

Genetic Underpinnings in Alzheimer's disease – a review

Moustafa, A. A.*^{1,2} Hassan, M.*³, Hewedi, D.⁴, Garami, J.¹, Alashwal, H⁵., Zaki, N.⁵, Seo, S.Y³., Cutsuridis, V.⁶, Angulo, S. L.⁷, Hewedi, E.⁸, Natesh, J. Y.^{9,10}, Herzallah, M. M.^{9,10}, Frydecka, D.,¹¹ Misiak, B.¹², Mohamed Salama¹³, Wael Mohamed^{14,15}, Mohamad El Haj¹⁶, Hornbeger, M.^{17,18}

¹School of Social Sciences and psychology & ²MARCS Institute for Brain and Behaviour, Western Sydney University, Sydney, New South Wales, Australia.

³Department of Biology, College of Natural Sciences, Kongju National University, Gongju, 314-701, Republic of Korea & Institute of Molecular Science and Bioinformatics, Lahore, Pakistan.

⁴Psychogeriatric Research Center, Institute of Psychiatry, Faculty of Medicine, Ain Shams University, Cairo, Egypt.

⁵ College of Information Technology, United Arab Emirates University, Al-Ain, 15551, UAE.

⁶ Institute of Molecular Biology & Biotechnology, Foundation for Research and Technology Hellas (FORTH), Heraklion, Crete, Greece

⁷Departments of Physiology/Pharmacology, The Robert F. Furchgott Center for Neural and Behavioral Science, SUNY Downstate Medical Center, Brooklyn, NY, USA

⁸ Department of Pathology, Faculty of Medicine, Ain Shams University, Cairo, Egypt

⁹ Center for Molecular and behavioural Neuroscience, Rutgers University, Newark, NJ, USA

¹⁰ Palestinian Neuroscience Initiative, Faculty of Medicine, Al-Quds University, Abu Dis, Jerusalem, Palestine

¹¹ Wroclaw Medical University, Department and Clinic of Psychiatry, Wroclaw, Poland

¹² Wroclaw Medical University, Department of Genetics, Wroclaw, Poland

¹³ School of Medicine, Mansoura University, Mansoura, 35516, Egypt.

¹⁴ International Islamic University Malaysia, Jalan Gombak, Selangor, 53100Malaysia

¹⁵ Clinical Pharmacology Department, Menoufia Medical School, Menoufia University and American University in Cairo, 75419, Egypt.

¹⁶ Univ. Lille, CNRS, CHU Lille, UMR 9193 - SCALab - Sciences Cognitive Sciences Affectives, F-59000 Lille, France.

¹⁷ Norwich Medical School, University of East Anglia, Norwich, UK.

¹⁸ Dementia and Complexity in Later Life, NHS Norfolk and Suffolk Foundation Trust, UK.

To whom correspondence should be addressed:

Ahmed A. Moustafa,

School of Social Sciences and Psychology & Marcs Institute for Brain and Behaviour, Western Sydney University, Sydney, NSW.

Email: a.moustafa@westernsydney.edu.au

*Both authors contributed equally to this manuscript.

Key words: Alzheimer's disease, genetics, clinical implications, Amyloid beta, AChE, BChE, EOAD, LOAD, APP, Presenilin, Immunotherapy, prevalence vs. penetrance of genes.

Acknowledgement:

HA and NZ are funded by the United Arab Emirates University (CIT 31T085 Fund).

MH is funded by Alzheimer's Research UK and Wellcome Trust.

Abbreviations

AChE: Acetylcholinesterase,

AD: Alzheimer`s disease,

APP: Amyloid Precursor Protein,

Apo E: Apolipoprotein E,

A β : Amyloid beta,

BChE: Buterylcholinesterase

CSF: Cerebro Spinal Fluid,

ERC: Entorhinal Cortex,

EOAD: Early onset alzheimer disease,

LOAD: Late onset alzheimer disease,

MTL: Medial Temporal Lobe,

NFT: Neuro Fibrillary Tangles,

PSEN: Presenilin,

SNP: Single nucleotide polymorphism,

Abstract

In this review, we discuss the genetic etiologies of Alzheimer's disease (AD). Further, we review genetic links to protein signaling pathways as novel pharmacological targets to treat AD. Moreover, we also discuss the clumps of AD mediated genes according to their single nucleotide polymorphism mutations. Rigorous data mining approaches justified the significant role of genes in AD prevalence. Pedigree analysis and twin studies suggest that genetic components are part of the etiology, rather than only being risk factors for AD. The first autosomal dominant mutation in amyloid precursor protein (*APP*) gene was described in 1991. Later, AD was also associated with mutated early-onset (Presenilin1/2, *PSEN1/2* and *APP*) and late-onset (Apolipoprotein E, *ApoE*) genes. Genome-wide association and linkage analysis studies with identified multiple genomic areas have implications for the treatment of AD. We conclude this review with future directions and clinical implications of genetic research in AD.

1- Introduction

Alzheimer's disease

Alzheimer's disease (AD) is the most common form of dementia. Age is the strongest risk factor for AD. The projected growth of elderly population (65 years and older) worldwide means that AD cases will increase by 15-25% by 2050 (Alzheimer's Association, 2014). If no preventive or curative measures are available, this growing number of elderly will pose a huge burden on our societies with AD patients to triple by the mid of the 21st century (Brookmeyer, Johnson, Ziegler-Graham, & Arrighi, 2007). Indeed, the cost of AD is currently estimated to be \$100 billion per year in the United States; \$26 and \$7 billion of which account for lost productivity of caregivers and for long-term health care, respectively. Therefore, there is an urgent need to develop better diagnostic, management and treatment options for patients to allow delaying or preventing disability; hence, reduce the financial and emotional costs associated with AD (Bastin & Salmon, 2014).

Current early identification and diagnosis of AD is strongly focused on clinical features such as memory loss, which can be accompanied by a complex array of other cognitive and behavioral symptoms. These clinical features have been related to the onset and spread of underlying amyloid and tau pathology in AD in the brain. Although, the substantial advances made over the years have identified that amyloid and tau pathology are the potential cause of AD, the sequence of events that lead to neuronal loss or dysfunction in dementia are still unclear. An understanding of these underlying mechanisms will form the basis for devising better strategies for diagnosis, prevention, and treatment (Lippa et al., 2000). Indeed, in particular, genetic risk factors have been little taken into account so far at the clinical level, which have a great potential to reduce risk or even delay the onset of AD. In this article, we review the literature on the underlying genetic underpinnings of AD. We hope that this will inform new clinical approaches to take this information into account.

AD is characterized by the formation of senile plaques and neurofibrillary tangles. The senile plaque core consists primarily of the 4 kDa amyloid β (A β) peptide, which is derived from the amyloid precursor protein (APP) through proteolytic processing by recently identified proteases β and gamma (γ)-secretases. The A β peptides of 40 and 42 residues are normally present in the brain, CSF and plasma of normal individuals and are constitutively secreted from cultured cells, suggesting that these peptides do not intrinsically cause AD. However, the levels of A β 42, the major species of A β deposited in AD brain, are increased by all identified mutations linked to familial AD. Recent studies have shown that in conventional sporadic AD, as in familial AD, there are genetic determinants that result in an increase in levels of A β 42 in the plasma. Therefore, taking family history and other genetic factors into account, high plasma A β levels may serve as a useful diagnostic marker for predisposition to AD.

Evidence suggests that AD is caused by the deposition of A β 42, which forms toxic aggregates of senile plaques. Thus, the regulation of A β 42 to lower physiological levels may be an important therapeutic goal for the prevention of amyloidosis in AD. The mechanism by which amyloid deposition eventually leads to neurodegeneration and dementia remains unknown. In fact, its role as the predominant cause of AD has been questioned, as A β plaques have been seen in healthy aged individuals with no signs of dementia. Furthermore, the severity of dementia is more closely correlated with numbers of neurofibrillary tangles than with senile plaques. Nevertheless, both observations can be readily explained by assuming that amyloid deposition is an early step in a sequential cascade, which eventually leads to neuronal loss. The genesis of the neurofibrillary tangles may be closely linked to the amyloid induced neuron loss, either as a direct cause or as a consequence. Understanding the pathways for the induction of neurofibrillary tangles by A β may provide useful therapeutic targets and diagnostic markers to cure AD (Hansell et al., 2015).

An overview of genetic etiology of AD

AD is believed to result from a series of steps in pathogenic pathways leading to amyloid deposition and neurodegeneration in key areas of the brain involved in memory and cognition. Recently, AD is justified as a genetically complex and heterogeneous disorder. Mutations and polymorphisms in multiple genes (*APP*, *PSEN1*, *PSEN2* and *ApoE*), which are located on at least four different chromosomes (1, 14, 19, and 21), are directly involved in AD (Ridge, Mukherjee, Crane, & Kauwe, 2013). Besides *APP*, products of other gene (mainly proteins) are also associated with AD. The *APP*, *PSEN1* and *PSEN2* follow the dominant inheritance pattern and lead to early-onset AD (EOAD) with 100% virtually penetrance, while inheritance of *ApoE* (e4) allele has strong increasing influence on the development of AD at an earlier age-. [The Early-onset familial Alzheimer's disease \(EO-FAD\) is also a condition characterized by early onset dementia \(age at onset < 65 years\) and a positive family history for dementia](#) (Bird, 2008; Wu et al., 2012). There are some recent reports of a susceptibility locus for AD on chromosome 10 and a genetic linkage of AD to its sister chromatid. A linkage of plasma A β 42 to a quantitative locus on chromosome 10 in the late-onset Alzheimer's disease (LOAD) pedigree has also been observed (Shen et al., 2014). Alternative theories about AD, such as considering the AD process as similar to cancer due to a loss of cell cycle control or viewing AD as a result of a dysfunctional signaling pathway mediated by APP, has also been proposed (Bali, Gheinani, Zurbriggen, & Rajendran, 2012). Further, other approaches, such as nutritional and environmental factors in AD are being studied (van de Rest, Berendsen, Haveman-Nies, & de Groot, 2015). The depiction of genes and their involvement in AD is illustrated in Fig. 1.

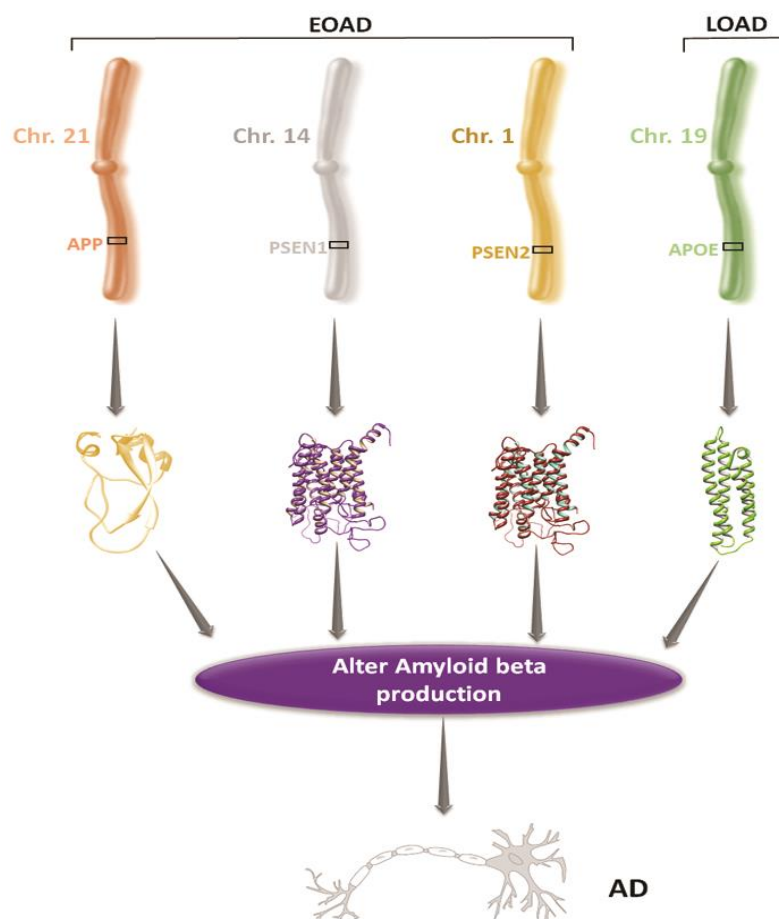


Figure 1: The involvement of some salient genes in the prevalence of AD. Four different chromosomal location depictions are represented by maroon, purple, yellow and green colors for genes APP, PSEN1, PSEN2 and ApoE, respectively. The gene mediated proteins are also highlighted in same colors which govern β peptides in irregular fashion resulting in AD. Three genes APP, PSEN1 and PSEN2 are related to EOAD, while ApoE is related to LOAD.

AD risk genes and mechanisms of disease pathogenesis

There are some other genes that may cause AD by genetic alterations. Many genetic studies including mutational databases analysis showed that monogenic mutation of a single gene may cause AD by a single nucleotide polymorphism (SNP). Multiple emerging genetic studies have listed various mutations and polymorphisms may contribute to the development of AD. These genes follow the Mendelian pattern of inheritance and serve as risk factors in both EOAD and LOAD (Karch & Goate, 2015). Here, we enlist 31 genes with encoded proteins, which are associated with AD or can modestly increase the AD risk (see Table 1 for details).

Human gene mutations database (<http://www.hgmd.cf.ac.uk/ac/index.php>) also justified that *APP* possess 35 mutations that are associated with AD. Similarly, *PSEN1*, *PSEN2* and *ApoE* contain

165, 13 and 13 mutations, respectively. *ADAM10*, *CRI* and *BIN1* are also reported as AD-associated genes.

ADAM10

Wolfsberg, Primakoff, Myles, and White (1995) identified several proteins as members of the ADAM family, including ADAM10 and purification of ADAM10 as a TNF-processing enzyme from membrane extracts of a human monocytic cell line (Rosendahl et al., 1997). *ADAM10* is located on chromosome 15 having total size of 161,172 bases (Prinzen, Muller, Endres, Fahrenholz, & Postina; Yamazaki, Mizui, & Tanaka; Yavari, Adida, Bray-Ward, Brines, & Xu). Functionally, ADAM10 splits ephrin (Eph family receptor), within the ephrin/eph complex and moulded between two cell surfaces. After separating ephrin from opposing cells, the ephrin/eph complex is endocytosed. This shedding event in trans had not been previously exposed, but may be intricate in other shedding events (Janes *et al.*, 2005; Haass *et al.*, 2012). In neuronal cells, the ADAM10 enzyme is functionally involved in proteolytic activity of the AMPs with α -secretase (Haass *et al.*, 2012). The missense mutational effects in ADAM10 pro-domain are directly linked with LOAD. In Tg2576 AD mice two rare mutations (Q170H and R181G) impair the pro-domain chaperon functions, decreasing the α -secretase activity, and reducing the adult hippocampal neurogenesis. By knowing such functional effects, presently it has been suggested that ADAM10 could be a novel target for treating AD (Suh *et al.*, 2013). It has also been shown that ADAM10 gene product in synaptic junctions may interact with AP2 and cause AD (Marcello et al., 2013).

CRI

The *CRI* gene present on chromosome 1 which encodes the Complement Receptor Type 1 (CR1) protein (Weis et al.). Genetic studies have shown that various mutations of CR1 are associated with the development of AD (Schjeide *et al.*, 2011). Furthermore, AlzGene meta-analysis also show that *CLU*, *PICALM* and *CRI* SNPs are associated with the development of AD (Corneveaux *et al.*, 2010). A detailed replication study also provides additional evidence that CR1 is related to the risk of developing LOAD (Carrasquillo *et al.*, 2010). The multiple alleles of *CRI* have been observed in association with LOAD (J.-C. Lambert et al., 2009). GWAS study identified the variants of CR1 have significant association with AD (Fonseca *et al.*, 2016).

BIN1

Bridging integrator 1 (BIN1) also known as amphiphysin 2, is a novel human gene product with features of a tumor suppressor protein (Negorev et al., 1996). ~~It is a protein~~ encoded by the *BIN1* gene present on chromosome number 2 (Negorev et al., 1996). ~~BIN1 is a tumor suppressor protein~~

~~(Kinney et al., 2008)~~. Various BIN1 isoforms which are expressed in the CNS may be involved in synaptic vesicle endocytosis. In the CNS, the *BIN1* gene expression can interact with some other regulatory signaling proteins such as synaptojanin, endophilin, and clathrin. Mouse model study showed that the *BIN1* gene is critically involved in the cardiac muscle development (Alexander et al., 2003). Moreover, mutations in the *BIN1* gene also cause centronuclear myopathy (i.e, the condition which is characterized by muscle weakness) by interfering with remodeling of T tubules and/or endocytic membranes, and that the functional interaction between BIN1 and DNM2 is necessary for normal muscle function and positioning of nuclei (Nicot et al., 2007). The genome-wide association study (GWAS) showed that *BIN1* is significantly associated with AD (Carrasquillo et al., 2011; Hu et al., 2011). The BIN1 protein and its seven isoforms are expressed in the brain and interact with clathrin and AP2/ α -adaptin (CLAP) proteins and lead to endocytosis. Epigenetic studies suggested that the *BIN1* gene acts in AD pathogenesis and might be considered as a novel target for AD therapy (Tan, Yu, & Tan, 2013). The exact mechanisms of *BIN1* polymorphism and how it leads to AD are still unknown. However, it has been observed that genetic variation in *BIN1* confers AD risk by changing tau pathology (Chapuis et al., 2013).

CD2AP

Mutations in other known genes such as *CD2AP*, *EPHA1*, *MS4A6A/MS4A4E*, *ABCA7* and *CD33* were also found to lead to AD symptoms (Hollingworth et al., 2011). CD2-associated protein (CD2AP) is a human protein encoded by the *CD2AP* gene located on chromosome 6 (Lowik et al.). Generally, *CD2AP* gene is involved in the molecular scaffolding which regulates the cytoskeleton of actin protein (Cochran, Rush, Buckingham, & Roberson). Furthermore, CD2AP protein also interacts with filamentous actin and various other membrane embedded proteins by different actin binding sites. In *CD2AP*, the rs9296559 and rs9349407 SNPs are directly associated with LOAD risk (Naj et al., 2011; Hollingworth et al., 2011). The rs9349407 SNP of *CD2AP* is correlated with neuritic plaques formations in brains of AD patients (Shulman et al., 2013). A recent meta-analysis of 74,046 individuals showed that the rs10948363 SNP is a risk factor for AD (Lambert et al., 2013). However, the functional impact of this SNP remains unknown since the *CD2AP* gene expression is not changed in AD brains (Karch et al., 2012).

The *CD2AP* Knockdown ortholog drosophila model of AD displays tau neurotoxicity (Dustin et al., 1998). The CD2AP mediates functional effects and plays a significant role in the blood-brain barrier (BBB) integrity and cerebrovascular circulation, which could contribute to its effects on AD risk (Nicholas et al., 2015). Polymorphisms in the endocytosis and synaptic function associated genes (*BIN1*, *PICALM*, *CD2AP*, *EPHA1*, and *SORL1*) were identified as LOAD risk factors in several

GWAS (Harold *et al.*, 2009; Naj *et al.*, 2001; Hollingworth *et al.*, 2011; Lambert *et al.*, 2013). CD2AP is known as a scaffold adaptor protein (Dustin *et al.*, 1998). It interacts with cortactin, which plays an important role in the regulation of receptor-mediated endocytosis (Lynch *et al.*, 2003). The allelic polymorphism data show that polymorphism of the CD2AP gene is a risk factor for AD (Cochran *et al.*, 2015).

EPHA1

Maru, Hirai, Yoshida, and Takaku (1988) reported the general characterization of the novel receptor tyrosine kinase gene, called EPH. EPH receptor A1 (EPHA1) is a protein encoded by the *EPHA1* gene. *EPHA1* gene is present on chromosome 7q34. The *EPHA1* SNP rs11767557 is related to reduce LOAD risk (Naj *et al.*, 2011; Hollingworth *et al.*, 2011). A recent GWAS data showed that the rs11771145 polymorphism was also associated with reduced LOAD risk (Lambert *et al.*, 2013). However, there is no indication that mRNA expression of *EPHA1* is changed in AD brains (Karch *et al.*, 2012). EPHA1 also plays a significant roles in cell and axonal guidance and synaptic plasticity (Martinez *et al.*, 2005; Lai *et al.*, 2009; (Lai & Ip, 2009). EPHA1 is expressed by CD4-positive T lymphocytes and monocytes (Sakamoto *et al.*, 2011). Moreover, its assessment of genetic variation in this gene revealed that it plays a role in the pathogenesis of AD (Carrasquillo *et al.*, 2011).

MS4A

MS4A is a family of genes such as MS4A4A, MS4A4E, and MS4A6E which are poorly characterized. MS4A is structurally similar to CD20 (Howie *et al.*, 2009). FISH and radiation hybrid analysis mapped the MS4A5 gene to chromosome 11q12-q13 in a cluster with MS4A1, MS4A2, and MS4A3 (Hulett *et al.*, 2001). The MS4A genes are expressed in monocytes and myeloid cells. In GWAS, two SNPs including rs983392 (near MS4A6A) and rs670139 (near MS4A4E) were recognized as LOAD risk alleles (Naj *et al.*, 2011; Hollingworth *et al.*, 2011; Lambert *et al.*, 2013). The rs670139 SNP is associated with increased LOAD risk, while rs983392 is correlated with reduced LOAD risk. The SNP variants in MS4A6A were found to be related to AD symptoms. The heterozygous AD patient study further supported this association. On inhibition of its expression, it shows neuroprotective effects (Proitsi *et al.*, 2014).

PICALM

Phosphatidylinositol binding clathrin assembly (PICALM) protein is significantly involved in clathrin assembly, cellular trafficking and regulation of endocytosis. It is tightly associated with iron homeostasis and cell proliferation (Stern *et al.*, 2014). *PICALM* gene is present on chromosome 11q14 (Stern *et al.*) and mostly expressed in neurons (Xiao *et al.*, 2012). Recent studies have demonstrated that rs3851179 and rs541458 of *PICALM* are directly correlated with reduced LOAD risk (Harold *et*

al., 2009; Lambert *et al.*, 2013; Lambert *et al.*, 2009). However, the functional effects of these SNPs still remain unclear. *PICALM* is also functionally involved in synaptic vesicle fusion to the presynaptic membrane through the trafficking of VAMP2 protein (Harel *et al.*, 2008). Mice study showed that, deficiency of *PICALM* results in abnormal iron metabolism and have no overt neurologic phenotypes (Duce *et al.*, 2010). The in-vitro analysis showed that the expression of *PICALM* changes the APP trafficking, whereas in-vivo results depicts that overexpression of *PICALM* enhances the plaque deposition in AD transgenic mice (Xiao *et al.*, 2012).

CLU

Clusterin (*CLU*) is an apolipoprotein encoded by the *CLU* gene located on chromosome 8p21.1 (Dietzsch, Murphy, Kirszbaum, Walker, & Garson). [CLU gene is organized into 9 exons, ranging in size from 47 bp \(exon 1\) to 412 bp \(exon 5\), and spanning a region of 16,580 bp](#) (Wong *et al.*, 1994). Generally, clusterin is involved in complement regulation, apoptosis, lipid transport, membrane protection, and cell-cell interactions (Jones & Jomary, 2002). Various SNPs have been identified in *CLU* that confer protection against LOAD, including rs11136000, rs9331888, rs2279590, rs7982, and rs7012010 (Harold *et al.*, 2009; Naj *et al.*, 2011; Hollingworth *et al.*, 2011). Studies show that the SNPs rs9331888 and rs11136000 are correlated with plasma clusterin levels, whereas rs9331888 is also associated with expression of an alternative splice variant (Castellano *et al.*, 2011; Szymanski *et al.*, 2011; Xing *et al.*, 2012). The mRNA of clusterin is highly expressed in brains of AD patients (Karch *et al.*, 2012; Allen *et al.*, 2012) and can be identified in amyloid plaques (May *et al.*, 1990; Calero *et al.*, 2000). Clusterin likely influences A β clearance, amyloid deposition, and neuritic toxicity. APOE-deficient and clusterin-deficient APP transgenic mice exhibit earlier and more extensive A β deposition compared with control mice (DeMattos *et al.*, 2004). Clusterin is also associated with the complement system. Clusterin modulates the membrane attack complex, where it inhibits the inflammatory response associated with complement activation (Jones & Jomary, 2002). Because neuroinflammation is a hallmark of AD, SNPs that alter clusterin expression or its functions as an amyloid response agent could affect AD pathogenesis and downstream effects. The allelic mutational data show that both genes (*PICALM* and *CLU*) are associated with AD symptoms (Harold *et al.*, 2009).

SORL1

Sortilin-related receptor L (*SORL1*) protein encoded by the *SORL1* gene which is present on 11q23.2 (Jacobsen *et al.*). [SORL1 is a mosaic protein with a domain structure that suggests it is a member of both the vacuolar protein sorting-10 \(Vps10\) domain-containing receptor family and the low density lipoprotein receptor family](#) (Jacobsen *et al.*, 2001). *SORL1* is involved in vesicle trafficking from the cell surface to the Golgi-endoplasmic reticulum. *SORL1* is known as an AD risk

gene in candidate-based approaches (Rogaeva *et al.*, 2007; Lee *et al.*, 2008). A recent GWAS of 74,046 individuals revealed that the rs11218343 polymorphism near *SORL1* is associated with reduced AD risk (Lambert *et al.*, 2013). It has been also shown that brain DNA methylation in *HLA-DRB5* and *SORL1* genes is associated with AD pathology (Yu *et al.*, 2015).

ABCA7

ATP-binding cassette transporter A7 (ABCA7) is encoded by the *ABCA7* gene located on chromosome 19p13.3 (Kaminski, Piehler, & Schmitz). ABCA7 protein is a member of ABC transporter superfamily and important for substrates transportation across cell membranes (Kim *et al.*, 2008). The alternative splicing event in ABCA7 generates two transcripts which are expressed in the brain (Ikeda *et al.*, 2003). ABCA7 gene confers the risk factor for the development of AD upon allelic variation. Genetic variations in ABCA7 gene (c.4416+2T>G and c.5570+5G>C) result in AD susceptibility (Steinberg *et al.*, 2015). There are various SNPs, such as rs3764650 that have been identified as LOAD risk alleles near ABCA7 gene by GWAS analysis (Naj *et al.*, 2011; Hollingworth *et al.*, 2011; Lambert *et al.*, 2013). The rs4147929 SNP was highly susceptible in the meta-analysis of 74,046 individuals (Lambert *et al.*, 2013). The impact of these polymorphisms on ABCA7 gene function and in AD is still poorly understood (Karch *et al.*, 2012, Vasquez *et al.*, 2013). The mRNA expression of ABCA7 in autopsy brain tissue is also correlated with advanced cognitive decline (Karch *et al.*, 2012; Vasquez *et al.*, 2013). In vitro analysis showed that A β secretion is inhibited by ABCA7 through the stimulation of cholesterol efflux (Chan *et al.*, 2008). Moreover, ABCA7 also modulates the phagocytic activity of apoptotic cells by macrophages (Jehle *et al.*, 2006). It has been observed that ABCA7 may lead to the development of AD by clearing A β aggregates or cholesterol transfer to APOE (Chan *et al.*, 2008; Wildsmith *et al.*, 2013).

CD33

Sialic Acid Binding Ig-Like Lectin 3 (CD33) is a receptor molecule located on chromosome 19q13.3 (Trask *et al.*). CD33 is highly expressed on microglia and myeloid cells (Crocker *et al.*, 1997; Malik *et al.*, 2013; Griuciuc *et al.*, 2013). The LOAD GWAS analysis showed that, CD33 SNPs (e.g., rs3865444) have been found to reduce LOAD risk (Naj *et al.*, 2011; Hollingworth *et al.*, 2011; Bertram *et al.*, 2008; Sullivan, Daly, & O'Donovan, 2012). The rs3865444 and rs12459419 SNPs are associated with increase in CD33 in lacking and modulating the exon 2 (splicing event), respectively (Malik *et al.*, 2013). A recent analysis of data from 74,046 individuals showed that the rs3865444 SNP is failed to attain the genome-wide significance. However, studies suggest that CD33 may play a significant role in AD (Lambert *et al.*, 2013). It has been found that the mRNA expression of CD33 is enhanced in microglia, while the expression in autopsy brain tissue is correlated with advanced cognitive decline

(Karch *et al.*, 2012; 53, Griciuc *et al.*, 2013). The inhibition of A β phagocytosis effect in immortalized microglial of CD33 is abolished due to a lack of exon 2 (Griciuc *et al.*, 2013). The allelic SNP such as rs3865444 is correlated with reduced CD33 mRNA expression and insoluble A β 42 in brains with AD (Griciuc *et al.*, 2013). Another significant function of CD33 is A β clearance and mediation of neuroinflammatory pathways through microglia in the brain (Griciuc *et al.*, 2013).

PTK2B

Protein tyrosine kinase 2 beta which is encoded by the *PTK2B* gene [located on 8p21.2](#) (Herzog, Nicholl, Hort, Sutherland, & Shine) is midway between neuropeptide-activated receptors or neurotransmitters that may enhance Ca⁺² flux and cascade of mediating signaling like MAPK (Pandey *et al.*, 1999). Another study shows that focal adhesion kinase CAK β /Pyk2 is directly involved in the long-term potentiation of region CA1 of the hippocampus (Huang *et al.*, 2001). One recent GWAS of 74046 Caucasian individuals on SNPs (rs10498633) in *SLC24A4* gene showed that this allele is associated with LOAD risk (Lu *et al.*, 2016). In another GWAS, other genes such as *RIN3*, *DSG2*, *INPP5D* and *MEF2C* were found to play key roles in the development of AD. Furthermore, other reported genes (*NME8*, *ZCWPW1*, *NYAPI*, *CELF1*, *MADD*, *FERMT2* and *CASS4*) are also associated with the risk of developing AD (Karch, Cruchaga, & Goate, 2014; Karch & Goate, 2015). Another gene, *TREM2*, also causes autosomal recessive form of dementia-like symptoms after homozygous mutations (Paloneva *et al.*, 2002). A significant missense mutation (rs75932628-T) in *TREM2* gene was observed to be associated with AD (Hickman & El Khoury, 2014; Lue, Schmitz, & Walker, 2015). The phospholipase D protein that is encoded by *PLD* is involved in catalyzing the hydrolysis of phospholipids membrane. Mutations in *PLD* gene are associated with AD (Wang *et al.*, 2015).

Prevalence and penetrance of genes in AD

Polymorphisms associated with AD appear with various prevalence and penetrance. While variation in some genes is more penetrant (i.e., genes that will definitely lead to develop AD), other variants have low prevalence (i.e., do not commonly occur in AD). Three known genes (*APP*, *PSEN1* and *PSEN2*) are significantly involved in the prevalence of autosomal dominant AD through fully penetrant mutations (Van Cauwenberghe, Van Broeckhoven & Sleegers, 2015). Research showed that mutations in the *APP* gene have a 100%-penetrance, mostly in carriers (Tanzi, 1999).

The autosomal dominant mutations in *APP* and the *PSEN1/2* are recognized as having low prevalence/incidence and high pathobiological impact (early age of onset) (Tanzi, 1999). In detailed analysis, the *PSEN1* mutation causes a severe form of AD with complete penetrance and has a wide variability of onset age (25-65 years), rate of progression, and disease severity (Cruts *et al.*, 2012). In contrast, missense mutations carriers in *PSEN2* have incomplete penetrance and mostly affect older

age (39-83 years) of onset disease, but the age of onset is highly variable among *PSEN2*-affected families (Sherrington *et al.*, 1995; Sherrington *et al.*, 1996; Jayadev *et al.*, 2010). The EOAD mutations are related to calamitous phenotypic consequences that present early in the adult life. Therefore, such mutations govern some biological impact and are exceedingly rare. In contrast, the *APOE* E4 polymorphism has a relatively high prevalence, but is weakly penetrant, and carries a low biological impact, as found by the relatively late onset of symptoms (Tanzi, 1999). Genin and colleagues reported that *APOE* E4 is consistent with semi-dominant inheritance of a moderately penetrant gene on the basis of Caucasian ancestry using Rochester (USA) incidence data (Genin *et al.*, 2011).

Two more genes, such as *SORL1* and *ABCA7*, which are directly involved in AD, have rare variants and seem to have higher penetrance. However, the rare variants of *CLU* have low penetrance (Van Cauwenberghe, Van Broeckhoven & Sleegers, 2015). Kim and colleagues reported that two LOAD-associated mutations in *ADAM10* would appear to be strong candidates for the first rare, highly penetrant pathogenic mutations to be genetically associated with LOAD (Kim *et al.* 2009). Rare highly penetrant mutations in the *ADAM10* gene, Q170H and R181G were also reported in 7 out of 1000 LOAD families. Both mutations are located in the prodomain region and dramatically impair the ability of ADAM10 to cleave APP at the α -secretase site of APP *in vitro* and *in vivo* (Kim *et al.*, 2009).

In conclusion, while APP and PSEN1/2 are highly penetrant and are associated with AD, *APOE* polymorphism has a high prevalence. Moreover, other rare genetic variants with high penetrance and low prevalence such as *SORL1*, *ADAM10* and *ABCA7* are directly involved in AD pathology. Conversely, other rare variants with low penetrance and high prevalence effects such as *CLU* have also been linked to AD.

Although it is controversial whether mutations in the microtubule-associated protein tau (*MAPT*) gene are associated with AD, they were found to be linked to frontotemporal dementia (Goedert & Spillantini, 2001). Only one mutation in *MAPT* has been associated with AD-like dementia, but it has not been shown to cause AD (Ostojic *et al.*; Rademakers *et al.*, 2003). One study revealed that mutations in *MAPT* can cause familial frontotemporal dementia (Wilhelmsen, Lynch, Pavlou, Higgins, & Nygaard, 1994), and four other mutations (R406W, V337M, G272V, and P301L) have been shown to promote hyperphosphorylation and aggregation of tau protein (Alonso, Mederlyova, Novak, Grundke-Iqbal, & Iqbal, 2004; Iqbal, Liu, Gong, & Grundke-Iqbal, 2010). The aggregates of hyperphosphorylated wild type *tau* protein have a prevalent pathology of AD and other sporadic tauopathies, and they induce disruption of the microtubules (King *et al.*, 2006). The inhibition of the phosphorylation/aggregation or increased clearance of tau can prevent a molecular cascade that leads to cellular death (Iqbal, Liu, & Gong, 2016; Ittner *et al.*, 2010; Piedrahita *et al.*, 2010). Based on

its therapeutic functionality, tau protein is considered to be a target of interest in AD (Iqbal et al., 2016). In addition to *APP* and *PSEN1*, there are some studies on other genes which are considered target molecules for AD treatment (Dingwall, 2001). Finally, APP has been proposed to be linked with kinesin-I, a motor protein and forms a dimeric complex. This possible functional interaction between kinesin-I and APP may implicate the role of alterations in kinesin-I based transport in the development of AD (Naj et al., 2014).

Many genes along with their risk assessments are still under investigation to confirm their association with AD. However, the largest risk factor for AD is age: cases double with every 5 years between the age of 65 and 85 years. Up to date, there are several risk factors that are known to lead to EOAD. The mutation in *APP* accounts for familial AD. The significance of the *APP* gene is confirmed by the emergence of EOAD in patients with Down’s syndrome who have an additional copy of this gene. However, the mechanism by which these genetic alterations influence the amyloid beta ($A\beta$) formation remains unclear. Additionally, the E4 allele of *APOE* constitutes a major susceptibility factor for the development of the familial and sporadic forms of LOAD. The prevalence of AD has increased up to 20% among those individuals aged 80 years and older. This may depict that there are some other risk factors that may govern AD symptoms. For example, the transcriptional control of *APP* has not yet been fully explored (Reitz & Mayeux, 2014). Genetic variations in *CLU* (previously known as apolipoprotein J) have been associated with the risk of AD in multiple independent GWAS of diverse ethnic groups. The relationship between clusterin levels and the risk for stroke in the current analysis showed that both stroke and dementia share some common factors. It has been observed that clusterin was also found to alter the risk of cardiovascular and metabolic diseases which was observed by measuring the clusterin (α , β) and C-reactive protein levels (Weinstein et al., 2016).

Table 1. Mutations in genes associated with AD. “–” means information on prevalence and penetrance of genes are not known.

Genes	Encoded proteins	Locations	Mutations	Penetrance	Prevalence
<i>APP</i>	Amyloid precursor protein	21q21.3	35	high	low
<i>PSEN1</i>	Presenilin 1	14q24.3	165	high	low
<i>PSEN2</i>	Presenilin 2	1q31-q42	13	high	low
<i>ApoE</i>	Apolipoprotein-E	19q13.2	13	low	high
<i>ADAM10</i>	ADAM Domain 10	15q21.3	1	high	low
<i>CRI</i>	Complement Component 3b/4b Receptor 1	1q32	8	-	-

<i>BINI</i>	Bridging Integrator 1	2q14	1	-	-
<i>CD2AP</i>	CD2-Associated Protein	6p12	1	-	-
<i>EPHA1</i>	EPH Receptor A1	7q35	1	-	-
<i>CLU</i>	Clusterin	8p21.1	5	low	high
<i>MS4A6A</i>	Membrane Spanning 4-Domains A6A	11q12.1	1	-	-
<i>PICALM</i>	Phosphatidylinositol Binding Clathrin Assembly Protein	11q14	1	-	-
<i>ABCA7</i>	ATP Binding Cassette Subfamily A Member 7	19p13.3	1	high	low
<i>CD33</i>	CD33 molecule	19q13.3	1	-	-
<i>HLA-DRB5</i>	Major Histocompatibility Complex, Class II, DR Beta 5	6p21.32	8	-	-
<i>PTK2B</i>	Protein Tyrosine Kinase 2 Beta	8p21.1	1	-	-
<i>SORL1</i>	Sortilin-Related Receptor, L(DLR Class) A Repeats Containing	11q23.2-q24.2	6	high	low
<i>SLC24A4</i>	Solute Carrier Family 24 Member 4	14q32.12	8	-	-
<i>RIN3</i>	Ras And Rab Interactor 3	14q32.12	1	-	-
<i>DSG2</i>	Desmoglein 2	18q12.1	1	-	-
<i>INPP5D</i>	Inositol Polyphosphate-5-Phosphatase D	2q37.1	1	-	-
<i>MEF2C</i>	Myocyte Enhancer Factor 2C	5q14	17	-	-
<i>NME8</i>	NME/NM23 Family Member 8	7p14.1	1	-	-
<i>ZCWPW1</i>	Zinc Finger CW-Type And PWWP Domain Containing 1	7q22.1	1	-	-
<i>NYAP1</i>	Neuronal Tyrosine Phosphorylated Phosphoinositide-3-Kinase Adaptor 1	7q22.1	1	-	-

<i>CELF1</i>	CUGBP, Elav-Like Family Member 1	11p11.2	1	-	-
<i>MADD</i>	MAP Kinase Activating Death Domain	11p11.2	1	-	-
<i>FERMT2</i>	Fermitin Family Member 2	14q22.1	1	-	-
<i>CASS4</i>	Cas Scaffolding Protein Family Member 4	20q13.31	1	-	-
<i>TREM2</i>	Triggering Receptor Expressed On Myeloid Cells 2	6p21.1	7	-	-
<i>PLD3</i>	Phospholipase D Family Member 3	19q13.2	1	-	-

Research on AD is rapidly expanding and currently encompasses various cellular, molecular, clinical and therapeutic aspects. Reviewing all these diverse areas is beyond the scope of the present work. However, we will briefly address the salient features of the definitive review work of other investigators in different fields of AD. The molecular genetics of AD and its relationship to other primary neurodegenerative diseases have recently been reviewed (Karch et al., 2014). There are also recent studies which explore some protein molecules that are believed to play a role in AD pathogenesis. For example, the cell biology of AD, particularly the roles of secretases (α , β , and γ), presenilin 1/2 and notch have been reviewed (J. Lambert et al., 2013).

Below, we discuss how genes affect the following aspects of AD: (a) memory, (b) amyloid plaques formation and tangle deposition, and (c) neurotransmitters related to AD.

2- Genes and their influence on memory in AD

Progressive memory deterioration is the hallmark feature of AD that results from a number of genetic factors. Because procedural memory is generally preserved in AD (Van Halteren-Van Tilborg, Scherder, & Hulstijn, 2007), declarative memory is mainly the target of AD studies, which are predominantly focused on the episodic memory subset. Episodic memory is one's collection of interior events and the spatial-temporal-emotional context in which they occurred (Tulving, 1972). Episodic memory is strongly associated with the medial temporal lobe, in particular the hippocampus and entorhinal cortex, which are impacted by the progression of AD (Braak & Braak, 1991).

Unsurprisingly, AD related deficits in episodic memory have widely been found to involve the mediotemporal lobe and related neural networks (D. A. Wolk, Dunfee, Dickerson, Aizenstein, &

Dekosky, 2011). A relationship between reduced hippocampal volume and episodic memory has been observed by multiple lines of AD research (Choo et al., 2010; Mormino et al., 2008; Sexton et al., 2010). Additionally, studies have found that patients with AD show deterioration of semantic memory, which directly influences episodic memory in the area of recognition and reflects the damage to the hippocampus that occurs early in AD pathogenesis (Drebing et al., 1994).

Genetic factors play a key role in understanding why memory deterioration is characteristic for AD. Expression of the APOE E4 allele is a strong risk factor for AD. Further, AD patients who are carriers of this allele tend to perform more poorly on episodic memory tasks than non-carriers (Van Der Vlies et al., 2007). A dose-dependent relationship between *APOE E4* and episodic memory task performance has been observed (Kerchner et al., 2014). Moreover, a mouse model with induced expression of *APOE E4* showed spatial memory deficits and neuronal network dysfunction in the hippocampus, especially in aged mice that were dependent of hippocampal interneurons loss (Andrews-Zwilling et al., 2010; Gillespie et al., 2016). In humans, young *APOE E4* carriers have a dysfunction in spatial navigation, and disarray of grid-cell like representations in the entorhinal cortex with fMRI during a spatial navigation task (Kunz et al., 2015). *APOE E4* may contribute to memory impairment by augmenting *APP* recycling, thereby increasing the production of A β peptides. The accretion of A β senile plaques and tau-related NFTs have been attributed to cognitive decline in AD; however, there is now substantial evidence that the soluble variants of A β and tau are associated with memory loss in AD (see(Ashe & Zahs, 2010)for a review).

Rodent studies can give us clearer insight into the relationship between genes and memory, as they are thought to have comparable hippocampus-based memory systems to that of primates (Eriksen & Janus, 2007). These studies have found that periodical injections of synthetic A β into normal rats have resulted in transient memory deficits for a sequence lever pressing task (Cleary et al., 2005). Further, injecting normal rats with A β from AD patients significantly impaired rats' memory of earned behavior in a passive avoidance task (Shankar et al., 2008). Additionally, in a mouse study, it was observed that extracellular accumulation of a 56-kDa soluble A β assembly, named A β *56, in young mice disrupted memory (Lesné et al., 2006).

It is thought that A β activates the phosphorylation of tau proteins (Hernández & Avila, 2010), and it is widely accepted that the accumulation of hyper-phosphorylated tau and resulting neurofibrillary tangles are also implicated in AD memory decline. It has been found that neurofibrillary tangles are not solely responsible for AD memory disturbance (Santacruz et al., 2005). Studies on the toxicity of tau oligomers support this theory. Injecting mutant tau mice with tau oligomer antibodies has shown to improve working memory as well as to maintain the improvement for 2 months (Castillo-

Carranza et al., 2014). When pro-aggregants of tau expression are turned off in mice displaying neurological features of AD, their impaired memory is improved (Sydow et al., 2011).

Damage to episodic memory-related brain structures, such as the medial temporal lobe can, at least partly, account for the relationship between aberrant gene expression and memory decline in AD. *APOE E4* has a thinning effect on areas of the brain related to episodic memory including the medial temporal lobe (Geroldi et al., 1999; Pievani et al., 2009; David A. Wolk & Dickerson, 2010); in particular, the hippocampus (Kerchner et al., 2014). A β plaque deposition in humans has a direct link to hippocampal volume which may mediate the relationship between A β accumulation and episodic memory (Mormino et al. (2008). Compared to other brain regions, the medial temporal lobe is the site of a disproportional amount of neurofibrillary tangles (Nestor, Fryer, & Hodges, 2006; D. A. Wolk et al., 2011). Tau aggregation and neurofibrillary tangles density in the hippocampus are strong correlates with spatial memory impairment (Mustroph, King, Klein, & Ramirez, 2012) as well as symptom severity and cognitive decline in AD (Braak & Braak, 1991).

Memory impairment in AD may also be due to disruptions in neural circuitry, such as the progression of neurofibrillary tangles damage to the projection neurons that connect the hippocampus to other parts of the brain. It has been observed that neurofibrillary tangles follow a specific trajectory of accumulation in the entorhinal cortex similar to the pattern on AD neurodegeneration (Braak & Braak, 1991). Neurofibrillary tangles can affect the hippocampal network by disconnecting the hippocampus from the cerebral cortex (De Calignon et al., 2012). A mouse model for AD (mutated *APP* expression driven only in the entorhinal cortex) showed a trans-synaptic spread of AD pathology that mimicked the natural history of the disease (Harris et al., 2010; Khan et al., 2014; Liu et al., 2012). Induction of over-expression of mutated human APP and tau in the EC layer II/III spread to specific areas of the hippocampus including the dentate gyrus, CA1 and subiculum (De Calignon et al., 2012; Harris et al., 2010; Harris et al., 2012; Khan et al., 2014; Liu et al., 2012). However, cognitive deficits were only observed in mice having overexpression of mutated human *APP* in the entorhinal cortex, whereas the overexpression of mutated human tau did not cause cognitive decline in the animals (Harris et al., 2010; Harris et al., 2012). Oligomeric A β accumulation and hyper-phosphorylated tau may cause memory deficits by disrupting synaptic plasticity in the hippocampus, such as long-term potentiation (Shankar et al., 2008; Sheng, Sabatini, & Südhof, 2012; Tu, Okamoto, Lipton, & Xu, 2014). Soluble A β oligomers have been found to be synapto-toxic (Haass & Selkoe, 2007; Shankar et al., 2008) and may also alter the neural networks involved in learning and memory (Palop & Mucke, 2010).

3- Genetic influence on amyloid plaques formation and tangle deposition

The most common hypothesis that invokes the implication of APP in the neuronal cell death in AD is the amyloid hypothesis. This hypothesis postulates that deposition of amyloid plaques or partially aggregated soluble A β trigger a neurotoxic cascade, thereby causing neurodegeneration and AD. This theory is based on studies suggesting that A β is toxic to neurons. The transfected cell line study showed that expressing familial AD mutant genes leads to increased A β release. A study showing a close correlation among memory deficits, A β elevation and amyloid plaques in transgenic mice supports the amyloid hypothesis (Guerrero et al., 2009).

A modified version of the amyloid hypothesis postulates that the primary contributor to the etiology of AD lies within the cytoplasmic domain of APP. This has also been used to explain the neurotoxicity of the carboxyl-terminal 99 amino acids fragment of the APP (*APP-C100*), which includes the 42 residues of A β peptide and 57 adjacent amino acids in the carboxyl-terminus of APP. The mechanism underlying the amyloidogenic and the neurotoxic property of *APP-100* fragment is still not known (Cerpa et al., 2008).

However, a recent model has been suggested in which intracellular amyloidogenic fragments, such as *APP-C100*, kill neurons “from inside,” in contrast to the popular hypothesis that extracellular A β causes neurodegeneration “from outside”. The *APP-C100* fragment is a normal metabolic product of APP in the human brain. Recently, Sykora and coworkers showed that a 31-residues of C-terminal fragment was generated by caspase cleavage of APP within its cytoplasmic domain in cells undergoing apoptosis. Expression study justified that 31 residues fragment was sufficient to induce apoptosis. Deletion of 31-residues from *APP-C100* removed its neurotoxicity, suggesting that this region may mediate toxicity. The proteolysis of APP to A β 40 and A β 42 should also yield a cognate C-terminal fragment (CTFg) of 59 and 57 residues, respectively. All conditions that increase the A β 42 production automatically increases CTFg57 fragment. Thus, the observed high correlation between AD and A β 42 levels may naturally extend to CTFg57 (Sykora et al., 2015).

The second major lesion characteristic of AD is the intracellular deposition of the microtubule-binding protein, tau, in the form of neurofibrillary tangles. Multiple reports suggest that the load of this lesion may be more closely linked to dementia characteristic of AD than amyloid plaque burden. The tau model suggests that the creation of neurofibrillary tangles is the most important characteristic of AD and their density correlates positively with disease severity (Moore et al., 2015). According to the tau hypothesis, structural modification of tau such as hyper-phosphorylation and aggregation interferes with tau function leading to the neuronal dysfunction that may cause AD. In support of this hypothesis, abnormally phosphorylated tau has been observed in the CSF of AD patients at a very

early stage. Furthermore, mutations in *tau* lead to dementia and neurofibrillary tangles formation. However, it is important to note that these mutations do not lead to amyloid deposition characteristic of AD. One report has suggested that the formation of neurofibrillary tangles in P3011 tau transgenic mice is induced by A β 42 fibrils (Götz, Chen, van Dorpe, & Nitsch, 2001), and a second report has observed enhanced neurofibrillary degeneration in transgenic mice expressing mutant *tau* and *APP* genes (Lewis et al., 2001). Multiple genes which are associated with A β functionality are mentioned in Fig. 2.

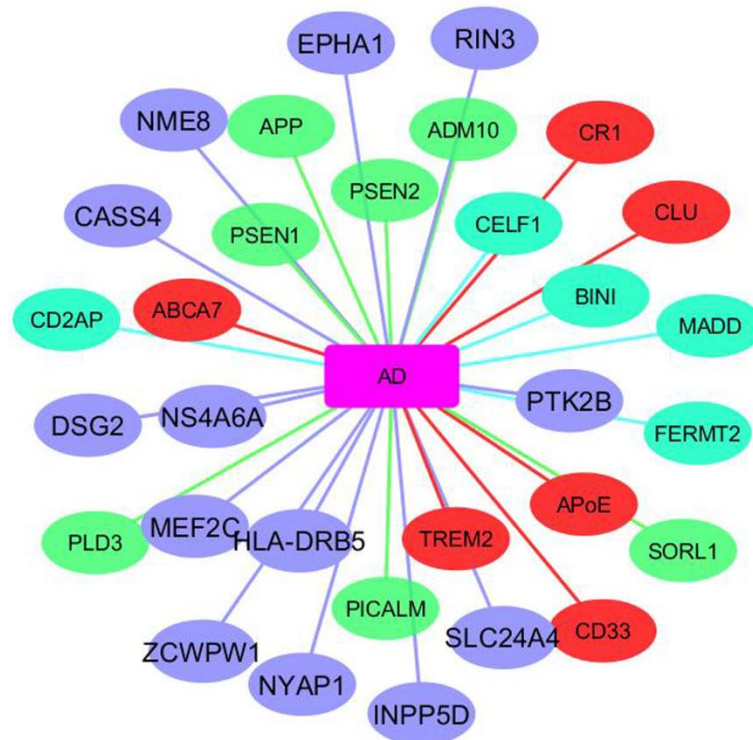


Figure 2: Clump of AD mediated genes which have functional association with A β . The genes in light green are associated with cleavage of APP. The genes in red color are depicted for A β . The cyan color genes are associated with tau toxicity and purple color genes are still under investigation.

4- Genetic and functional deficiencies of neurotransmitters in AD

The relationship between cholinergic neuronal loss and causative amyloid plaques produced from mutant genes is a major area that has been under intensive research. In this regard, several recent studies using cell culture and animal models have shed light onto the effects of anticholinesterase drugs on levels of amyloid proteins. Specific agents possess amyloid lowering actions as a consequence of their cholinergic as well as non-classical, non-cholinergic activities. This overlap in actions of particular agents may be critical in light of the extensive colocalization of the G1 forms of acetyl- and buteryl-cholinesterase (AChE and BChE) and amyloid plaques, which correlate with plaque load and

disease progression. Indeed, there is a colocalization of BChE and all of the pathological hallmarks of AD such as amyloid plaques, neurofibrillary tangles, and dystrophic neurons. The reasons underpinning such colocalization have yet to be elucidated, but may be related to a host of non-cholinergic actions associated with acetylcholine esterase (AChE) and butyrylcholine esterase (BChE). For example, both enzymes are known to play a role in cell proliferation and differentiation in embryonic brain as well as to bear a structural similarity to adhesion molecules (e.g., neurotactin, neuroligin, and gliotactin) that possess trophic and regenerative functions. In addition, BChE has been reported to cleave substrates other than choline esters and likely has amylase and protease activities. Unfortunately, the coexistence of AChE and BChE with A β peptide may amplify the toxicity and latterly cause spiraling deleterious events within the brain (Barber et al., 1996). Whether or not cholinesterase agonist can block the interaction between the enzymes and A β peptides remain to be elucidated and likely will depend on the wide presence of genetically influenced binding sites involved in the enzyme/drug and enzyme/peptide interactions (Kumar, Singh, & Ekavali, 2015).

In AD, the severe loss of cholinergic neurons in the nucleus basalis and associated areas that form the cholinergic forebrain area, and their projections to the cerebral cortices are marked with decreased levels of acetylcholine and its rate-limiting synthetic enzyme, choline acetyltransferase, in the cortex (Bartus, Dean, Beer, & Lippa, 1982). There is also a matching reduction in the level of the enzyme, AChE; in particular, the G4 form (Atack, Perry, Bonham, Candy, & Perry, 1986), which is responsible for terminating the physiological role of acetylcholine at cholinergic synapses. The reduction of cholinergic activity in the central nervous system of AD patients is controlled by mutant *APP* proteins and correlates with deterioration of scores on dementia rating scales. Coincidental with these changes, the level of its sister enzyme BChE is raised.

BChE shares 65% homology with AChE and likewise metabolizes acetylcholine, but have topological differences. BChE is predominantly localized in the glial cells, increases during AD progression, and likely functions to hydrolyze the excessive acetylcholine in the healthy brain. The ratio of AChE to BChE change from 0.3 in the normal area to 11 in some brain areas as AD develops. Undoubtedly, mismatching results were observed between acetylcholine release and its optimal metabolism that likely contributes to cholinergic dysfunction. In addition, a recent study has demonstrated that 10-15% cholinergic neurons in the hippocampus and amygdala of healthy human brain have BChE, rather than AChE, at the synapse as their metabolizing enzyme (Greig et al., 2000).

Another study hypothesize that specific neuronal pathways may function via BChE, which prompted the recent development of selective reversible agents to inhibit BChE. The selected inhibitors work to augment these pathways and to normalize the BChE versus AChE ratio in the AD

brain. All these findings, along with the known role of cholinergic neurotransmission in memory processing and storage, led to the hypothesis that cholinergic augmentation might improve cognition in AD. This cognition AD improvement is the results of amplification of acetylcholine's action (muscarinic and nicotinic) through inhibition of its metabolizing enzymes by direct use of agonists that combat the effect of synaptic signaling initiated by *APP* mutant genes (Craig, Hong, & McDonald, 2011).

Currently, cholinesterase inhibition is the most effective, widely studied, and developed approach for treating the symptoms of AD. In this regard, four currently administered drugs for AD (tacrine, donepezil, rivastigmine, and galantamine) have been approved by the Food and Drug Administration (FDA) for prescription as cholinesterase inhibitors. All of them are centrally active and have been shown to improve memory and cognition in some patients with mild to moderate AD. Their effects become more apparent after several weeks of therapy and all members of the same drug class vary in some unexpected ways. This dissimilarity likely derives from their divergent chemical structures, different binding sites and pharmacokinetics values of AChE and BChE. Resulting from this, donepezil and galantamine possess selectivity for the acetyl form of cholinesterase, whereas both tacrine and rivastigmine co-inhibit both AChE and BChE. Furthermore, likely due to their mechanisms of binding action and long half-lives, the former two agents gradually induce up-regulation of their target AChE, whereas the latter do not. The other differences plausibly account for the observation that patients not benefiting from one agent may benefit from another, although all are of the same class (Zemek et al., 2014).

Conclusions and future directions

Genes are now considered key players to explore the etiology of AD. In this article, we reviewed some known genetic risk and protective factors of AD. We discussed 31 genes with respect to their mutations and known functional effects (penetration/prevalence). The recognition of AD risk variants may provide a new gateway to properly understand the underlying AD mechanism. Recently, the novel identified genes showed significance association with A β production and clearance, which exposed significance of this mechanistic pathway (A β) in the pathogenesis of AD. In our review, we highlighted the few genes such as *ABCA7*, *BINI*, *CASS4*, *CD33*, *CD2AP*, *CELF1*, *CLU*, *CRI*, *DSG2*, *EPHA1*, *FERMT2*, *HLA-DRB5-DBR1*, *INPP5D*, *MS4A*, *MEF2C*, *NME8*, *PICALM*, *PTK2B*, *SLC24H4-RIN3*, *SORL1*, and *ZCWPW1* are associated with AD risk.

Mutated genes and common variants actively participate in the pathogenesis of AD by exploring the underlying A β -signaling pathways. Most of genes (*APP*, *PSEN1*, *PSEN2* and *APOE*) were understood

as key regulators in the A β production and have significant effect on the synaptic receptors in both EOAD and LOAD stages. Multiple cellular and molecular genetic approaches showed the significance of these genes mediated proteins and their downstream signaling pathways which may be considered as novel targets in the therapeutics of AD. Recently, different research groups are synthesizing their agonists by taking these proteins as novel targets to treat AD. Multiple factors such as nutritional, genetic and environmental stress may also highlight more effective and preventive approaches for AD. Taken together, this review gives a brief updating of genetic etiology of AD and of the mechanistic pathways of common mediated proteins which may be considered as novel targets against AD pathology in future. Studies on neurobiological mechanisms to provide new targets for drug development in AD are expanding rapidly, and current investigations cover a broad area of cellular, molecular, genetic, and clinical research.

Herein, we have made an attempt to review recent trends in AD research in these aforementioned areas. The molecular genetics of AD and the role of key proteins (known and to be discovered) that are believed to participate in AD pathogenesis are important fields for further research. Similarly, the cell biology of AD, particularly the roles of secretases, presenilin, notch and tau proteins should provide new light on the cascade of AD neurodegenerative pathways. In addition to *APP* and *PSEN1*, there is significant active research underway in the development of new inhibitors for *PSEN1* and γ -secretase as targets for treatment of AD. Research is also underway to dissect and characterize *APP* genetic regulatory elements for the development of potential drug targets. Furthermore, research on the clusterin, *ABAC7*, *SORL1* genes could produce novel therapeutic targets for treatment of AD. Newer technologies, such as DNA microarray technologies to study gene expression profiles in AD, proteomics to analyze the protein profiling of AD brain tissues, and transgenic mouse models of AD, should yield new and useful clues to further characterize the pathobiochemical processes of AD. Other approaches, such as nutritional, genetic and environmental factors, may also highlight more effective preventive strategies for AD. Indeed, our current understanding of the role of oxidative stress in AD has resulted in the wide use of antioxidants, such as vitamin E, to potentially delay the progression of AD. Finally, it should be stressed that both early diagnosis of AD and the development of quantitative markers to better follow the course of the disease are also extremely important for the evaluation and successful development of therapeutic strategies (Imtiaz, Tolppanen, Kivipelto, & Soininen, 2014).

Competing interests: The authors declare that they have no competing interests.

References

- Alonso, A. D. C., Mederlyova, A., Novak, M., Grundke-Iqbal, I., & Iqbal, K. (2004). Promotion of hyperphosphorylation by frontotemporal dementia tau mutations. *Journal of Biological Chemistry*, 279(33), 34873-34881. doi: 10.1074/jbc.M405131200
- Alzheimer's Association. (2014). Alzheimer's disease facts and figures. *Alzheimer's & Dementia*, 10, e47-92. doi: 10.1016/j.jalz.2013.02.003
- Andrews-Zwilling, Y., Bien-Ly, N., Xu, Q., Li, G., Bernardo, A., Yoon, S. Y., . . . Huang, Y. (2010). Apolipoprotein E4 Causes Age- and Tau-Dependent Impairment of GABAergic Interneurons, Leading to Learning and Memory Deficits in Mice. *J. Neurosci.*, 30(41), 13707-13717. doi: 10.1523/JNEUROSCI.4040-10.2010
- Ashe, K. H., & Zahs, K. R. (2010). erProbing the Biology of Alzheimer's Disease in Mice. *Neuron*, 66, 631-645. doi: 10.1016/j.neuron.2010.04.031
- Attack, J. R., Perry, E. K., Bonham, J. R., Candy, J. M., & Perry, R. H. (1986). Molecular forms of acetylcholinesterase and butyrylcholinesterase in the aged human central nervous system. *J Neurochem*, 47(1), 263-277.
- Bali, J., Gheinani, a. H., Zurbriggen, S., & Rajendran, L. (2012). Role of genes linked to sporadic Alzheimer's disease risk in the production of γ -amyloid peptides. *proceedings of the national academy of sciences*, 109(38), 15307-15311. doi: 10.1073/pnas.1201632109
- Barber, K., Mala, R. R., Lambert, M. P., Qiu, R., MacDonald, R. C., & Klein, W. L. (1996). Delivery of membrane-impermeant fluorescent probes into living neural cell populations by lipotransfer. *Neurosci Lett*, 207(1), 17-20. doi: 10.1016/0304-3940(96)12497-6
- Bartus, R. T., Dean, R. L., Beer, B., & Lippa, a. S. (1982). The cholinergic hypothesis of geriatric memory dysfunction. *Science (New York, N.Y.)*, 217(4558), 408-414. doi: 10.1126/science.7046051
- Bastin, C., & Salmon, E. (2014). Early neuropsychological detection of Alzheimer's disease. *European Journal of Clinical Nutrition*, 68(11), 1192-1199. doi: 10.1038/ejcn.2014.176
- Bird, T. D. (2008). Genetic aspects of Alzheimer disease. *Genet Med*, 10(4), 231-239. doi: 10.1097/GIM.0b013e31816b64dc
- Braak, H., & Braak, E. (1991). Acta H ' pathologica Neuropathological staging of Alzheimer-related changes. *Acta Neuropathol*, 82, 239-259. doi: 10.1007/BF00308809
- Brookmeyer, R., Johnson, E., Ziegler-Graham, K., & Arrighi, H. M. (2007). Forecasting the global burden of Alzheimer's disease. *Alzheimer's and Dementia*, 3(3), 186-191. doi: 10.1016/j.jalz.2007.04.381
- Carrasquillo, M. M., Belbin, O., Hunter, T. a., Ma, L., Bisceglia, G. D., Zou, F., . . . Younkin, S. G. (2011). Replication of BIN1 Association with Alzheimer's Disease and Evaluation of Genetic Interactions. *Journal of Alzheimer's disease : JAD*, 24(4), 751-758. doi: 10.3233/JAD-2011-101932
- Castillo-Carranza, D. L., Sengupta, U., Guerrero-Muñoz, M. J., Lasagna-Reeves, C. A., Gerson, J. E., Singh, G., . . . Kayed, R. (2014). Passive immunization with Tau oligomer monoclonal antibody reverses tauopathy phenotypes without affecting hyperphosphorylated neurofibrillary tangles. *The Journal of neuroscience*, 34(12), 4260-4272. doi: 10.1523/JNEUROSCI.3192-13.2014
- Cerpa, W., Dinamarca, M. C., Inestrosa, N. C., W, C., M.C, D., Cerpa, W., . . . Inestrosa, N. C. (2008). Structure-function implications in Alzheimer's disease: Effect of Abeta oligomers at central synapses. *Current Alzheimer Research*, 5(3), 233-243.
- Chapuis, J., Hansmannel, F., Gistelinc, M., Mounier, a., Van Cauwenberghe, C., Kolen, K. V., . . . Lambert, J. C. (2013). Increased expression of BIN1 mediates Alzheimer genetic risk by modulating tau pathology. *Mol Psychiatry*, 18(11), 1225-1234. doi: 10.1038/mp.2013.1
- Choo, I. H., Lee, D. Y., Oh, J. S., Lee, J. S., Lee, D. S., Song, I. C., . . . Woo, J. I. (2010). Posterior cingulate cortex atrophy and regional cingulum disruption in mild cognitive impairment and Alzheimer's disease. *Neurobiol Aging*, 31(5), 772-779. doi: 10.1016/j.neurobiolaging.2008.06.015
- Cleary, J. P., Walsh, D. M., Hofmeister, J. J., Shankar, G. M., Kuskowski, M. a., Selkoe, D. J., & Ashe, K. H. (2005). Natural oligomers of the amyloid-beta protein specifically disrupt cognitive function. *Nat Neurosci*, 8(1), 79-84. doi: 10.1038/nn1372

- Cochran, J. N., Rush, T., Buckingham, S. C., & Roberson, E. D. (2015). The Alzheimer's disease risk factor CD2AP maintains blood-brain barrier integrity. *Human Molecular Genetics*, *24*(23), 6667-6674. doi: 10.1093/hmg/ddv371
- Craig, L. A., Hong, N. S., & McDonald, R. J. (2011). Revisiting the cholinergic hypothesis in the development of Alzheimer's disease. *Neurosci Biobehav Rev*, *35*, 1397-1409. doi: 10.1016/j.neubiorev.2011.03.001
- De Calignon, A., Polydoro, M., Suárez-Calvet, M., William, C., Adamowicz, D. H., Kopeikina, K. J., . . . Hyman, B. T. (2012). Propagation of Tau Pathology in a Model of Early Alzheimer's Disease. *Neuron*, *73*(4), 685-697. doi: 10.1016/j.neuron.2011.11.033
- Dietzsch, E., Murphy, B. F., Kirszbaum, L., Walker, I. D., & Garson, O. M. (1992). Regional localization of the gene for clusterin (SP-40,40; gene symbol CLI) to human chromosome 8p12-->p21. *Cytogenet Cell Genet*, *61*(3), 178-179.
- Dingwall, C. (2001). Spotlight on BACE: The secretases as targets for treatment in Alzheimer disease. *Journal of Clinical Investigation*, *108*, 1243-1246. doi: 10.1172/JCI200114402
- Drebing, C. E., Moore, L. H., Cummings, J. L., van Gorp, W. G., Hinkin, C., Perlman, S. L., . . . Cedarbaum, S. D. (1994). Patterns of neuropsychological performance among forms of subcortical dementia: A case study approach. *Neuropsychiatry Neuropsychol Behav Neurol*, *7*, 57-66.
- Dustin, M. L., Olszowy, M. W., Holdorf, A. D., Li, J., Bromley, S., Desai, N., . . . Shaw, A. S. (1998). A novel adaptor protein orchestrates receptor patterning and cytoskeletal polarity in T-cell contacts. *Cell*, *94*(5), 667-677. doi: 10.1016/S0092-8674(00)81608-6
- Eriksen, J. L., & Janus, C. G. (2007). Plaques, tangles, and memory loss in mouse models of neurodegeneration. *Behavior Genetics*, *37*, 79-100. doi: 10.1007/s10519-006-9118-z
- Geroldi, C., Pihlajamäki, M., Laakso, M. P., Decarli, C., Beltramello, A., Bianchetti, A., . . . Frisoni, G. B. (1999). APOE-epsilon4 is associated with less frontal and more medial temporal lobe atrophy in AD. *Neurology*, *53*(8), 1825-1832. doi: 10.1212/WNL.53.8.1825
- Gillespie, A. K., Jones, E. A., Lin, Y. H., Karlsson, M. P., Kay, K., Yoon, S. Y., . . . Huang, Y. (2016). Apolipoprotein E4 Causes Age-Dependent Disruption of Slow Gamma Oscillations during Hippocampal Sharp-Wave Ripples. *Neuron*, *90*(4), 740-751. doi: 10.1016/j.neuron.2016.04.009
- Goedert, M., & Spillantini, M. G. (2001). Tau gene mutations and neurodegeneration. *Biochem Soc Symp*, *1*(67), 59-71.
- Götz, J., Chen, F., van Dorpe, J., & Nitsch, R. M. (2001). Formation of neurofibrillary tangles in P301L tau transgenic mice induced by Abeta 42 fibrils. *Science (New York, N.Y.)*, *293*(5534), 1491-1495. doi: 10.1126/science.1062097
- Greig, N. H., De Micheli, E., Holloway, H. W., Yu, Q. S., Utsuki, T., Perry, T. a., . . . Soncrant, T. T. (2000). The experimental Alzheimer drug phenserine: preclinical pharmacokinetics and pharmacodynamics. *Acta neurologica Scandinavica. Supplementum*, *176*(October 2016), 74-84. doi: 10.1034/j.1600-0404.2000.00311.x
- Guerrero, R., Navarro, P., Gallego, E., Garcia-Cabrero, A. M., Avila, J., & Sanchez, M. P. (2009). Hyperphosphorylated tau aggregates in the cortex and hippocampus of transgenic mice with mutant human FTDP-17 Tau and lacking the PARK2 gene. *Acta Neuropathologica*, *117*(2), 159-168. doi: 10.1007/s00401-008-0470-3
- Haass, C., & Selkoe, D. J. (2007). Soluble protein oligomers in neurodegeneration: lessons from the Alzheimer's amyloid beta-peptide. *Nature reviews. Molecular cell biology*, *8*(2), 101-112. doi: 10.1038/nrm2101
- Hansell, N. K., Halford, G. S., Andrews, G., Shum, D. H. K., Harris, S. E., Davies, G., . . . Wright, M. J. (2015). Genetic basis of a cognitive complexity metric. *PLoS One*, *10*(4). doi: 10.1371/journal.pone.0123886
- Harold, D., Abraham, R., Hollingworth, P., Sims, R., Gerrish, A., Hamshere, M. L., . . . Williams, J. (2009). Genome-wide association study identifies variants at CLU and PICALM associated with Alzheimer's disease. *Nat.Genet.*, *41*(10), 1088-1093. doi: 10.1038/ng.440

- Harris, J. A., Devidze, N., Verret, L., Ho, K., Halabisky, B., Thwin, M. T., . . . Mucke, L. (2010). Transsynaptic Progression of Amyloid- β -Induced Neuronal Dysfunction within the Entorhinal-Hippocampal Network. *Neuron*, *68*(3), 428-441. doi: 10.1016/j.neuron.2010.10.020
- Harris, J. A., Koyama, A., Maeda, S., Ho, K., Devidze, N., Dubal, D. B., . . . Mucke, L. (2012). Human P301L-Mutant Tau Expression in Mouse Entorhinal-Hippocampal Network Causes Tau Aggregation and Presynaptic Pathology but No Cognitive Deficits. *PLoS One*, *7*(9). doi: 10.1371/journal.pone.0045881
- Hernández, F., & Avila, J. (2010). Intra and extracellular protein interactions with tau. *Current Alzheimer Research*, *7*(8), 670-676. doi: 10.2174/156720510793611583
- Herzog, H., Nicholl, J., Hort, Y. J., Sutherland, G. R., & Shine, J. (1996). Molecular cloning and assignment of FAK2, a novel human focal adhesion kinase, to 8p11.2-p22 by nonisotopic in situ hybridization. *Genomics*, *32*(3), 484-486. doi: 10.1006/geno.1996.0149
- Hickman, S. E., & El Khoury, J. (2014). TREM2 and the neuroimmunology of Alzheimer's disease. *Biochemical Pharmacology*, *88*(4), 495-498. doi: 10.1016/j.bcp.2013.11.021
- Hollingworth, P., Harold, D., Sims, R., Gerrish, A., Lambert, C., Carrasquillo, M. M., . . . Brice, A. (2011). Common variants in ABCA7, MS4A6A/MS4A4E, EPHA1, CD33 and CD2AP are associated with Alzheimer's disease. *Nature*, *43*(5), 429-435. doi: 10.1038/ng.803.Common
- Hu, X., Pickering, E., Liu, Y. C., Hall, S., Fournier, H., Katz, E., . . . Soares, H. (2011). Meta-analysis for genome-wide association study identifies multiple variants at the BIN1 locus associated with late-onset Alzheimer's disease. *PLoS One*, *6*(2), e16616-e16616. doi: 10.1371/journal.pone.0016616
- Huang, Y. Q., Lu, W. Y., Ali, D. W., Pelkey, K. A., Pitcher, G. M., Lu, Y. M., . . . MacDonald, J. F. (2001). CAK β /Pyk2 kinase is a signaling link for induction of long-term potentiation in CA1 hippocampus. *Neuron*, *29*(2), 485-496. doi: 10.1016/S0896-6273(01)00220-3
- Hulett, M. D., Pagler, E., Hornby, J. R., Hogarth, P. M., Eyre, H. J., Baker, E., . . . Parish, C. R. (2001). Isolation, tissue distribution, and chromosomal localization of a novel testis-specific human four-transmembrane gene related to CD20 and Fc ϵ RI-beta. *Biochem Biophys Res Commun*, *280*(1), 374-379. doi: 10.1006/bbrc.2000.4088
- Imtiaz, B., Tolppanen, A.-M., Kivipelto, M., & Soininen, H. (2014). Future directions in Alzheimer's disease from risk factors to prevention. *Biochemical Pharmacology*, *88*(4), 661-670. doi: 10.1016/j.bcp.2014.01.003
- Iqbal, K., Liu, F., & Gong, C.-X. (2016). Tau and neurodegenerative disease: the story so far. *Nature reviews. Neurology*, *12*(1), 15-27. doi: 10.1038/nrneurol.2015.225
- Iqbal, K., Liu, F., Gong, C.-X., & Grundke-Iqbal, I. (2010). Tau in Alzheimer disease and related tauopathies. *NIH Public Access*, *7*(8), 656-664. doi: 10.2174/156720510793611592
- Ittner, L. M., Ke, Y. D., Delerue, F., Bi, M., Gladbach, A., van Eersel, J., . . . Götz, J. (2010). Dendritic function of tau mediates amyloid-beta toxicity in Alzheimer's disease mouse models. *Cell*, *142*(3), 387-397. doi: 10.1016/j.cell.2010.06.036
- Jacobsen, L., Madsen, P., Jacobsen, C., Nielsen, M. S., Gliemann, J., & Petersen, C. M. (2001). Activation and functional characterization of the mosaic receptor SorLA/LR11. *J Biol Chem*, *276*(25), 22788-22796. doi: 10.1074/jbc.M100857200
- Jacobsen, L., Madsen, P., Moestrup, S. K., Lund, A. H., Tommerup, N., Nykjaer, A., . . . Petersen, C. M. (1996). Molecular characterization of a novel human hybrid-type receptor that binds the alpha2-macroglobulin receptor-associated protein. *J Biol Chem*, *271*(49), 31379-31383.
- Kaminski, W. E., Piehler, A., & Schmitz, G. (2000). Genomic organization of the human cholesterol-responsive ABC transporter ABCA7: tandem linkage with the minor histocompatibility antigen HA-1 gene. *Biochem Biophys Res Commun*, *278*(3), 782-789. doi: 10.1006/bbrc.2000.3880
- Karch, C. M., Cruchaga, C., & Goate, A. M. (2014). Alzheimer's disease genetics: From the bench to the clinic. *Neuron*, *83*, 11-26. doi: 10.1016/j.neuron.2014.05.041
- Karch, C. M., & Goate, A. M. (2015). Alzheimer's disease risk genes and mechanisms of disease pathogenesis. *Biol Psychiatry*, *77*, 43-51. doi: 10.1016/j.biopsych.2014.05.006

- Kerchner, G. A., Berdnik, D., Shen, J. C., Bernstein, J. D., Fenesy, M. C., Deutsch, G. K., . . . Rutt, B. K. (2014). APOE e4 worsens hippocampal CA1 apical neuropil atrophy and episodic memory. *Neurology*, *82*(8), 691-697. doi: 10.1212/WNL.000000000000154
- Khan, U. a., Liu, L., Provenzano, F. a., Berman, D. E., Profaci, C. P., Sloan, R., . . . Small, S. a. (2014). Molecular drivers and cortical spread of lateral entorhinal cortex dysfunction in preclinical Alzheimer's disease. *Nat Neurosci*, *17*(2), 304-311. doi: 10.1038/nn.3606
- King, M. E., Kan, H. M., Baas, P. W., Erisir, A., Glabe, C. G., & Bloom, G. S. (2006). Tau-dependent microtubule disassembly initiated by prefibrillar ??-amyloid. *Journal of Cell Biology*, *175*(4), 541-546. doi: 10.1083/jcb.200605187
- Kumar, A., Singh, A., & Ekavali. (2015). A review on Alzheimer's disease pathophysiology and its management: An update. *Pharmacological Reports*, *67*, 195-203. doi: 10.1016/j.pharep.2014.09.004
- Kunz, L., Schroder, T. N., Lee, H., Montag, C., Lachmann, B., Sariyska, R., . . . Axmacher, N. (2015). Reduced grid-cell-like representations in adults at genetic risk for Alzheimer's disease. *Science*, *350*(6259), 430-433. doi: 10.1126/science.aac8128
- Lai, K. O., & Ip, N. Y. (2009). Synapse development and plasticity: roles of ephrin/Eph receptor signaling. *Curr Opin Neurobiol*, *19*, 275-283. doi: 10.1016/j.conb.2009.04.009
- Lambert, J.-C., Heath, S., Even, G., Campion, D., Sleegers, K., Hiltunen, M., . . . Amouyel, P. (2009). Genome-wide association study identifies variants at CLU and CR1 associated with Alzheimer's disease. *Nature genetics*, *41*(10), 1094-1099. doi: 10.1038/ng.439
- Lambert, J., Ibrahim-Verbaas, C. A., Harold, D., Naj, A. C., Sims, R., Bellenguez, C., . . . Amouyel, P. (2013). Meta-analysis of 74,046 individuals identifies 11 new susceptibility loci for Alzheimer's disease. *Nature genetics*, *45*(12), 1452-1458. doi: 10.1038/ng.2802
- Lesné, S., Koh, M. T., Kotilinek, L., Kaye, R., Glabe, C. G., Yang, A., . . . Ashe, K. H. (2006). A specific amyloid-beta protein assembly in the brain impairs memory. *Nature*, *440*(7082), 352-357. doi: 10.1038/nature04533
- Lewis, J., Dickson, D. W., Lin, W. L., Chisholm, L., Corral, A., Jones, G., . . . Nitsch, R. M. (2001). Enhanced neurofibrillary degeneration in transgenic mice expressing mutant tau and APP. *Science (New York, N.Y.)*, *293*(5534), 1487-1491. doi: 10.1126/science.1058189
- Lippa, C. F., Schmidt, M. L., Nee, L. E., Bird, T., Nochlin, D., Hulette, C., . . . Trojanowski, J. Q. (2000). AMY plaques in familial AD - Comparison with sporadic Alzheimer's disease. *Neurology*, *54*(1), 100-104.
- Liu, L., Drouet, V., Wu, J. W., Witter, M. P., Small, S. A., Clelland, C., & Duff, K. (2012). Trans-synaptic spread of tau pathology in vivo. *PLoS One*, *7*(2). doi: 10.1371/journal.pone.0031302
- Lowik, M. M., Groenen, P. J., Pronk, I., Lilien, M. R., Goldschmeding, R., Dijkman, H. B., . . . van den Heuvel, L. P. (2007). Focal segmental glomerulosclerosis in a patient homozygous for a CD2AP mutation. *Kidney Int*, *72*(10), 1198-1203. doi: 10.1038/sj.ki.5002469
- Lu, H., Zhu, X. C., Wang, H. F., Cao, L., Tan, M. S., Tan, C. C., . . . Tan, L. (2016). Lack of Association Between SLC24A4 Polymorphism and Late-Onset Alzheimer's Disease in Han Chinese. *Curr Neurovasc Res*, *13*(3), 239-243. doi: 10.2174/1567202613666160524144739
- Lue, L. F., Schmitz, C., & Walker, D. G. (2015). What happens to microglial TREM2 in Alzheimer's disease: Immunoregulatory turned into immunopathogenic? *Neuroscience*, *302*, 138-150. doi: 10.1016/j.neuroscience.2014.09.050
- Lynch, D. K., Winata, S. C., Lyons, R. J., Hughes, W. E., Lehrbach, G. M., Wasinger, V., . . . Daly, R. J. (2003). A cortactin-CD2-associated protein (CD2AP) complex provides a novel link between epidermal growth factor receptor endocytosis and the actin cytoskeleton. *Journal of Biological Chemistry*, *278*(24), 21805-21813. doi: 10.1074/jbc.M211407200
- Marcello, E., Saraceno, C., Musardo, S., Vara, H., De La Fuente, A. G., Pelucchi, S., . . . Di Luca, M. (2013). Endocytosis of synaptic ADAM10 in neuronal plasticity and Alzheimer's disease. *Journal of Clinical Investigation*, *123*(6), 2523-2538. doi: 10.1172/JCI65401
- Maru, Y., Hirai, H., Yoshida, M. C., & Takaku, F. (1988). Evolution, expression, and chromosomal location of a novel receptor tyrosine kinase gene, eph. *Mol Cell Biol*, *8*(9), 3770-3776.

- Moore, S., Evans, L. D. B., Andersson, T., Portelius, E., Smith, J., Dias, T. B., . . . Livesey, F. J. (2015). APP Metabolism Regulates Tau Proteostasis in Human Cerebral Cortex Neurons. *Cell Reports*, *11*(5), 689-696. doi: 10.1016/j.celrep.2015.03.068
- Mormino, E. C., Kluth, J. T., Madison, C. M., Rabinovici, G. D., Baker, S. L., Miller, B. L., . . . Jagust, W. J. (2008). Episodic memory loss is related to hippocampal-mediated beta-amyloid deposition in elderly subjects. *Brain*, *132*, 1310-1323. doi: 10.1093/brain/awn320
- Mustroph, M. L., King, M. A., Klein, R. L., & Ramirez, J. J. (2012). Adult-onset focal expression of mutated human tau in the hippocampus impairs spatial working memory of rats. *Behav Brain Res*, *233*(1), 141-148. doi: 10.1016/j.bbr.2012.04.034
- Naj, A. C., Jun, G., Reitz, C., Kunkle, B. W., Perry, W., Park, Y. S., . . . Yu, L. (2014). Effects of multiple genetic loci on age at onset in late-onset Alzheimer disease: a genome-wide association study. *JAMA Neurology*, *71*(11), 1394-1404. doi: 10.1001/jamaneurol.2014.1491
- Negorev, D., Riethman, H., Wechsler-Reya, R., Sakamuro, D., Prendergast, G. C., & Simon, D. (1996). The Bin1 gene localizes to human chromosome 2q14 by PCR analysis of somatic cell hybrids and fluorescence in situ hybridization. *Genomics*, *33*(2), 329-331. doi: 10.1006/geno.1996.0205
- Nestor, P. J., Fryer, T. D., & Hodges, J. R. (2006). Declarative memory impairments in Alzheimer's disease and semantic dementia. *Neuroimage*, *30*(3), 1010-1020. doi: 10.1016/j.neuroimage.2005.10.008
- Ostojic, J., Elfgren, C., Passant, U., Nilsson, K., Gustafson, L., Lannfelt, L., & Fabre, S. F. The tau R406W mutation causes progressive presenile dementia with bitemporal atrophy. *Dementia and Geriatric Cognitive Disorders*, *17*, 298-301. doi: 10.1159/000077158
- Paloneva, J., Manninen, T., Christman, G., Hovanes, K., Mandelin, J., Adolfsson, R., . . . Peltonen, L. (2002). *Mutations in Two Genes Encoding Different Subunits of a Receptor Signaling Complex Result in an Identical Disease Phenotype.*
- Palop, J. J., & Mucke, L. (2010). Amyloid- β Induced Neuronal Dysfunction in Alzheimer's Disease: From Synapses toward Neural Networks. *Nat Neurosci*, *13*(7), 812-818. doi: 10.1038/nn.2583
- Pandey, P., Avraham, S., Kumar, S., Nakazawa, A., Place, A., Ghanem, L., . . . Kharbanda, S. (1999). Activation of p38 mitogen-activated protein kinase by PYK2/related adhesion focal tyrosine kinase-dependent mechanism. *Journal of Biological Chemistry*, *274*(15), 10140-10144. doi: 10.1074/jbc.274.15.10140
- Piedrahita, D., Hernández, I., López-Tobón, A., Fedorov, D., Obara, B., Manjunath, B. S., . . . Cardona-Gómez, G. P. (2010). Silencing of CDK5 reduces neurofibrillary tangles in transgenic alzheimer's mice. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, *30*(42), 13966-13976. doi: 10.1523/JNEUROSCI.3637-10.2010
- Pievani, M., Rasser, P. E., Galluzzi, S., Benussi, L., Ghidoni, R., Sabbatoli, F., . . . Frisoni, G. B. (2009). Mapping the effect of APOE epsilon 4 on gray matter loss in Alzheimer's disease in vivo. *Neuroimage*, *45*(4), 1090-1098. doi: 10.1016/j.neuroimage.2009.01.009
- Prinzen, C., Muller, U., Endres, K., Fahrenholz, F., & Postina, R. (2005). Genomic structure and functional characterization of the human ADAM10 promoter. *FASEB J*, *19*(11), 1522-1524. doi: 10.1096/fj.04-3619fje
- Proitsi, P., Lee, S. H., Lunnon, K., Keohane, A., Powell, J., Troakes, C., . . . Hodges, A. (2014). Alzheimer's disease susceptibility variants in the MS4A6A gene are associated with altered levels of MS4A6A expression in blood. *Neurobiol Aging*, *35*(2), 279-290. doi: 10.1016/j.neurobiolaging.2013.08.002
- Rademakers, R., Dermaut, B., Peeters, K., Cruts, M., Heutink, P., Goate, A., & Van Broeckhoven, C. (2003). Tau (MAPT) Mutation Arg406Trp Presenting Clinically with Alzheimer Disease Does Not Share a Common Founder in Western Europe [1]. *Human Mutation*, *22*(5), 409-411. doi: 10.1002/humu.10269
- Reitz, C., & Mayeux, R. (2014). Alzheimer disease: Epidemiology, diagnostic criteria, risk factors and biomarkers. *Biochemical Pharmacology*, *88*, 640-651. doi: 10.1016/j.bcp.2013.12.024
- Ridge, P. G., Mukherjee, S., Crane, P. K., & Kauwe, J. S. K. (2013). Alzheimer's disease: Analyzing the missing heritability. *PLoS One*, *8*(11). doi: 10.1371/journal.pone.0079771

- Rosendahl, M. S., Ko, S. C., Long, D. L., Brewer, M. T., Rosenzweig, B., Hedl, E., . . . Lichenstein, H. S. (1997). Identification and characterization of a pro-tumor necrosis factor-alpha-processing enzyme from the ADAM family of zinc metalloproteases. *J Biol Chem*, 272(39), 24588-24593.
- Santacruz, K., Lewis, J., Spires, T., Paulson, J., Kotilinek, L., Ingelsson, M., . . . Ashe, K. H. (2005). Tau suppression in a neurodegenerative mouse model improves memory function. *Science*, 309(5733), 476-481. doi: 10.1126/science.1113694
- Sexton, C. E., Mackay, C. E., Lonie, J. A., Bastin, M. E., Terrière, E., O'Carroll, R. E., & Ebmeier, K. P. (2010). MRI correlates of episodic memory in Alzheimer's disease, mild cognitive impairment, and healthy aging. *Psychiatry Research - Neuroimaging*, 184(1), 57-62. doi: 10.1016/j.psychres.2010.07.005
- Shankar, G. M., Li, S., Mehta, T. H., Garcia-Munoz, A., Shepardson, N. E., Smith, I., . . . Selkoe, D. J. (2008). Amyloid-beta protein dimers isolated directly from Alzheimer's brains impair synaptic plasticity and memory. *Nat Med*, 14(8), 837-842. doi: 10.1038/nm1782
- Shen, L., Thompson, P. M., Potkin, S. G., Bertram, L., Farrer, L. A., Foroud, T. M., . . . Saykin, A. J. (2014). Genetic analysis of quantitative phenotypes in AD and MCI: Imaging, cognition and biomarkers. *Brain Imaging and Behavior*, 8(2), 183-207. doi: 10.1007/s11682-013-9262-z
- Sheng, M., Sabatini, B. L., & Südhof, T. C. (2012). Synapses and Alzheimer's disease. *Cold Spring Harbor Perspectives in Biology*, 4(5), 10-10. doi: 10.1101/cshperspect.a005777
- Steinberg, S., Stefansson, H., Jonsson, T., Johannsdottir, H., Ingason, A., Helgason, H., . . . Stefansson, K. (2015). Loss-of-function variants in ABCA7 confer risk of Alzheimer's disease. *Nature genetics*, 47(5), 445-447. doi: 10.1038/ng.3246
- Stern, J. A., White, S. N., Lehmkuhl, L. B., Reina-Doreste, Y., Ferguson, J. L., Nascone-Yoder, N. M., & Meurs, K. M. (2014). A single codon insertion in PICALM is associated with development of familial subvalvular aortic stenosis in Newfoundland dogs. *Hum Genet*, 133(9), 1139-1148. doi: 10.1007/s00439-014-1454-0
- Sydow, A., Van Der Jeugd, A., Zheng, F., Ahmed, T., Balschun, D., Petrova, O., . . . Mandelkow, E. M. (2011). Reversibility of Tau-related cognitive defects in a regulatable FTD mouse model. *Journal of Molecular Neuroscience*, 45, 432-437. doi: 10.1007/s12031-011-9604-5
- Sykora, P., Misiak, M., Wang, Y., Ghosh, S., Leandro, G. S., Liu, D., . . . Bohr, V. A. (2015). DNA polymerase beta deficiency leads to neurodegeneration and exacerbates Alzheimer disease phenotypes. *Nucleic Acids Res*, 43(2), 943-959. doi: 10.1093/nar/gku1356
- Tan, M. S., Yu, J. T., & Tan, L. (2013). Bridging integrator 1 (BIN1): Form, function, and Alzheimer's disease. *Trends in Molecular Medicine*, 19, 594-603. doi: 10.1016/j.molmed.2013.06.004
- Trask, B., Fertitta, A., Christensen, M., Youngblom, J., Bergmann, A., Copeland, A., . . . et al. (1993). Fluorescence in situ hybridization mapping of human chromosome 19: cytogenetic band location of 540 cosmids and 70 genes or DNA markers. *Genomics*, 15(1), 133-145.
- Tu, S., Okamoto, S.-I., Lipton, S. A., & Xu, H. (2014). Oligomeric A β -induced synaptic dysfunction in Alzheimer's disease. *Molecular Neurodegeneration*, 9(48), 1-12. doi: 10.1186/1750-1326-9-48
- Tulving, E. (1972). Episodic and semantic memory. *Organization of memory*, 1, 381-403. doi: 10.1017/S0140525X00047257
- van de Rest, O., Berendsen, A. A., Haveman-Nies, A., & de Groot, L. C. (2015). Dietary patterns, cognitive decline, and dementia: a systematic review. *Advances in nutrition (Bethesda, Md.)*, 6(2), 154-168. doi: 10.3945/an.114.007617
- Van Der Vlies, A. E., Pijnenburg, Y. A. L., Koene, T., Klein, M., Kok, A., Scheltens, P., & Van Der Flier, W. M. (2007). Cognitive impairment in Alzheimer's disease is modified by APOE genotype. *Dementia and Geriatric Cognitive Disorders*, 24(2), 98-103. doi: 10.1159/000104467
- Van Halteren-Van Tilborg, I. A. D. A., Scherder, E. J. A., & Hulstijn, W. (2007). Motor-Skill learning in Alzheimer's disease: A review with an eye to the clinical practice. *Neuropsychol Rev*, 17(3), 203-212. doi: 10.1007/s11065-007-9030-1

- Wang, C., Tan, L., Wang, H. F., Yu, W. J., Liu, Y., Jiang, T., . . . Yu, J. T. (2015). Common variants in PLD3 and correlation to amyloid-related phenotypes in Alzheimer's disease. *Journal of Alzheimer's Disease*, *46*(2), 491-495. doi: 10.3233/JAD-150110
- Weinstein, G., Beiser, A. S., Preis, S. R., Courchesne, P., Chouraki, V., Levy, D., & Seshadri, S. (2016). Plasma clusterin levels and risk of dementia, Alzheimer's disease, and stroke. *Alzheimers Dement (Amst)*, *3*, 103-109. doi: 10.1016/j.dadm.2016.06.005
- Weis, J. H., Morton, C. C., Bruns, G. A., Weis, J. J., Klickstein, L. B., Wong, W. W., & Fearon, D. T. (1987). A complement receptor locus: genes encoding C3b/C4b receptor and C3d/Epstein-Barr virus receptor map to 1q32. *J Immunol*, *138*(1), 312-315.
- Wilhelmsen, K. C., Lynch, T., Pavlou, E., Higgins, M., & Nygaard, T. G. (1994). Localization of disinhibition-dementia-parkinsonism-amyotrophy complex to 17q21-22. *American Journal of Human Genetics*, *55*(6), 1159-1165.
- Wolfsberg, T. G., Primakoff, P., Myles, D. G., & White, J. M. (1995). ADAM, a novel family of membrane proteins containing A Disintegrin And Metalloprotease domain: multipotential functions in cell-cell and cell-matrix interactions. *J Cell Biol*, *131*(2), 275-278.
- Wolk, D. A., & Dickerson, B. C. (2010). Apolipoprotein E (APOE) genotype has dissociable effects on memory and attentional-executive network function in Alzheimer's disease. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(22), 10256-10261. doi: 10.1073/pnas.1001412107
- Wolk, D. A., Dunfee, K. L., Dickerson, B. C., Aizenstein, H. J., & Dekosky, S. T. (2011). A medial temporal lobe division of labor: Insights from memory in aging and early Alzheimer disease. *Hippocampus*, *21*(5), 461-466. doi: 10.1002/hipo.20779
- Wong, P., Taillefer, D., Lakins, J., Pineault, J., Chader, G., & Tenniswood, M. (1994). Molecular characterization of human TRPM-2/clusterin, a gene associated with sperm maturation, apoptosis and neurodegeneration. *Eur J Biochem*, *221*(3), 917-925.
- Wu, L., Rosa-Neto, P., Hsiung, G. Y., Sadovnick, A. D., Masellis, M., Black, S. E., . . . Gauthier, S. (2012). Early-onset familial Alzheimer's disease (EOFAD). *Can J Neurol Sci*, *39*(4), 436-445.
- Yamazaki, K., Mizui, Y., & Tanaka, I. (1997). Radiation hybrid mapping of human ADAM10 gene to chromosome 15. *Genomics*, *45*(2), 457-459. doi: 10.1006/geno.1997.4910
- Yavari, R., Adida, C., Bray-Ward, P., Brines, M., & Xu, T. (1998). Human metalloprotease-disintegrin Kuzbanian regulates sympathoadrenal cell fate in development and neoplasia. *Hum Mol Genet*, *7*(7), 1161-1167.
- Yu, L., Chibnik, L. B., Srivastava, G. P., Pochet, N., Yang, J., Xu, J., . . . Bennett, D. A. (2015). Association of Brain DNA methylation in SORL1, ABCA7, HLA-DRB5, SLC24A4, and BIN1 with pathological diagnosis of Alzheimer disease. *JAMA Neurology*, *72*(1), 15-24. doi: 10.1001/jamaneurol.2014.3049
- Zemek, F., Drtinova, L., Nepovimova, E., Sepsova, V., Korabecny, J., Klimes, J., & Kuca, K. (2014). Outcomes of Alzheimer's disease therapy with acetylcholinesterase inhibitors and memantine. *Expert Opinion On Drug Safety*, *13*(February 2016), 759-774. doi: 10.1517/14740338.2014.914168