics: definition, mechanisms and clinical perspective. *Semin Reprod Med* **27**, 351-357.
- [5] Gräff J, Kim D, Dobbin MM, Tsai LH (2011) Epigenetic regulation of gene expression in physiological and pathological brain processes. *Physiol Rev* **91**, 603-649.
- [6] Cacace R, Slegers K, van Broeckhoven C (2016) Molecular genetics of early-onset Alzheimer's disease revisited. *Alzheimers Dement* **12**, 733-748.
- [7] Rogers J, Mastroeni D, Grover A, Delvaux E, Whiteside C, Coleman PD (2011) The epigenetics of Alzheimer's disease-additional considerations. *Neurobiol Aging* **32**, 1196-1197.
- [8] Bradley-Whitman MA, Lovell MA (2013) Epigenetic changes in the progression of Alzheimer's disease. *Mech Ageing Dev* **134**, 486-495.
- [9] Siegfried Z, Simon I (2010) DNA methylation and gene expression. *Wiley Interdiscip. Rev. Syst. Biol Med* **2**, 362-371.
- [10] Pósfai J, Bhagwat AS, Roberts RJ (1988) Sequence motifs specific for cytosine methyltransferases. *Gene* **74**, 261-265.

- [11] Jabbari K, Bernardi G (2004) Cytosine methylation and CpG, TpG (CpA) and TpA frequencies. *Gene* **333**, 143-149.
- [12] Guo JU, Su Y, Zhong C, Ming GL, Song H (2011) Hydroxylation of 5-methylcytosine by TET1 promotes active DNA demethylation in the adult brain. *Cell* **145**, 423-434.
- [13] Kaas GA, Zhong C, Eason DE, Ross DL, Vachhani RV, Ming GL, King JR, Song H, Sweatt JD (2013) TET1 controls CNS 5-methylcytosine hydroxylation, active DNA demethylation, gene transcription, and memory formation. *Neuron* **79**, 1086-1093.
- [14] Rudenko A, Dawlaty MM, Seo J, Cheng AW, Meng J, Le T, Faull KF, Jaenisch R, Tsai LH (2013) Tet1 is critical for neuronal activity-regulated gene expression and memory extinction. *Neuron* **79**, 1109-1122.
- [15] Zhang RR, Cui QY, Murai K, Lim YC, Smith ZD, Jin S, Ye P, Rosa L, Lee YK, Wu HP, Liu W, Xu ZM, Yang L, Ding YQ, Tang F, Meissner A, Ding C, Shi Y, Xu GL (2013) Tet1 regulates adult hippocampal neurogenesis and cognition. *Cell Stem Cell* **13**, 237-245.
- [16] Horvath S. 2013. DNA methylation age of human tissues and cell types. *Genome Biol* **14**, R115. doi: 10.1186/gb-2013-14-10-r115.
- [17] Lashley T, Gami P, Valizadeh N, Li A, Revesz T, Balazs R (2015) Alterations in global DNA methylation and hydroxymethylation are not detected in Alzheimer's disease. *Neuropathol Appl Neurobiol* **41**, 497-506.
- [18] Mastroeni D, McKee A, Grover A, Rogers J, Coleman PD (2009) Epigenetic differences in cortical neurons from a pair of monozygotic twins discordant for Alzheimer's disease. *PLoS One* **4**, 8. doi: 10.1371/journal.pone.0006617.

- [19] Mastroeni D, Grover A, Delvaux E, Whiteside C, Coleman PD, Rogers J (2010) Epigenetic changes in Alzheimer's disease: decrements in DNA methylation. *Neurobiol Aging* **31**, 2025-2537.
- [20] Chouliaras L, Mastroeni D, Delvaux E, Grover A, Kenis G, Hof PR, Steinbusch HW, Coleman PD, Rutten BP, van den Hove DL (2013) Consistent decrease in global DNA methylation and hydroxymethylation in the hippocampus of Alzheimer's disease patients. *Neurobiol Aging* **34**, 2091-2099.
- [21] Keleshian VL, Modi HR, Rapoport SI, Rao JS (2013) Aging is associated with altered inflammatory, arachidonic acid cascade, and synaptic markers, influenced by epigenetic modifications, in the human frontal cortex. *J Neurochem* **125**, 63-73.
- [22] De Jager PL, Srivastava G, Lunnon K, Burgess J, Schalkwyk LC, Yu L, Eaton ML, Keenan BT, Ernst J, McCabe C, Tang A, Raj T, Replogle J, Brodeur W, Gabriel S, Chai HS, Younkin C, Younkin SG, Zou F, Szyf M, Epstein CB, Schneider JA, Bernstein BE, Meissner A, Ertekin-Taner N, Chibnik LB, Kellis M, Mill J, Bennett DA. 2014. Alzheimer's disease: early alterations in brain DNA methylation at ANK1, BIN1, RHBDF2 and other loci. *Nat Neurosci* **17**, 1156-1163.
- [23] Saxonov S, Berg P, Brutlag DL (2006) A genome-wide analysis of CpG dinucleotides in the human genome distinguishes two distinct classes of promoters. *Proc Natl Acad Sci USA* **103**, 1412-1417.
- [24] Bird A (2002) DNA methylation patterns and epigenetic memory. *Genes Dev* **16**, 6-21.
- [25] Smith RG, Hannon E, De Jager PL, Chibnik L, Lott SJ, Condliffe D, Smith AR, Haroutunian V, Troakes C, Al-Sarraj S, Bennett DA, Powell J, Lovestone S, Schalkwyk L, Mill J, Lunnon K (2018) Elevated DNA methylation across a 48-kb region spanning the HOXA gene cluster is

associated with Alzheimer's disease neuropathology. *Alzheimer & Dementia* **1-9**,  
<https://doi.org/10.1016/j.jalz.2018.01.017>.

- [26] Sung HY, Choi BO, Jeong JH, Kong KA, Hwang J, Ahn JH (2016) Amyloid beta-mediated hypomethylation of heme oxygenase 1 correlates with cognitive impairment in Alzheimer's disease. *PLoS One* **11**, 4. doi: 10.1371/journal.pone.0153156.
- [27] Zhang X, Wen H, Shi X (2012) Lysine methylation: beyond histones. *Acta Biochim Biophys Sinica* **44**, 14-27.
- [28] Pekowska A, Benoukrif T, Zacarias-Cabeza J, Belhocine M, Koch F, Holota H, Imbert J, Andrau JC, Ferrier P, Spicuglia S (2011) H3K4 tri-methylation provides an epigenetic signature of active enhancers. *EMBO J* **30**, 4198-4210.
- [29] Zhang T, Cooper S, Brockdorff N (2015) The interplay of histone modifications - writers that read. *EMBO Rep* **16**, 1467-1481.
- [30] Fleiss B, Nilsson B, Blomgren K, Mallard C (2012) Neuroprotection by the histone deacetylase inhibitor trichostatin A in a model of lipopolysaccharide-sensitized neonatal hypoxic-ischaemic brain injury. *J Neuroinflammation* **9**, 70. doi: 10.1186/1742-2094-9-70.
- [31] Correa F, Mallard C, Nilsson M, Sandberg M (2011) Activated microglia decrease histone acetylation and Nrf2-inducible anti-oxidant defence in astrocytes: restoring effects of inhibitors of HDACs, p38 MAPK and GSK3 $\beta$ . *Neurobiol Dis* **44**, 142-151.
- [32] Eberharter A, Becker PB (2002) Histone acetylation: a switch between repressive and permissive chromatin. Second in review series on chromatin dynamics. *EMBO Rep* **3**, 224-229.
- [33] Alarcón JM, Malleret G, Touzani K, Vronskaya S, Ishii S, Kandel ER, Barco A (2004) Chromatin acetylation, memory, and LTP are impaired in CBP $^{+/-}$  mice: a model for the cognitive deficit in Rubinstein-Taybi syndrome and its amelioration. *Neuron* **42**, 947-959.

- [34] Penney J, Tsai LH (2014) Histone deacetylases in memory and cognition. *Sci Signal* **7**, 355:re12. doi: 10.1126/scisignal.aaa0069.
- [35] Hanson JE, Deng L, Hackos DH, Lo SC, Lauffer BE, Steiner P, Zhou Q (2013) Histone deacetylase 2 cell autonomously suppresses excitatory and enhances inhibitory synaptic function in CA1 pyramidal neurons. *J Neurosci* **33**, 5924-5929.
- [36] Gräff J, Woldemichael BT, Berchtold D, Dewarrat G, Mansuy IM (2012) Dynamic histone marks in the hippocampus and cortex facilitate memory consolidation. *Nat Commun* **3**, 991. doi: 10.1038/ncomms1997.
- [37] Zhang J, Li X, Ren Y, Zhao Y, Xing A, Jiang C, Chen Y, An L (2018) Intermittent fasting alleviates the increase of lipoprotein lipase expression in brain of a mouse model of Alzheimer's Disease: possibly mediated by  $\beta$ -hydroxybutyrate. *Front Cell Neurosci* **12**, 1. doi: 10.3389/fncel.2018.00001.
- [38] Gräff J, Rei D, Guan JS, Wang WY, Seo J, Hennig KM, Nieland TJ, Fass DM, Kao PF, Kahn M, Su SC, Samiei A, Joseph N, Haggarty SJ, Delalle I, Tsai LH (2012) An epigenetic blockade of cognitive functions in the neurodegenerating brain. *Nature* **483**, 222-226.
- [39] Gräff J, Joseph NF, Horn ME, Samiei A, Meng J, Seo J, Rei D, Bero AW, Phan TX, Wagner F, Holson E, Xu J, Sun J, Neve RL, Mach RH, Haggarty SJ, Tsai LH (2014) Epigenetic priming of memory updating during reconsolidation to attenuate remote fear memories. *Cell* **156**, 261-267.
- [40] Falkenberg KJ, Johnstone RW (2014) Histone deacetylases and their inhibitors in cancer, neurological diseases and immune disorders. *Nat Rev Drug Discov* **13**, 673-691.



- [41] Gonzalez-Zuñiga M, Contreras PS, Estrada LD, Chamorro D, Villagra A, Zanlungo S, Seto E, Alvarez AR (2014) c-Abl stabilizes HDAC2 levels by tyrosine phosphorylation repressing neuronal gene expression in Alzheimer's disease. *Mol Cell* **56**, 163-173.
- [42] Yamakawa H, Cheng J, Penney J, Gao F, Rueda R, Wang J, Yamakawa S, Kritskiy O, Gjoneska E, Tsai LH (2017) The transcription factor Sp3 cooperates with HDAC2 to regulate synaptic function and plasticity in neurons *Cell Rep* **20**, 1319-1334.
- [43] Myung NH, Zhu X, Kruman II, Castellani RJ, Petersen RB, Siedlak SL, Perry G, Smith MA, Lee HG (2008) Evidence of DNA damage in Alzheimer disease: phosphorylation of histone H2AX in astrocytes. *Age (Dordr.)* **30**, 209-215.
- [44] Rao JS, Keleshian VL, Klein S, Rapoport SI (2012) Epigenetic modifications in frontal cortex from Alzheimer's disease and bipolar disorder patients. *Transl Psychiatry* **2**, e132. doi: 10.1038/tp.2012.55.
- [45] Ogawa O, Zhu X, Lee HG, Raina A, Obrenovich ME, Bowser R, Ghanbari HA, Castellani RJ, Perry G, Smith MA (2003) Ectopic localization of phosphorylated histone H3 in Alzheimer's disease: a mitotic catastrophe? *Acta Neuropathol* **105**, 524-528.
- [46] Neal M, Richardson JR (2018) Epigenetic regulation of astrocyte function in neuroinflammation and neurodegeneration. *Biochim Biophys Acta* **1864**, 432-443.
- [47] Carlomagno Y, Chung DC, Yue M, Castanedes-Casey M, Madden BJ, Dunmore J, Tong J, DeTure M, Dickson DW, Petrucelli L, Cook C (2017) An acetylation-phosphorylation switch that regulates tau aggregation propensity and function. *J Biol Chem* **292**, 15277-15286.
- [48] Molofsky AV, Pardal R, Iwashita T, Park IK, Clarke MF, Morrison SJ (2003) Bmi-1 dependence distinguishes neural stem cell self-renewal from progenitor proliferation. *Nature* **425**, 962-967.

- [49] Hay RT (2005) SUMO: a history of modification. *Mol Cell* **18**, 1-12.
- [50] Nathan D, Ingvarsdottir K, Sterner DE, Bylebyl GR, Dokmanovic M, Dorsey JA, Whelan KA, Krsmanovic M, Lane WS, Meluh PB, Johnson ES, Berger SL (2006) Histone sumoylation is a negative regulator in *Saccharomyces cerevisiae* and shows dynamic interplay with positive-acting histone modifications. *Genes Dev.* **20**, 966-976.
- [51] Tao CC, Hsu WL, Ma YL, Cheng SJ, Lee EH (2017) Epigenetic regulation of HDAC1 SUMOylation as an endogenous neuroprotection against A $\beta$  toxicity in a mouse model of Alzheimer's disease. *Cell Death Differ* **24**, 597-614.
- [52] Feligioni M, Nisticò R (2013) SUMO: a (oxidative) stressed protein. *Neuromolecular Med* **15**, 707-719.
- [53] Li T, Santockyte R, Shen RF, Tekle E, Wang G, Yang DC, Chock PB (2006) Expression of SUMO-2/3 induced senescence through p53- and pRB-mediated pathways. *J Biol Chem* **281**, 36221-36227.
- [54] Ahn K, Song JH, Kim DK, Park MH, Jo SA, Koh YH (2009) Ubc9 gene polymorphisms and late-onset Alzheimer's disease in the Korean population, a genetic association study *Neurosci Lett* **465**, 272-275.
- [55] Akar CA, Feinstein DL (2009) Modulation of inducible nitric oxide synthase expression by sumoylation. *J Neuroinflammation* **6**, 12. doi: 10.1186/1742-2094-6-12.
- [56] Hoppe JB, Salbego CG, Cimarosti H (2015) SUMOylation, novel neuroprotective approach for Alzheimer's disease? *Aging Dis* **6**, 322-330.
- [57] Lee JH, Park SM, Kim OS, Lee CS, Woo JH, Park SJ, Joe EH, Jou I (2009) Differential SUMOylation of LXRalpha and LXRbeta mediates transrepression of STAT1 inflammatory signaling in IFN-gamma-stimulated brain astrocytes. *Mol Cell* **35**, 806-817.

- [58] Knock E, Matsuzaki S, Takamura H, Satoh K, Rooke G, Han K, Zhang H, Staniszewski A, Katayama T, Arancio O, Fraser PE (2018) SUMO1 impact on Alzheimer disease pathology in an amyloid-depositing mouse model. *Neurobiol Dis* **110**, 154-165.
- [59] Bao J, Qin M, Mahaman YAR, Zhang B, Huang F, Zeng K, Xia Y, Ke D, Wang Q, Liu R, Wang JZ1, Ye K, Wang X (2018) BACE1 SUMOylation increases its stability and escalates the protease activity in Alzheimer's disease. *Proc Natl Acad Sci USA* **115**, 3954-3959.
- [60] Mattick JS, Rinn JL (2015) Discovery and annotation of long noncoding RNAs. *Nat Struct Mol Biol* **22**, 5-7.
- [61] He L, Hannon GJ (2004) MicroRNAs, small RNAs with a big role in gene regulation. *Nat Rev Genet* **5**, 522-531.
- [62] Hon CC, Ramilowski JA, Harshbarger J, Bertin N, Rackham OJ, Gough J, Denisenko E, Schmeier S, Poulsen TM, Severin J, Lizio M, Kawaji H, Kasukawa T, Itoh M, Burroughs AM, Noma S, Djebali S, Alam T, Medvedeva YA, Testa AC, Lipovich L, Yip CW, Abugessaisa I, Mendez M, Hasegawa A, Tang D, Lassmann T, Heutink P, Babina M, Wells CA, Kojima S, Nakamura Y, Suzuki H, Daub CO, de Hoon MJ, Arner E, Hayashizaki Y, Carninci P, Forrest AR (2017) An atlas of human long non-coding RNAs with accurate 5' ends. *Nature* **543**, 199-204.
- [63] Shi X, Sun M, Liu H, Yao Y, Song Y (2013) Long non-coding RNAs: a new frontier in the study of human diseases. *Cancer Lett* **339**, 159-166.
- [64] Batista PJ, Chang HY (2013) Long noncoding RNAs: cellular address codes in development and disease. *Cell* **152**, 1298-1307.
- [65] Esteller M (2011) Non-coding RNAs in human disease. *Nat Rev Genet* **12**, 861-874.

- [66] Mohr AM, Mott JL (2015). Overview of microRNA biology. *Semin Liver Dis* **35**, 3-11.
- [67] Valencia-Sanchez MA, Liu J, Hannon GJ, Parker R (2006) Control of translation and mRNA degradation by miRNAs and siRNAs. *Genes Dev* **20**, 515-524.
- [68] Fiore R, Khudayberdiev S, Saba R, Schratt G (2011) MicroRNA function in the nervous system. *Prog Mol Biol Transl Sci* **102**, 47-100.
- [69] Goodall EF, Heath PR, Bandmann O, Kirby J, Shaw PJ (2013) Neuronal dark matter, the emerging role of microRNAs in neurodegeneration. *Front Cell Neurosci* **7**, 178. doi: 10.3389/fncel.2013.00178.
- [70] Putteeraj M, Yahaya MF, Teoh SL (2017). MicroRNA Dysregulation in Alzheimer's Disease. *CNS Neurol Disord Drug Targets* **16**, 1000-1009.
- [71] Abramov AY, Canevari L, Duchen MR (2004)  $\beta$ -amyloid peptides induce mitochondrial dysfunction and oxidative stress in astrocytes and death of neurons through activation of NADPH oxidase. *J Neurosci* **24**, 565-595.
- [72] Hébert SS, Horré K, Nicolai L, Bergmans B, Papadopoulou AS, Delacourte A, De Strooper B (2009) MicroRNA regulation of Alzheimer's amyloid precursor protein expression. *Neurobiol Dis* **33**, 422-428.
- [73] Long JM, Ray B, Lahiri DK (2014) MicroRNA-339-5p down-regulates protein expression of beta-site amyloid precursor protein-cleaving enzyme 1 (BACE1) in human primary brain cultures and is reduced in brain tissue specimens of Alzheimer disease subjects. *J Biol Chem* **289**, 5184-5198.
- [74] Rockenstein EM, McConlogue L, Tan H, Power M, Masliah E, Mucke L (1995) Levels and alternative splicing of amyloid beta protein precursor (APP) transcripts in brains of APP transgenic mice and humans with Alzheimer's disease. *J Biol Chem* **270**, 28257-28267.

- [75] Donev R, Newall A, Thome J, Sheer D (2007) A role for SC35 and hnRNPA1 in the determination of amyloid precursor protein isoforms. *Mol Psychiatry* **12**, 681-690.
- [76] Smith P, Al Hashimi A, Girard J, Delay C, Hébert SS (2011) In vivo regulation of amyloid precursor protein neuronal splicing by microRNAs. *J Neurochem* **116**, 240-247.
- [77] Yang LB, Lindholm K, Yan R, Citron M, Xia W, Yang XL, Beach T, Sue L, Wong P, Price D, Li R, Shen Y (2003) Elevated  $\beta$ -secretase expression and enzymatic activity detected in sporadic Alzheimer disease. *Nat Med* **9**, 3-4,
- [78] Hébert SS, Horré K, Nicolai L, Papadopoulou AS, Mandemakers W, Silaharoglu AN, Kauppinen S, Delacourte A, De Strooper B (2008) Loss of microRNA cluster miR-29a/b-1 in sporadic Alzheimer's disease correlates with increased BACE1/beta-secretase expression. *Proc Natl Acad Sci USA* **105**, 6415-6420.
- [79] Zhu HC, Wang LM, Wang M, Song B, Tan S, Teng JF, Duan DX (2012) MicroRNA-195 downregulates Alzheimer's disease amyloid-beta production by targeting BACE1. *Brain Res Bull* **88**, 596-601.
- [80] Wang W-X, Rajeev BW, Stromberg AJ, Ren N, Tang G, Huang Q, Rigoutsos I, Nelson PT (2008) The expression of MicroRNA miR-107 decreases early in Alzheimer's disease and may accelerate disease progression through Regulation of -site amyloid precursor protein-cleaving enzyme 1. *J Neurosci* **28**, 1213-1223.
- [81] Serrano-Pozo A, Frosch MP, Masliah E, Hyman BT (2011) Neuropathological alterations in Alzheimer disease. *Cold Spring Harb Perspect Med* **1**, a006189. doi: 10.1101/cshperspect.a006189.
- [82] Ballatore C, Lee VM-Y, Trojanowski JQ (2007) Tau-mediated neurodegeneration in Alzheimer's disease and related disorders. *Nat Rev Neurosci* **8**, 663-672.

- [83] Schonrock N, Gotz J (2012) Decoding the non-coding RNAs in Alzheimer's disease. *Cell Mol Life Sci* **69**, 3543-3559.
- [84] Lau P, Bossers K, Janky R, Salta E, Frigerio CS, Barbash S, Rothman R, Sierksma AS, Thathiah A, Greenberg D, Papadopoulou AS, Achsel T, Ayoubi T, Soreq H, Verhaagen J, Swaab DF, Aerts S, De Strooper B (2013). Alteration of the microRNA network during the progression of Alzheimer's disease. *EMBO Mol Med* **5**, 1613-1634.
- [85] Zhu Q-B, Unmehopa U, Bossers K, Hu Y-T, Verwer R, Balesar R Zhao J, Bao AM, Swaab D (2016) MicroRNA-132 and early growth response-1 in nucleus basalis of Meynert during the course of Alzheimer's disease. *Brain* **139**, 908-921.
- [86] Santa-Maria I, Alaniz ME, Renwick N, Cela C, Fulga TA, Van Vactor D, Tuschl T, Clark LN, Shelanski ML, McCabe BD, Crary JF (2015) Dysregulation of microRNA-219 promotes neurodegeneration through post-transcriptional regulation of tau. *J Clin Invest* **125**, 681-686.
- [87] Carrettiero DC, Hernandez I, Neveu P, Papagiannakopoulos T, Kosik KS (2009) The cochaperone BAG2 sweeps paired helical filament- insoluble tau from the microtubule. *J Neurosci* **29**, 2151-2161.
- [88] Buée L, Bussièrè T, Buée-Scherrer V, Delacourte A, Hof PR (2000) Tau protein isoforms, phosphorylation and role in neurodegenerative disorders. *Brain Res Rev* **33**, 95-130.
- [89] Hébert SS, Papadopoulou AS, Smith P, Galas MC, Planel E, Silahtaroglu AN, Sergeant N, Buée L, De Strooper B (2010) Genetic ablation of Dicer in adult forebrain neurons results in abnormal tau hyperphosphorylation and neurodegeneration. *Hum Mol Genet* **19**, 3959-3969.
- [90] Cai Z, Zhao Y, Zhao B (2012) Roles of glycogen synthase kinase 3 in Alzheimer's disease. *Curr Alzheimer Res* **9**, 864-879.

- [91] Mohamed JS, Lopez MA, Boriek AM (2010) Mechanical stretch up-regulates MicroRNA-26a and induces human airway smooth muscle hypertrophy by suppressing glycogen synthase kinase-3 $\beta$ . *J Biol Chem* **285**, 29336-29347.
- [92] Caputo V, Sinibaldi L, Fiorentino A, Parisi C, Catalanotto C, Pasini A, Cogoni C, Pizzuti A (2011) Brain derived neurotrophic factor (BDNF) expression is regulated by MicroRNAs miR-26a and miR-26b allele-specific binding. *PLoS One* **6**, 12. doi: 10.1371/journal.pone.0028656.
- [93] Absalon S, Kochanek DM, Raghavan V, Krichevsky AM (2013) MiR-26b, upregulated in Alzheimer's disease, activates cell cycle entry, tau-phosphorylation, and apoptosis in postmitotic neurons. *J Neurosci* **33**, 14645-14659.
- [94] Cogswell JP, Ward J, Taylor IA, Waters M, Shi Y, Cannon B, Kelnar K, Kemppainen J, Brown D, Chen C, Prinjha RK, Richardson JC, Saunders AM, Roses AD, Richards CA (2008) Identification of miRNA changes in Alzheimer's disease brain and CSF yields putative biomarkers and insights into disease pathways. *J Alzheimers Dis* **14**, 27-41.
- [95] Zhao ZB, Wu L, Xiong R, Wang LL, Zhang B, Wang C, Li H, Liang L, Chen SD (2014) MicroRNA-922 promotes tau phosphorylation by downregulating ubiquitin carboxy-terminal hydrolase L1 (UCHL1) expression in the pathogenesis of Alzheimer's disease. *Neuroscience* **275**, 232-237.
- [96] Sweet RA, Bennett DA, Graff-Radford NR, Mayeux R; National Institute on Aging Late-Onset Alzheimer's Disease Family Study Group (2010) Assessment and familial aggregation of psychosis in Alzheimer's disease from the National Institute on Aging Late Onset Alzheimer's Disease Family Study. *Brain* **133**, 1155-1162.
- [97] Koppel J, Acker C, Davies P, Lopez OL, Jimenez H, Azose M, Greenwald BS, Murray PS, Kirkwood CM, Kofler J, Sweet RA (2014) *Neurobiol Aging* **35**, 2021-2028.

- [98] Kwon W, Kim HS, Jeong J, Sung Y, Choi M, Park S, Lee J, Jang S, Kim SH, Lee S, Kim MO, Ryoo ZY (2018) Tet1 overexpression leads to anxiety-like behavior and enhanced fear memories via the activation of calcium-dependent cascade through Egr1 expression in mice. *FASEB J* **32**, 390-403.
- [99] Corder EH, Saunders AM, Strittmatter WJ, Schmechel DE, Gaskell PC, Small GW, Roses AD, Haines JL, Pericak-Vance MA (1993) Gene dose of apolipoprotein E type 4 allele and the risk of Alzheimer's disease in late onset families. *Science* **261**, 921-923.
- [100] Kosicek M, Hecimovic S (2013) Phospholipids and Alzheimer's disease, alterations, mechanisms and potential biomarkers. *Int J Mol Sci* **14**, 1310-1322.
- [101] Goedeke L, Fernandez-Hernando C (2014) MicroRNAs, a connection between cholesterol metabolism and neurodegeneration. *Neurobiol Dis* **72**(Pt A), 48-53.
- [102] Fitz NF, Cronican AA, Saleem M, Fauq AH, Chapman R, Lefterov I, Koldamova R (2012) Abca1 deficiency affects Alzheimer's disease-like phenotype in human ApoE4 but not in ApoE3-targeted replacement mice. *J Neurosci* **32**, 13125-13136.
- [103] Rayner KJ, Suárez Y, Dávalos A, Parathath S, Fitzgerald ML, Tamehiro N, Fisher EA, Moore KJ, Fernández-Hernando C (2010) MiR-33 contributes to the regulation of cholesterol homeostasis. *Science* **328**, 1570-1573.
- [104] Kim J, Yoon H, Horie T, Burchett JM, Restivo JL, Rotllan N, Ramírez CM, Verghese PB, Ihara M, Hoe HS, Esau C, Fernández-Hernando C, Holtzman DM, Cirrito JR, Ono K, Kim J (2015) microRNA-33 Regulates ApoE Lipidation and Amyloid- $\beta$  Metabolism in the Brain. *J Neurosci* **35**, 14717-14726.
- [105] Ramirez CM, Dávalos A, Goedeke L, Salerno AG, Warriar N, Cirera-Salinas D, Suárez Y, Fernández-Hernando C (2011) MicroRNA-758 regulates cholesterol efflux through



posttranscriptional repression of ATP-binding cassette transporter A1. *Arterioscler Thromb Vasc Biol* **31**, 2707-2714.

- [106] Heneka MT, Carson MJ, El Khoury J, Landreth GE, Brosseron F, Feinstein DL, Jacobs AH, Wyss-Coray T, Vitorica J, Ransohoff RM, Herrup K, Frautschy SA, Finsen B, Brown GC, Verkhratsky A, Yamanaka K, Koistinaho J, Latz E, Halle A, Petzold GC, Town T, Morgan D, Shinohara ML, Perry VH, Holmes C, Bazan NG, Brooks DJ, Hunot S, Joseph B, Deigendesch N, Garaschuk O, Boddeke E, Dinarello CA, Breitner JC, Cole GM, Golenbock DT, Kummer MP (2015) Neuroinflammation in Alzheimer's disease. *Lancet Neurol* **14**, 388-405.
- [107] Altavilla D, Guarini S, Bitto A, Mioni C, Giuliani D, Bigiani A, Squadrito G, Minutoli L, Venuti FS, Messineo F, De Meo V, Bazzani C, Squadrito F (2006) Activation of the cholinergic anti-inflammatory pathway reduces NF-kappaB activation, blunts TNF-alpha production, and protects against splanchnic artery occlusion shock. *Shock* **25**, 500-506.
- [108] Coyle JT, Price DL, DeLong MR (1983) Alzheimer's disease, a disorder of cortical cholinergic innervation. *Science* **219**, 1184-1190.
- [109] Zhao Y, Bhattacharjee S, Jones BM, Dua P, Alexandrov PN, Hill JM, Lukiw WJ (2013) Regulation of TREM2 expression by an NF-kappaB-sensitive miRNA-34a. *Neuroreport* **24**, 318-323.
- [110] Bhattacharjee S, Zhao Y, Lukiw WJ (2014) Deficits in the miRNA-34a-regulated endogenous TREM2 phagocytosis sensor-receptor in Alzheimer's disease (AD); an update. *Front Aging Neurosci* **6**, 116. doi: 10.3389/fnagi.2014.00116.
- [111] Bhattacharjee S, Zhao Y, Dua P, Rogaev EI, Lukiw WJ (2016) microRNA-34a-mediated down-regulation of the microglial-enriched triggering receptor and phagocytosis-sensor TREM2 in age-related macular degeneration. *PLoS One* **11**, 3. doi: 10.1371/journal.pone.0150211.

- [112] Guerreiro R, Wojtas A, Bras J, Carrasquillo M, Rogaeva E, Majounie E, Cruchaga C, Sassi C, Kauwe JS, Younkin S, Hazrati L, Collinge J, Pocock J, Lashley T, Williams J, Lambert JC, Amouyel P, Goate A, Rademakers R, Morgan K, Powell J, St George-Hyslop P, Singleton A, Hardy J; Alzheimer Genetic Analysis Group (2013) TREM2 variants in Alzheimer's disease. *N Engl J Med.* **368**, 117-127.
- [113] Alexandrov PN, Dua P, Lukiw WJ (2014) Up-regulation of miRNA-146a in progressive age-related inflammatory neurodegenerative disorders of the human CNS. *Front Neurol* **5**, 181. doi: 10.3389/fneur.2014.00181.
- [114] Guedes JR, Custodia CM, Silva RJ, de Almeida LP, Pedroso de Lima MC, Cardoso AL (2014) Early miR-155 upregulation contributes to neuroinflammation in Alzheimer's disease triple transgenic mouse model. *Hum Mol Genet* **23**, 6286-6301.
- [115] Hutchison ER, Kawamoto EM, Taub DD, Lal A, Abdelmohsen K, Zhang Y, Wood WH 3rd, Lehrmann E, Camandola S, Becker KG, Gorospe M, Mattson MP (2013) Evidence for miR-181 involvement in neuroinflammatory responses of astrocytes. *Glia* **61**, 1018-1028.
- [116] Noh JH, Kim KM, McClusky WG, Abdelmohsen K, Gorospe M (2018) Cytoplasmic functions of long noncoding RNAs. *WIREs RNA* **e1471**. doi.org /10.1002/wrna.1471.
- [117] Derrien T, Johnson R, Bussotti G, Tanzer A, Djebali S, Tilgner H, Guernec G, Martin D, Merkel A, Knowles DG, Lagarde J, Veeravalli L, Ruan X, Ruan Y, Lassmann T, Carninci P, Brown JB, Lipovich L, Gonzalez JM, Thomas M, Davis CA, Shiekhhattar R, Gingeras TR, Hubbard TJ, Notredame C, Harrow J, Guigó R (2012). The GENCODE v7 catalog of human long noncoding RNAs: analysis of their gene structure, evolution, and expression. *Genome Res.* **22**, 1775-1789.
- [118] Montes M, Lund AH (2016) Emerging roles of lncRNAs in senescence. *FEBS J.* **283**, 2414-2426.

- [119] Cabili MN, Trapnell C, Goff L, Koziol M, Tazon-Vega B, Regev A, Rinn JL (2011) Integrative annotation of human large intergenic noncoding RNAs reveals global properties and specific subclasses. *Genes Dev* **25**, 1915-1927
- [120] Audas TE, Lee S (2016) Stressing out over long noncoding RNA. *Biochim Biophys Acta* **1859**, 184-191.
- [121] Chen YG, Satpathy AT, Chang HY (2017) Gene regulation in the immune system by long noncoding RNAs. *Nat Immunol* **18**, 962-972.
- [122] Grammatikakis I, Panda AC, Abdelmohsen K, Gorospe M (2014) Long noncoding RNAs (lncRNAs) and the molecular hallmarks of aging. *Aging (Albany NY)* **6**, 992-1009.
- [123] Li J, Tian H, Yang J, Gonz Z (2016) Long noncoding RNAs regulate cell growth, proliferation, and apoptosis. *DNA Cell Biol* **35**, 459-470.
- [124] Qureshi IA, Mattick JS, Mehler MF (2010) Long non-coding RNAs in nervous system function and disease. *Brain Res* **1338**, 20-35.
- [125] Briggs JA, Wolvetang EJ, Mattick JS, Rinn JL, Barry G (2015) Mechanisms of long non-coding RNAs in mammalian nervous system development, plasticity, disease, and evolution. *Neuron* **88**, 861-877.
- [126] Lyle R, Watanabe D, te Vrugte D, Lerchner W, Smrzka OW, Wutz A, Schageman J, Hahner L, Davies C, Barlow DP (2000) The imprinted antisense RNA at the *Igf2r* locus overlaps but does not imprint *Mas1*. *Nat Genet* **25**, 19-21.
- [127] Guttman M, Amit I, Garber M, French C, Lin MF, Feldser D, Huarte M, Zuk O, Carey BW, Cassady JP, Cabili MN, Jaenisch R, Mikkelsen TS, Jacks T, Hacohen N, Bernstein BE, Kellis M, Regev A, Rinn JL, Lander ES (2009) Chromatin signature reveals over a thousand highly conserved large non-coding RNAs in mammals. *Nature* **45**, 223-227.

- [128] Feng L, Liao YT, He JC, Xie CL, Chen SY, Fan HH, Su ZP, Wang Z (2018) Plasma long non-coding RNA BACE1 as a novel biomarker for diagnosis of Alzheimer disease. *BMC Neurol* **18**, 4. doi: 10.1186/s12883-017-1008-x.
- [129] Gui Y, Liu H, Zhang L, Lv W, Hu X (2015) Altered microRNA profiles in cerebrospinal fluid exosome in Parkinson disease and Alzheimer disease. *Oncotarget* **6**, 37043-37053.
- [130] Koh M, Lee H, Lee Y, Lee M (2014) Characterization of early-stage amyloid aggregates by incorporating extrinsic fluorescence and atomic force microscopy. *J Nanosci Nanotechnol* **14**, 8386-8389.
- [131] Zhou X, Xu J (2015) Identification of Alzheimer's disease-associated long noncoding RNAs. *Neurobiol Aging* **36**, 2925-2931.
- [132] Faghihi MA, Modarresi F, Khalil AM, Wood DE, Sahagan BG, Morgan TE, Finch CE, St Laurent G 3rd, Kenny PJ, Wahlestedt C (2008) Expression of a noncoding RNA is elevated in Alzheimer's disease and drives rapid feed-forward regulation of [beta]-secretase. *Nat Med* **14**, 723-730.
- [133] Faghihi MA, Zhang M, Huang J, Modarresi F, Van der Brug MP, Nalls MA, Cookson MR, St-Laurent G 3rd, Wahlestedt C (2010) Evidence for natural antisense transcript-mediated inhibition of microRNA function. *Genome Biol.* **11**, R56
- [134] Ma Z, Han D, Zuo X, Wang F, Jia J (2009) Association between promoter polymorphisms of the nicastrin gene and sporadic Alzheimer's disease in North Chinese Han population. *Neurosci Lett* **458**, 136-139.
- [135] Andersen OM, Reiche J, Schmidt V, Gotthardt M, Spoelgen R, Behlke J, von Arnim CA, Breiderhoff T, Jansen P, Wu X, Bales KR, Cappai R, Masters CL, Gliemann J, Mufson EJ, Hyman BT, Paul SM, Nykjaer A, Willnow TE (2005) Neuronal sorting protein-related

receptor sorLA/LR11 regulates processing of the amyloid precursor protein. *Proc Natl Acad Sci USA* **102**, 13461-13466.

- [136] Mus E, Hof PR, Tiedge H (2007) Dendritic BC200 RNA in aging and in Alzheimer's disease. *Proc Natl Acad Sci USA* **104**, 10679-10684.
- [137] Lukiw WJ, Handley P, Wong L, Crapper McLachlan DR (1992) BC200 RNA in normal human neocortex, non-Alzheimer dementia (NAD), and senile dementia of the Alzheimer type (AD). *Neurochem Res* **17**, 591-597.
- [138] Zhang M, Cai F, Zhang S, Zhang S, Song W (2014) Overexpression of ubiquitin carboxyl-terminal hydrolase L1 (UCHL1) delays Alzheimer's progression in vivo. *Sci Rep.* **4**, 7298. doi: 10.1038/srep07298.
- [139] Emanuele E, Lista S, Ghidoni R, Binetti G, Cereda C, Benussi L, Maletta R, Bruni AC, Politi P (2011) Chromosome 9p21.3 genotype is associated with vascular dementia and Alzheimer's disease. *Neurobiol Aging* **32**, 1231-1235.
- [140] Tamura Y, Kunugi H, Ohashi J, Hohjoh H (2007) Epigenetic aberration of the human REELIN gene in psychiatric disorders. *Mol Psychiatry* **12**, 593-600.
- [141] Riva P, Ratti A, Venturin M (2017) The Long Non-Coding RNAs in Neurodegenerative Diseases: Novel Mechanisms of Pathogenesis. *Curr Alzheimer Res.* **13**, 1219-1231.
- [142] Arisi I, D'Onofrio M, Brandi R, Felsani A, Capsoni S, Drovandi G, Felici G, Weitschek E, Bertolazzi P, Cattaneo A (2011) Gene expression biomarkers in the brain of a mouse model for Alzheimer's disease: mining of microarray data by logic classification and feature selection. *J Alzheimers Dis* **24**, 721-738.

- [143] Magistri M, Velmeshev D, Makhmutova M, Faghihi MA (2015) Transcriptomics profiling of Alzheimer's disease reveal neurovascular defects, altered amyloid-beta homeostasis, and deregulated expression of long noncoding RNAs. *J Alzheimers Dis* **48**, 647-665.
- [144] Urduingio RG, Sanchez-Mut JV, Esteller M (2009) Epigenetic mechanisms in neurological diseases, genes, syndromes, and therapies. *Lancet Neurol* **8**, 1056-1072.
- [145] Lahiri DK, Maloney B, Zawia NH (2009) The LEARN model, an epigenetic explanation for idiopathic neurobiological diseases. *Mol Psychiatry* **14**, 992-1003.
- [146] Dubois B, Padovani A, Scheltens P, Rossi A and Dell'Agnello G (2016) Timely diagnosis for Alzheimer's disease, A literature review on benefits and challenges. *J Alzheimers Dis* **49**, 617-631
- [147] Schwarzenbach H, Nishida N, Calin GA, Pantel K (2014) Clinical relevance of circulating cell-free microRNAs in cancer. *Nat Rev Clin Oncol* **11**, 145-156.
- [148] Maoz R, Garfinkel BP, Soreq H (2017) Alzheimer's Disease and ncRNAs. *Adv Exp Med Biol* **978**, 337-361.
- [149] Denk J, Boelmans K, Siegismund C, Lassner D, Arlt S, Jahn H (2015) MicroRNA Profiling of CSF reveals potential biomarkers to detect Alzheimer's disease. *PLoS One* **10**, 5. doi: 10.1371/journal.pone.0126423.
- [150] Djebali S, Davis CA, Merkel A, Dobin A, Lassmann T, Mortazavi A, Tanzer A, Lagarde J, Lin W, Schlesinger F, Xue C, Marinov GK, Khatun J, Williams BA, Zaleski C, Rozowsky J, Röder M, Kokocinski F, Abdelhamid RF, Alioto T, Antoshechkin I, Baer MT, Bar NS, Batut P, Bell K, Bell I, Chakraborty S, Chen X, Chrast J, Curado J, Derrien T, Drenkow J, Dumais E, Dumais J, Dutttagupta R, Falconnet E, Fastuca M, Fejes-Toth K, Ferreira P, Foissac S, Fullwood MJ, Gao H, Gonzalez D, Gordon A, Gunawardena H, Howald C, Jha S, Johnson R,

Kapranov P, King B, Kingswood C, Luo OJ, Park E, Persaud K, Preall JB, Ribeca P, Risk B, Robyr D, Sammeth M, Schaffer L, See LH, Shahab A, Skancke J, Suzuki AM, Takahashi H, Tilgner H, Trout D, Walters N, Wang H, Wrobel J, Yu Y, Ruan X, Hayashizaki Y, Harrow J, Gerstein M, Hubbard T, Reymond A, Antonarakis SE, Hannon G, Giddings MC, Ruan Y, Wold B, Carninci P, Guigó R, Gingeras TR (2012) Landscape of transcription in human cells. *Nature* **489**, 101-108.

- [151] Dean M, Rzhetsky A, Allikmets R (2001) The human ATP-binding cassette (ABC) transporter superfamily. *Genome Res* **11**, 1156-1166.
- [152] Steinberg S, Stefansson H, Jonsson T, Johannsdottir H, Ingason A, Helgason H, Sulem P, Magnusson OT, Gudjonsson SA, Unnsteinsdottir U, Kong A, Helisalmi S, Soininen H, Lah JJ; DemGene, Aarsland D, Fladby T, Ulstein ID, Djurovic S, Sando SB, White LR, Knudsen GP, Westlye LT, Selbæk G, Giegling I, Hampel H, Hiltunen M, Levey AI, Andreassen OA, Rujescu D, Jonsson PV, Bjornsson S, Snaedal J (2015) Loss-of-function variants in ABCA7 confer risk of Alzheimer's disease. *Nat Genet* **47**, 445-447.
- [153] Keller A, Backes C, Haas J, Leidinger P, Maetzler W, Deuschle C, Berg D, Ruschil C, Galata V, Ruprecht K, Stähler C, Würstle M, Sickert D, Gogol M, Meder B, Meese E. (2016) Validating Alzheimer's disease micro RNAs using next-generation sequencing. *Alzheimers Dement* **12**, 565-576.
- [154] Bhatnagar S, Chertkow H, Schipper HM, Yuan Z, Shetty V, Jenkins S, Jones T, Wang E (2014) Increased microRNA-34c abundance in Alzheimer's disease circulating blood plasma. *Front Mol Neurosci* **7**, 2. doi: 10.3389/fnmol.2014.00002.
- [155] Jia LH, Liu YN (2016) Downregulated serum miR-223 serves as biomarker in Alzheimer's disease. *Cell Biochem Funct* **34**, 233-237.

- [156] Tan L, Yu JT, Liu QY, Tan MS, Zhang W, Hu N, Wang YL, Sun L, Jiang T, Tan L (2014) Circulating miR-125b as a biomarker of Alzheimer's disease. *J Neurol Sci* **336**, 52-56.
- [157] Müller M, Jäkel L, Bruinsma IB, Claassen JA, Kuiperij HB, Verbeek MM (2016) MicroRNA-29a Is a Candidate Biomarker for Alzheimer's Disease in Cell-Free Cerebrospinal Fluid. *Mol Neurobiol* **53**, 2894-2899.
- [158] Kumar S, Vijayan M, Reddy PH (2017) MicroRNA-455-3p as a potential peripheral biomarker for Alzheimer's disease. *Hum Mol Genet* **26**, 3808-3822.
- [159] Yılmaz ŞG, Erdal ME, Özge AA, Sungur MA (2016) Can peripheral microRNA expression data serve as epigenomic (upstream) biomarkers of Alzheimer's disease? *OMICS* **20**, 456-461.
- [160] Ren RJ, Zhang YF, Dammer EB, Zhou Y, Wang LL, Liu XH, Feng BL, Jiang GX, Chen SD, Wang G, Cheng Q (2016) Peripheral blood microRNA expression profiles in Alzheimer's disease: screening, validation, association with clinical phenotype and implications for molecular mechanism. *Mol Neurobiol* **53**, 5772-5781.
- [161] Dong H, Li J, Huang L, Chen X, Li D, Wang T, Hu C, Xu J, Zhang C, Zen K, Xiao S, Yan Q, Wang C, Zhang CY (2015) Serum microRNA profiles serve as novel biomarkers for the diagnosis of Alzheimer's disease. *Dis Markers* **625659** doi: 10.1155/2015/625659.
- [162] Galimberti D, Villa C, Fenoglio C, Serpente M, Ghezzi L, Cioffi SM, Arighi A, Fumagalli G, Scarpini E (2014) Circulating miRNAs as potential biomarkers in Alzheimer's disease. *J Alzheimers Dis* **42**, 1261-1267.
- [163] Tan L, Yu JT, Tan MS, Liu QY, Wang HF, Zhang W, Jiang T, Tan L (2014) Genome-wide serum microRNA expression profiling identifies serum biomarkers for Alzheimer's disease. *J Alzheimers Dis* **40**, 1017-1027.



- [164] Bekris LM, Lutz F, Montine TJ, Yu CE, Tsuang D, Peskind ER, Leverenz JB (2013) MicroRNA in Alzheimer's disease: an exploratory study in brain, cerebrospinal fluid and plasma. *Biomarker* **18**, 455-466.
- [165] Lusardi TA, Phillips JI, Wiedrick JT, Harrington CA, Lind B, Lapidus JA, Quinn JF, Saugstad JA (2017) MicroRNAs in human cerebrospinal fluid as biomarkers for Alzheimer's disease. *J Alzheimers Dis* **55**, 1223-1233.

## Box 1

### **The ATP-binding cassette sub-family A member 7 (ABCA7) gene**

*ABCA7* codes for a member of the superfamily of ATP-binding cassette (ABC) transporters, whose function being to carry a variety of molecules across extra- and intra-cellular membranes [151].

ABC genes comprise seven subfamilies: ABC1, MDR/TAP, CFTR/MRP, ALD

(adrenoleukodystrophy), OABP, GCN20, and White. *ABCA7* belongs to the ABC1 subfamily,

whose members are the only major ABC subfamily exclusive to multicellular eukaryotes. *ABCA7*

is found mainly in myelo-lymphatic tissues, with greatest expression in peripheral leukocytes,

spleen, thymus, and bone marrow. This transporter's function remains unknown, although its

expression pattern points to a role in lipid homeostasis in immune system cells. Two transcript

variants result from alternative splicing *ABCA7*, both predisposing to AD [152]. Indeed, the

Icelandic database of Decode Genetics points to a two-fold greater risk of developing AD when

*ABCA7* inactive variants of are present.

**Table 1.** A selection of genes in AD patients subject to methylation (inhibiting) and demethylation (activating) processes

<b>CNS area and methylation state in AD</b>	<b>Gene</b>	<b>Protein encoded</b>
<i>Cortex and hypermethylation</i>	ABCA7	One of the superfamily of ATP-binding cassette (ABC) transporters that carry molecules across extra- and intra-cellular membranes (see Box 1)
	ANK1, ANK1 (5hmC)	Ankyrins: Link integral membrane proteins to the underlying spectrin-actin cytoskeleton; involved in cell motility, activation, proliferation, contact and maintenance of specialized membrane domains
	BDNF	A member of the nerve growth factor family of proteins
	BIN1; BIN1 (5hmC)	Nucleocytoplasmic adaptor proteins expressed in CNS; may be involved in synaptic vesicle endocytosis and may interact with dynamin, synaptojanin, endophilin, and clathrin
	CREB	CREB or CREB-like proteins (CREB1-3). Likely involved in long-term memory formation and late stage of long-term potentiation. Important role also in development of drug addiction/ psychological dependence
	DIP2A	Disco-interacting protein 2 homolog A may provide positional cues for axon pathfinding and patterning in CNS
	DNMT1	DNA (cytosine-5-)-methyltransferase 1 transfers methyl groups to cytosine nucleotides of genomic DNA
	HLA-DRB5	Belongs to the HLA class II beta chain paralogues
	HOXA3	In vertebrates, the genes encoding the class of transcription factors called homeobox genes are found in clusters named A, B, C, and D, on four separate chromosomes. Expression of these proteins is spatially and temporally regulated during embryonic development. This gene is part of the A cluster on chromosome 7 and encodes a DNA-binding transcription factor which may regulate gene expression, morphogenesis, and differentiation.
	MTHFR	Methylenetetrahydrofolate reductase catalyzes conversion of 5,10-methylenetetrahydrofolate to 5-methyltetrahydrofolate, a co-substrate for homocysteine remethylation to methionine
RHBDF2	Rhomboid 5 Homolog 2 lacks protease activity but regulates	

		secretion of several epidermal growth factor receptor ligands
	SERPINF1/2	Serpin Family F Member 1: a serpin family member that lacks serine protease inhibitor activity of many other serpin proteins. Strongly inhibits angiogenesis and promotes neuronal differentiation of retinoblastoma cells
	SLC2A4	Solute Carrier Family 2 Member 4: an insulin-regulated facilitative glucose transporter. An integral membrane protein sequestered within muscle and adipose tissue cells; rapidly moves to cell surface following insulin stimulation to transport glucose across cell membrane
	SORBS3	Sorbin and SH3 Domain Containing 3: a SH3 domain-containing adaptor protein. The SH3 domain facilitates binding other cytoplasmic molecules and contributes to cytoskeletal organization, cell adhesion and migration, signaling, and gene expression
	SORL1	SORL1 (Sortilin Related Receptor 1): encodes a mosaic protein belonging to the vacuolar protein sorting 10 domain-containing receptor family, and the low-density lipoprotein receptor family. Preproprotein proteolytically processed to the mature receptor, which likely plays roles in endocytosis and sorting, also contains fibronectin type III repeats and an epidermal growth factor repeat. Mutations in SORL1 may be associated with AD
	Spectrin Beta, Non-Erythrocytic 4 (SPTBN4)	An actin crosslinking and molecular scaffold protein that links plasma membrane to actin cytoskeleton: functions in determining cell shape, and organization of transmembrane proteins and organelles. Composed of two antiparallel dimers of alpha- and beta- subunits. A member of a family of beta-spectrin genes. Localizes to the nuclear matrix, promyelocytic leukemia nuclear bodies, and cytoplasmic vesicles.
	TBXA2R	Thromboxane A2 receptor: belongs to the G protein-coupled receptor family. Interacts with thromboxane A2 to induce platelet aggregation and regulate hemostasis.
<i>Cortex and hypomethylation</i>	COX2	Prostaglandin-endoperoxide synthase or cyclooxygenase. Key enzyme in prostaglandin biosynthesis; acts as a dioxygenase and a peroxidase.
	DIP2A (5hmC)	Disco-interacting protein 2 homolog A: may provide positional cues for CNS axon pathfinding and patterning

	DUSP22 (5hmC)	Dual Specificity Phosphatase 22: activates c-Jun N-terminal kinase signaling pathway. Dephosphorylates/inactivates p38 and stress-activated protein kinase/c-Jun N-terminal kinase
	IGFBP	Insulin-like growth factor binding proteins are important in cell migration and metabolism. Low levels may be associated with impaired glucose tolerance, vascular disease and hypertension in man
	NF-κB	Nuclear factor kappa B subunit: transcription factor activated by intra- and extra-cellular stimuli (cytokines, oxidant-free radicals, ultraviolet irradiation, bacterial/viral products). Translocates to nucleus and stimulates expression of genes involved in numerous biological functions. Inappropriate activation of NF-κB associated with inflammatory diseases; persistent inhibition leads to inappropriate immune cell development or delayed cell growth
	PSEN1	Presenilins regulate APP processing via the APP-cleaving enzyme gamma-secretase. May be involved in Notch receptor cleavage, such that they either directly regulate gamma-secretase activity or themselves are protease enzymes. Mutations in presenilin proteins (PSEN1; PSEN2) or in APP associated with familial AD
	TMEM59	Transmembrane Protein 59 regulates autophagy in response to bacterial infection. May also regulate the retention of APP in the Golgi apparatus through control of APP glycosylation.
<i>Entorhinal cortex e/o hippocampus</i> Hypermethylation	ANK1	See above
	BIN1	See above
	DIP2A	See above
	DUSP22	See above
	RHBDF2	See above
	SERPINF1/2	See above
	TREM and TREM2 (5hmC)	Transmembrane Protein 2 is a type II transmembrane protein that belongs to the interferon-induced transmembrane (IFITM) protein superfamily. Functions as a cell surface hyaluronidase that cleaves extracellular high molecular weight hyaluronan into intermediate size fragments before internalization and

		degradation in the lysosome. It also has an interferon-mediated antiviral function in humans through activation of the JAK STAT signaling pathway
<i>Entorhinal cortex e/o hippocampus</i> Hypomethylation	MT-ND1	Mitochondrially NADH:Ubiquinone Oxidoreductase Core Subunit 1 is a subunit of the mitochondrial membrane respiratory chain NADH dehydrogenase (Complex I) thought to belong to the minimal assembly required for catalysis. Complex I transfers electrons from NADH to respiratory chain, whose immediate electron acceptor is believed to be ubiquinone
	NF-kB	See above
<i>Temporal lobe</i> Hypermethylation	DUSP6	Dual Specificity Phosphatase 6: A member of the dual specificity protein phosphatase subfamily that inactivate kinases by dephosphorylating both phosphoserine/threonine and phosphotyrosine residues. Negatively regulate members of the mitogen-activated protein (MAP) kinase superfamily (MAPK/ERK, SAPK/JNK, p38) associated with cellular proliferation and differentiation. Different members have distinct substrate specificities, different tissue distribution and subcellular localization, and differ in their induction by extracellular stimuli
	HOXA3	See above
<i>Temporal lobe</i> Hypomethylation	APP	Encodes a cell surface receptor and transmembrane precursor protein cleaved by secretases. Some peptide products are secreted and bind to the acetyltransferase complex APBB1/TIP60 to promote transcriptional activation. Other peptides form amyloid plaques in brain. Two of the peptides are endowed also with bactericidal and antifungal activities. APP gene mutations implicated in autosomal dominant AD and cerebral amyloid angiopathy. Gene found to have multiple transcript variants that encode several different isoforms

5hmC: 5-hydroxymethylcytosine. The first oxidative product in the demethylation of 5-methylcytosine (see Fig 1)

Table 2. Biomarker assay in blood, plasma and CSF (analyzed by ROC)

Study	Fluid	Cohort	Technology	Main Results
[153]	Blood	54 AD, 22 C and 49 AD, 55 C, 20 mild cognitive impairment (MCI), 90 multiple sclerosis	Next-generation sequencing	Five hundred eighty miRNAs were detected. Overlap of 68 dysregulated miRNAs in two cohorts.
[154]	Blood	100 AD, 150 control	qPCR	In mild and moderate cognitively impaired AD patients (defined by MMSE) there was a relatively strong inverse relationship between increased miR-34c levels and MMSE score.
[155]	Serum	84 AD, 64 control	qPCR	miR-29, miR-125b and miR-223 were significantly decreased, but miR-519 significantly increased in AD patients. In addition, miR-223 showed a strong positive correlation with MMSE score in AD patients.
[156]	Serum	105 AD, 150 control	qPCR	miR-125b and miR-181c were down-regulated while miR-9 was up-regulated in AD patients Among ROC results, miR-125b alone showed its priority with a specificity up to 68.3% and a sensitivity of 80.8%. Importantly, it correlated with MMSE in AD patients.
[157]	CSF	18 AD, 20 controls	qPCR	In AD patients CSF levels of miR-29a were increased whereas miR-27a, miR-29b, and miR-125b were unchanged. Spiking of small amounts of blood into CSF revealed miR-27a and miR-29a, but not miR-125b levels to be strongly influenced by the number of blood cells in the sample.
[128]	Blood	88 AD, 72	qPCR	LncRNA BACE1 level of AD patients was significantly higher than in

		controls		healthy controls. Levels of lncRNA 17A, 51A and BC200 did not show a significant difference between the two groups. No correlation found for expression of these lncRNAs in both control and AD groups with age or MMSE score.
[158]	Serum	10 AD, 16 MCI, 14 controls	Affymetrix microarray analysis and validated differentially expressed miRNAs using q-PCR	A gradual up-regulation of miR-455-3p, miR-4668-5p and a down-regulation of miR-6722 was found in persons with AD and mild cognitive impairment compared with controls. Further, qRT-PCR analysis of AD postmortem brains with different Braak stages also showed up-regulation of miR-455-3p in serum and brain of AD patients. Human and mouse neuroblastoma cells treated with A $\beta$ (1-42) also showed a similarly higher expression of miR-455-3p.
[159]	Blood	172 AD, 109 controls	q-PCR	Reductions in expression of hsa-miR-9-5p, hsa-miR-106a-5p, hsa-miR-106b-5p, and hsa-miR-107 were significantly associated with increased risk of AD. Notably, after ROC analyses, hsa-miR-106a-5p displayed, as a predictor variable, 93% specificity and 68% sensitivity. On the other hand, expression of hsa-miR-29a-3p, hsa-miR-125a-3p, and hsa-miR-125b-5p was not significantly different between patients and controls.
[160]	Blood	8 AD, 4 controls	Microarray screening followed by q-PCR	Two differentially expressed miRNAs (miR-339 and miR-425) as potential diagnostic biomarkers for AD were identified. Potential involvement in modulating AD pathogenesis via BACE1 inhibition.
[161]	Serum	127 AD, 30 MCI, and 30 vascular	qPCR	miR-31, miR-93, miR-143, and miR-146a) were markedly decreased in AD patients' serum compared with

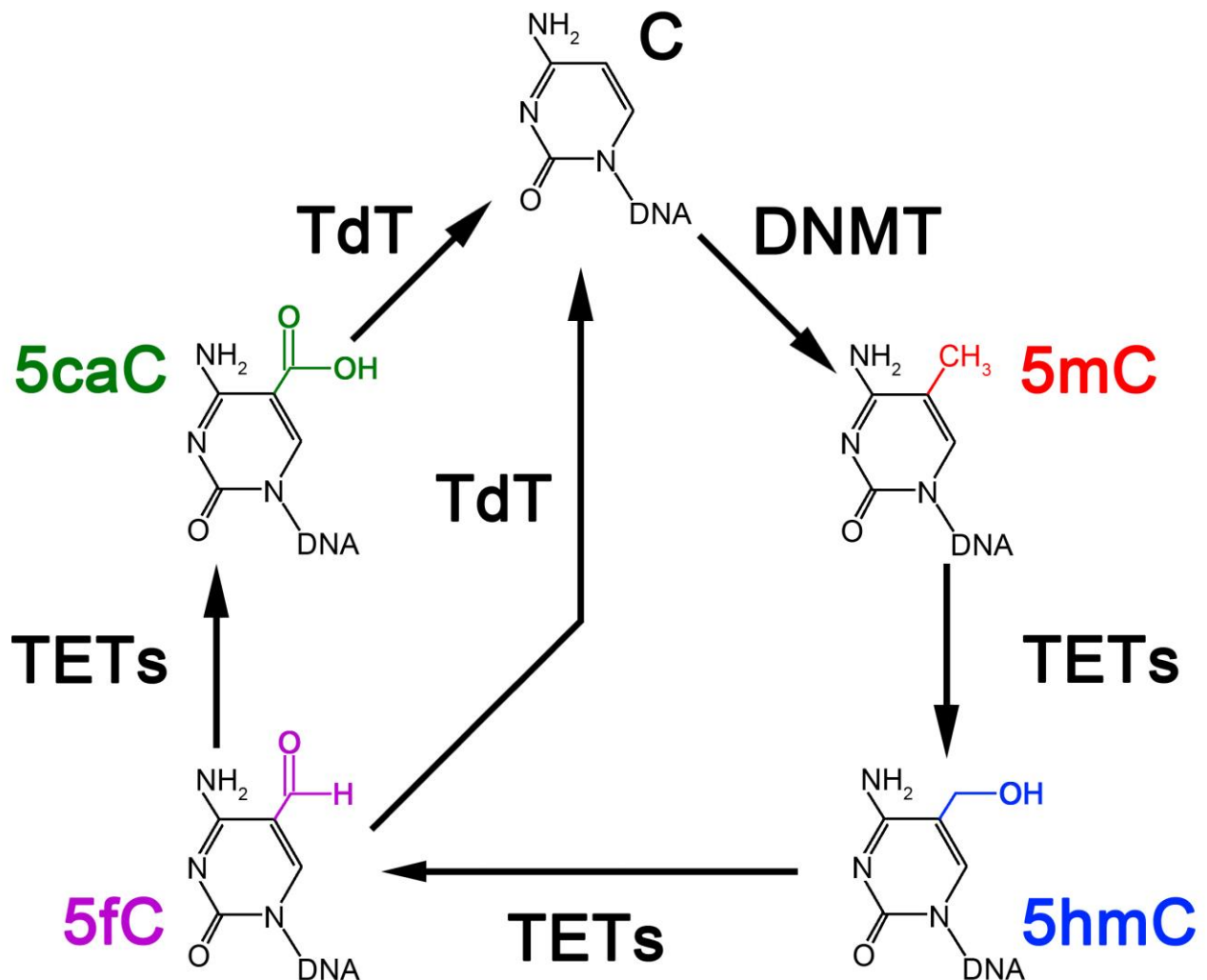


		dementia, 123 controls		controls. Receiver operating characteristic curve analysis demonstrated that these miRNAs could be used as potential biomarkers for AD. Furthermore, miR-93 and miR-146a were significantly elevated in MCI compared with controls, proposing the use of miR-31, miR-93, and miR-146a to discriminate AD from vascular dementia.
[162]	Serum, CSF	22 AD, 10 patients with frontotemporal dementia, 18 non-inflammatory and 8 inflammatory neurological controls	Array screening followed by qPCR	Down-regulation of miR-125b, miR-23a, and miR-26b in serum. Significant down-regulation of miR-125b and miR-26b was also confirmed in CSF from AD patients.
[163]	Serum	50 AD, 50 controls	qPCR	MiR-98-5p, miR-885-5p, miR-483-3p, miR-342-3p, miR-191-5p, and miR-let-7d-5p displayed significantly different expression levels in AD compared with controls. Among these, miR-342-3p had the best sensitivity (81.5%) and specificity (70.1%) and was correlated to MMSE.
[164]	Serum and CSF	Post mortem study: 21 AD, 21 controls (samples obtained from cerebellum and hippocampus)	qPCR	Plasma miR-15a expression was significantly correlated with increasing neuritic plaque score in hippocampus.
[165]	CSF	50 AD, 49 controls	qPCR	36 miRNAs that discriminate AD from control CSF were identified. Top-performing linear combinations of 3 miRNAs (decreased expression in miR-146a-p and miR-125b-5p, and increased expression of miR-29a-3p)

				in CSF have AUC of 0.80. Addition of ApoE genotype to the model improved performance, i.e., AUC of 3 miRNA plus ApoE4 improves to 0.84.
--	--	--	--	---

CSF, cerebrospinal fluid; MCI, mild cognitive impairment; MMSE, Mini Mental State Exam; qPCR, quantitative Real Time polymerase chain reaction; ROC, receiver operating characteristic

**Figure 1: Epigenetic DNA modification**



DNA methyltransferases (DNMT) add and maintain methyl groups on cytosine (C) to form 5-methylcytosine (5mC). Ten-eleven translocation (TET) family of DNA hydroxylases are responsible for executing active DNA demethylation. This process occurs through 5-hydroxymethylcytosine (5hmC) conversion to 5-formylcytosine (5fC) and 5-carboxycytosine (5caC). Both 5fC and 5caC can be converted to unmodified C by terminal deoxynucleotidyl transferase (TdT) by base excision repair.