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The Road Ahead to Cure Alzheimer's Disease: Development of Biological Markers and Neuroimaging Methods for Prevention Trials Across all Stages and Target Populations

E. Cavedo¹, S. Lista², Z. Khachaturian³, P. Aisen⁴, P. Amouyel⁵, K. Herholz⁶, C.R. Jack Jr⁷, R. Sperling⁸, J. Cummings⁹, K. Blennow¹⁰, S. O'Bryant¹¹, G.B. Frisoni¹², A. Khachaturian¹³, M. Kivipelto¹⁴, W. Klunk¹⁵, K. Broich¹⁶, S. Andrieu¹⁷, M. Thiebaut de Schotten¹⁸, J.-F. Mangin¹⁹, A.A. Lammertsma²⁰, K. Johnson²¹, S. Teipel²², A. Drzezga²³, A. Bokde²⁴, O. Colliot²⁵, H. Bakardjian²⁶, H. Zetterberg²⁷, B. Dubois²⁸, B. Vellas²⁹, L.S. Schneider³⁰, and H. Hampel³¹

¹Sorbonne Universités, Université Pierre et Marie Curie, Paris 06, Institut de la Mémoire et de la Maladie d'Alzheimer (IM2A) Hôpital de la Pitié-Salpêtrière & Institut du Cerveau et de la Moelle épinière (ICM), UMR S 1127, Hôpital de la Pitié-Salpêtrière Paris & CATI multicenter neuroimaging platform, France; Laboratory of Epidemiology, Neuroimaging and Telemedicine, IRCCS San Giovanni di Dio Fatebenefratelli Brescia, Italy ²AXA Research Fund & UPMC Chair; Sorbonne Universités, Université Pierre et Marie Curie, Paris 06, Institut de la Mémoire et de la Maladie d'Alzheimer (IM2A) Hôpital de la Pitié-Salpêtrière & Inserm U1127 Institut du Cerveau et de la Moelle épinière (ICM), Hôpital de la Pitié-Salpêtrière Paris, France ³The Campaign to Prevent Alzheimer's Disease by 2020 (PAD2020), Potomac, MD, USA ⁴Department of Neurosciences, University of California San Diego, San Diego, CA, USA ⁵Inserm, U744, Lille, 59000, France; Université Lille 2, Lille, 59000, France; Institut Pasteur de Lille, Lille, 59000, France; Centre Hospitalier Régional Universitaire de Lille, Lille, 59000, France ⁶Institute of Brain, Behaviour and Mental Health, University of Manchester, UK ⁷Department of Radiology, Mayo Clinic, Rochester, MN, USA ⁸Center for Alzheimer Research and Treatment, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA ⁹Department of Neurology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA ¹⁰Department of Neurology, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA ¹¹Cleveland Clinic Lou Ruvo Center for Brain Health, 888 West Bonneville Avenue, Las Vegas, Nevada 89106, USA ¹²Clinical Neurochemistry Laboratory, Institute of Neuroscience and Physiology, the Sahlgrenska Academy at the University of Gothenburg, Mölndal, Sweden ¹³Department of Internal Medicine, Institute for Aging & Alzheimer's Disease Research, University of North Texas Health Science Center, Fort Worth, TX, USA ¹⁴IRCCS Istituto Centro S. Giovanni di Dio Fatebenefratelli, Brescia, Italy; University Hospitals and University of Geneva, Geneva, Switzerland ¹⁵Executive Editor, Alzheimer's & Dementia ¹⁶Karolinska Institutet Alzheimer Research Center, NVS, Stockholm, Sweden ¹⁷Department of Psychiatry, University of Pittsburgh School of Medicine, USA; Department of Neurology, University of Pittsburgh School of Medicine,

USA ¹⁶Federal Institute of Drugs and Medical Devices (BfArM), Bonn, Germany ¹⁷Inserm UMR1027, Université de Toulouse III Paul Sabatier, Toulouse, France; Public health department, CHU de Toulouse ¹⁸Natbrainlab, Department of Forensic and Neurodevelopmental Sciences, Institute of Psychiatry, King's College London, London, UK; Université Pierre et Marie Curie-Paris 6, Centre de Recherche de l'Institut du Cerveau et de la Moelle épinière (ICM), UMRS 1127 Paris, France; Inserm, U 1127, Paris, France; CNRS, UMR 7225, Paris, France ¹⁹CEA UNATI, Neurospin, CEA Gif-sur-Yvette, France & CATI multicenter neuroimaging platform ²⁰Department of Radiology & Nuclear Medicine, VU University Medical Center, PO Box 7057, 1007 MB, Amsterdam, The Netherlands ²¹Departments of Radiology and Neurology, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA ²²Department of Psychosomatic Medicine, University of Rostock, and DZNE, German Center for Neurodegenerative Diseases, Rostock, Germany ²³Department of Nuclear Medicine, University Hospital of Cologne, Cologne Germany ²⁴Cognitive Systems Group, Discipline of Psychiatry, School of Medicine, Trinity College Dublin, Dublin, Ireland and Trinity College Institute of Neuroscience, Trinity College Dublin, Dublin, Ireland ²⁵Sorbonne Universités, UPMC Univ Paris 06, UMR S 1127, F-75013, Paris, France; Institut du Cerveau et de la Moelle épinière, ICM, Inserm, U1127, F-75013, Paris, France; CNRS, UMR 7225 ICM, 75013, Paris, France; Inria, Aramis project-team, Centre de Recherche Paris-Rocquencourt, France ²⁶Institute of Memory and Alzheimer's Disease (IM2A), Pitié-Salpêtrière University Hospital, Paris, France; IHU-A-ICM - Paris Institute of Translational Neurosciences, Paris, France ²⁷Clinical Neurochemistry Laboratory, Institute of Neuroscience and Physiology, the Sahlgrenska Academy at the University of Gothenburg, Mölndal, Sweden; UCL Institute of Neurology, Queen Square, London, UK ²⁸Sorbonne Universités, Université Pierre et Marie Curie, Paris 06, Institut de la Mémoire et de la Maladie d'Alzheimer (IM2A) Hôpital de la Pitié-Salpêtrière & Inserm U1127 Institut du Cerveau et de la Moelle épinière (ICM), Hôpital de la Pitié-Salpêtrière Paris, France ²⁹Inserm UMR1027, University of Toulouse, Toulouse, France ³⁰Keck School of Medicine, University of Southern California, Los Angeles, CA, USA ³¹AXA Research Fund & UPMC Chair; Sorbonne Universités, Université Pierre et Marie Curie, Paris 06, Institut de la Mémoire et de la Maladie d'Alzheimer (IM2A) Hôpital de la Pitié-Salpêtrière & Inserm U1127 Institut du Cerveau et de la Moelle épinière (ICM), Hôpital de la Pitié-Salpêtrière Paris, France

Abstract

Alzheimer's disease (AD) is a slowly progressing non-linear dynamic brain disease in which pathophysiological abnormalities, detectable in vivo by biological markers, precede overt clinical symptoms by many years to decades. Use of these biomarkers for the detection of early and preclinical AD has become of central importance following publication of two international expert working group's revised criteria for the diagnosis of AD dementia, mild cognitive impairment (MCI) due to AD, prodromal AD and preclinical AD. As a consequence of matured research evidence six AD biomarkers are sufficiently validated and partly qualified to be incorporated into operationalized clinical diagnostic criteria and use in primary and secondary prevention trials. These biomarkers fall into two molecular categories: biomarkers of amyloid-beta (A β) deposition and plaque formation as well as of tau-protein related hyperphosphorylation and neurodegeneration. Three of the six gold-standard ("core feasible) biomarkers are neuroimaging

measures and three are cerebrospinal fluid (CSF) analytes. CSF A β 1-42 (A β 1-42), also expressed as A β 1-42 : A β 1-40 ratio, T-tau, and P-tau Thr181 & Thr231 proteins have proven diagnostic accuracy and risk enhancement in prodromal MCI and AD dementia. Conversely, having all three biomarkers in the normal range rules out AD. Intermediate conditions require further patient follow-up. Magnetic resonance imaging (MRI) at increasing field strength and resolution allows detecting the evolution of distinct types of structural and functional abnormality pattern throughout early to late AD stages. Anatomical or volumetric MRI is the most widely used technique and provides local and global measures of atrophy. The revised diagnostic criteria for “prodromal AD” and “mild cognitive impairment due to AD” include hippocampal atrophy (as the fourth validated biomarker), which is considered an indicator of regional neuronal injury. Advanced image analysis techniques generate automatic and reproducible measures both in regions of interest, such as the hippocampus and in an exploratory fashion, observer and hypothesis-independent, throughout the entire brain. Evolving modalities such as diffusion-tensor imaging (DTI) and advanced tractography as well as resting-state functional MRI provide useful additionally useful measures indicating the degree of fiber tract and neural network disintegration (structural, effective and functional connectivity) that may substantially contribute to early detection and the mapping of progression. These modalities require further standardization and validation. The use of molecular in vivo amyloid imaging agents (the fifth validated biomarker), such as the Pittsburgh Compound-B and markers of neurodegeneration, such as fluoro-2-deoxy-D-glucose (FDG) (as the sixth validated biomarker) support the detection of early AD pathological processes and associated neurodegeneration. How to use, interpret, and disclose biomarker results drives the need for optimized standardization. Multimodal AD biomarkers do not evolve in an identical manner but rather in a sequential but temporally overlapping fashion. Models of the temporal evolution of AD biomarkers can take the form of plots of biomarker severity (degree of abnormality) versus time. AD biomarkers can be combined to increase accuracy or risk. A list of genetic risk factors is increasingly included in secondary prevention trials to stratify and select individuals at genetic risk of AD. Although most of these biomarker candidates are not yet qualified and approved by regulatory authorities for their intended use in drug trials, they are nonetheless applied in ongoing clinical studies for the following functions: (i) inclusion/exclusion criteria, (ii) patient stratification, (iii) evaluation of treatment effect, (iv) drug target engagement, and (v) safety. Moreover, novel promising hypothesis-driven, as well as exploratory biochemical, genetic, electrophysiological, and neuroimaging markers for use in clinical trials are being developed. The current state-of-the-art and future perspectives on both biological and neuroimaging derived biomarker discovery and development as well as the intended application in prevention trials is outlined in the present publication.

Keywords

Alzheimer’s disease; prevention trials; biomarkers; molecular imaging; neuroimaging

Introduction

A first wave of disease-modifying candidate treatments for Alzheimer disease (AD) has so far failed to demonstrate efficacy in systematic clinical trials and therefore have not gained regulatory approval. Part of the reason is considered to be due to an intervention in a too late

stage of AD when pathophysiological mechanisms and irreversible neuropathological lesions of AD have largely spread through the brain (1). Therefore, prevention at earlier preclinical stages seems a promising way to decrease the incidence of this age-associated neurodegenerative disease, and its associated burden for society (2). Further roadblocks to successful development are due to shortcomings and challenges in appropriate trial design (3–5).

A biomarker (biological marker) is defined as “a characteristic that is objectively measured and evaluated as an indicator of normal biological processes, pathogenic processes, or pharmacologic responses to a therapeutic intervention” (6). Biological and neuroimaging markers of AD are assumed to present central tools for prevention trials and most of them are applied in prevention trials for AD (for an overview, see Table 1). They can be divided into: (i) diagnostic markers, used to enrich, select, and stratify individuals at risk of AD; (ii) endpoint biomarkers, used as outcome measures to monitor the rate of disease progression and detect treatment effects (7), and finally (iii) markers of target engagement, used to target directly the pathophysiology of AD during the preclinical stages (8, 9). Owing to the advances in discovery, development, and validation of AD related neuroimaging and biological markers, it has now become possible to significantly improve the detection and diagnosis of AD by using a combined “multimodal” approach (10, 11). In particular, biomarkers derived from structural/functional/metabolic/molecular neuroimaging and/or neurophysiology (12, 13), and/or neurobiochemistry of cerebrospinal fluid (CSF) (14–16), blood (plasma/serum) and/or (17–19) neurogenetic markers (18, 20, 21) have been introduced. Moreover, the combination of different source biomarkers (22) is believed to make the selection of asymptomatic individuals at risk of AD possible who are a particularly attractive target population for prevention trials. The development of this scenario requires the involvement of regulatory bodies and industry stakeholders providing critical guidance in the area of AD biomarker discovery and application in prevention trials (18, 23).

Here, we review the current and future role of multimodal gold-standard (“core, feasible”) biomarkers –derived from structural, functional, metabolic and molecular neuroimaging, from neurochemistry and genetics – in AD prevention trials, adding some perspectives on biomarker discovery, development, and application in the future prevention trials. In addition, regulatory issues and perspectives related to biomarkers applications in clinical trials will be discussed.

The meaning of prevention in the context of Alzheimer clinical trials

From a public health perspective, treatments as well as clinical trials of therapeutics are classified in terms of primary, secondary, and tertiary prevention interventions (24). Primary prevention aims at reducing the incidence of illness across the broad population by treating the subjects before disease onset, thus promoting the maintenance of good health or eliminating potential causes of disease. Two paradigms of primary prevention approaches are reducing population risk of illness (1) by altering environmental and cardiovascular risk factors, and (2) by using disease-specific mechanistic approaches such as polio vaccination (Figure 1). Secondary prevention aims at preventing disease at preclinical phases of illness,

from progressing to clearly diagnosed disease, while tertiary prevention is focused on treating the disease when it has been clinically diagnosed and its consequences.

The above definitions are conceptually direct but they do not practically work well with the developing concepts of AD therapeutics. The traditional diagnosis of AD refers to “Alzheimer disease dementia”, that is when the illness is at the late dementia stage (25). Under these considerations, primary and secondary prevention involve delaying or impeding the onset of dementia, while tertiary prevention involves subjects already diagnosed and treated by cognitive enhancers, psychotherapeutic drugs, as well as psychosocial and environmental approaches.

In this perspective, the difference between primary and secondary prevention is whether individuals to be treated have or not signs of cognitive impairment. The recent use of biomarkers or bioscales to establish population risk or to enrich a treatment sample for those more likely than others to develop AD, together with the related evolution of clinical diagnostic constructs of ‘prodromal Alzheimer disease’ or ‘MCI due to AD (26, 27) has created a milieu in which the meaning of ‘prevention of AD’ becomes more nuanced and complex. Indeed, there is a shared clinical presentation and underlying pathobiology with both prodromal AD and AD (dementia) such that ‘prevention’ might be better considered as delaying the onset of prodromal AD or AD (27).

Secondary prevention may then focus on people who may be at particular, specific risk, have early signs of the illness, or evidence of AD neuropathology that, if further expressed, would lead to the illness. Here, the illness would be represented by the earliest stage of AD that can be accurately diagnosed, and which, currently, is represented by ‘prodromal AD’ or ‘MCI due to AD’ (any attempt to diagnose illness earlier, e.g., ‘pre-clinical’ AD would be far less certain and must rely mainly on the presence of biomarkers of AD neuropathology).

An illustrative exception is the example of the recent Dominantly Inherited Alzheimer Network Trial (DIAN-TU), involving dominantly-inherited AD neuropathology and disease caused by single gene mutations that have nearly 100% penetrance such that it appears that all people with the mutation will sooner or later develop a dementia syndrome (28). In this scenario, the consideration with respect to describing a primary or secondary prevention effort is whether or not the mutation itself without clinical signs can be considered the disease and therefore ‘preclinical AD’.

The concept of ‘primary prevention’ can be taken further by including in clinical trials subjects who are considered to have no evidence of AD pathology based on the absence of clinical signs and negative amyloid biomarker status, assuming that these individuals have a lower risk for AD than the overall population. The complementary approach, however, is selecting a sample with no clinical evidence of AD pathology but that is biomarker positive. This latter sample would have a somewhat higher actuarial risk for illness; and here treatment could be considered either primary or secondary prevention depending on whether the biomarker itself is considered as defining the pathology of AD and diagnosis of the illness (Figure 2) (24). For instance, the Anti-Amyloid Treatment in Asymptomatic Alzheimer’s Disease (A4) trial (<http://a4study.org>) (29, 30) selects participants with or

without a memory complaint and who are PET amyloid positive for randomized treatment with an antibody targeting A β or with placebo. This study may be considered either as primary or secondary prevention trial depending on one's interpretation of the sample selected for treatment (30–32).

Several current prevention trials focus on individuals who are cognitively within the normal range but are at increased risk for AD due to a mutation (28, 33), amyloid deposition in the brain (A4 trial) (30), an apolipoprotein E and TOMM40 (ApoE/TOMM40) genotype combination (TOMMORROW trial) (34), or ApoE ϵ 4 homozygous status (Alzheimer Prevention Initiative (API), Phoenix) (35). These studies have been developed to prevent the progression from normal or slightly impaired cognition to clear cognitive impairment or, in the TOMMORROW trial, to 'MCI due to AD' or AD. Other trials begin with patients in prodromal AD or MCI due to AD and aim at delaying the progression to AD dementia. The majority of these studies include neuroimaging and biological markers to select target population or as secondary outcome measures. Although biomarkers are potentially useful to select clinical trials sample likely to develop AD, they are not validated as primary surrogate outcomes yet. Thus, clinical outcomes should continue to remain the primary outcomes used in preventive trials.

Finally, preventive interventions should be targeted for those most at risk by determining each individual's or group's risk for cognitive impairment and dementia. It may be possible to identify individuals who are relatively more likely than others to benefit from intensive lifestyle or risk-reduction changes and/or pharmacological interventions. Given the heterogeneous and multifactorial etiology of AD, preventive strategies targeting several risk factors simultaneously may be needed for an optimal preventive effect. Many modifiable risk factors (e.g. high blood pressure, obesity, physical inactivity, cigarette-smoking, and unhealthy diet) are shared among dementia/AD and other late-life chronic conditions (36). Thus, prevention agendas linking dementia and other non-communicable diseases should be developed. Because AD develops over decades, an overall life-course approach to prevention is needed. Different preventive interventions may be needed at different ages and in different contexts (37).

Structural, functional and diffusion Magnetic Resonance Imaging (MRI) markers: current applications and future methods

Structural MRI markers

Magnetic resonance imaging (MRI) is highly versatile and, thus, multi-modality information can be acquired in a single patient examination, including those discussed in the present section. The most widely studied MRI modality is structural MRI (sMRI). In AD, cerebral atrophy – detected by sMRI – occurs in a characteristic topographic distribution (38, 39) which mirrors the Braak (40) and Delacourte (41) neurofibrillary tangles (NFT) staging. Here, atrophy begins in the medial temporal lobe and spreads to the temporal pole, basal and lateral temporal areas, and medial and lateral parietal areas (42). The primary proteinopathies associated with atrophy in AD are tau and TDP43 (43–45). Atrophy, however, does not follow the topography of A β nor is atrophy particularly well correlated

with plaque counts A β or immunostaining in imaging-autopsy correlations (46, 47). Thus, sMRI is correctly viewed as a direct measure of neurodegeneration.

The location and severity of atrophy can be extracted from grey scale images by qualitative visual grading (48), by quantification of the volume of specific structures, or by measuring volume/thickness from multiple regions of interest to form AD-signature composite measures (49, 50). The most common sMRI measure employed in AD is the atrophy of the hippocampus, recently recommended by the revised criteria for AD as one of AD core biomarkers (25–27, 32, 51, 52). For this reason, international efforts to harmonize the definition of the hippocampus were carried out (53–55). Fully automated MR-based hippocampal volumetry seems to fulfill the requirements for a relevant core feasible biomarker for detection of AD associated neurodegeneration in everyday patient care, such as in a secondary care memory clinic for outpatients. Software used is partly freely available, e.g. as an SPM8 toolbox. These methods seem robust and fast and may be easily integrated into routine workflow (56).

In clinical trials, sMRI is or can be used in a variety of capacities. T2-weighted and FLAIR scans can be used to exclude patients with extensive white matter changes, where cognitive impairment might be significantly contributed by or solely due to microvascular disease (57, 58). Hippocampal atrophy has been approved by the European Medicine Agency (EMA) as a means of enriching trials in prodromal AD populations based on the observation in natural history studies that greater hippocampal atrophy predicts more rapid cognitive decline (59–64). Measures of the rate of brain atrophy have been used as endpoints based on the observation in natural history studies that atrophy rates correlate highly with the rate of concurrent clinical decline (65, 66). Of all known outcome measures (including clinical, psychometric, neuroimaging, and biofluid biomarkers), sMRI seems to have the highest measurement precision and thus has been viewed as an attractive outcome measure for clinical trials (67). However, unexpected or counter intuitive results (i.e. more rapid rates of brain shrinkage in treated subjects) in several disease modifying trials (68) have dampened the enthusiasm of some in the pharmaceutical industry for sMRI as an outcome measure. The most rational explanation for such findings, however, is that there may be first wave of short term volume losses associated with amyloid removal perhaps due to a reduction in activated microglia that were associated with plaques. If and when interventions effective on neurodegeneration will be available, sMRI may be able to map a second wave of volume loss sparing that will map onto AD-specific regions of neurodegeneration. Moreover, if/when interventions that target other aspects of the AD pathophysiological pathway (e.g. tau stabilization, or neuroprotection) will be entered into clinical trials, interest in sMRI as an outcome measure might experience a rapid resurgence. In light of this, we believe that sMRI will continue to have a role in AD clinical trials as an outcome measure.

In addition to its role as a measure of AD-related neurodegeneration, sMRI is also an important safety monitor in clinical trials. Both micro bleeds and transient cerebral edema (known as ARIAH and ARIAE respectively) have been reported in some subjects treated with active A β immunization and administration of anti A β monoclonal antibodies (68–70). ARIAH is best captured by T2* imaging and ARIAE by FLAIR imaging.

Functional MRI markers

The blood oxygenation level dependent (BOLD) signal measured with Functional Magnetic resonance imaging (fMRI) reflects primarily the local vascular response to regional neuronal activation and intracortical processing (71). At the moment the main use for the BOLD signal would be in secondary prevention trials where the signal would be used to predict conversion of MCI subjects to AD dementia. One approach is to use a cognitive paradigm that “stresses” the brain or structure that is known to be affected in the preclinical stages of the disease. For example a learning paradigm will activate the hippocampus and it has been shown to vary linearly from high to low from HC to MCI to AD dementia patient groups, respectively (72, 73). Another learning paradigm (encode face & name pairing) leads to a nonlinear response in hippocampus, with higher activation in MCI subjects compared to HC and AD dementia patients (74–77). Not only memory but also attention-related paradigms may be used as a secondary prevention biomarker such as working memory (78–80) and perceptual tasks (81–83).

Another strategy for BOLD-based biomarkers that could be used for secondary prevention trials are the intrinsic coherent networks (ICN) (84, 85). The biomarkers would be based on measures of neural network integrity, which have been shown to differentiate among HC, MCI subjects and AD dementia groups (86, 87) and also between HC groups with different amyloid loads (88, 89). Functional MRI based biomarkers could provide an approach to select patients for secondary prevention trials and to track progression from preclinical to clinical stages of the disease but also further work needs to be done to better understand the relationship between the BOLD signal and clinical changes.

As a primary prevention biomarker it still needs considerable research and development work, one of the primary issues is the potential confound between normal aging and development of AD-related pathology. Normal aging alters the potential fMRI biomarker (a recent review (90)) and alterations that are seen in MCI group (74–77) are similar due to middle aged HC with different ApoE status (91). The fMRI signal is shown to be dynamic and further investigation is required before the normal aging related changes can be separated from those due to pathology.

Based on these preliminary results, fMRI represents a promising approach for the selection and the stratification of individuals at risk of AD in clinical prevention trials.

Diffusion weighted imaging

Magnetic resonance diffusion weighted imaging quantifies the diffusion characteristics of water molecules in any tissue (92). White matter microstructure integrity can be estimated applying the tensor model to diffusion weighted images. In so doing, monocentric studies report an accuracy between 77% and 98% for diffusion tensor imaging (DTI) metrics of limbic white matter and of whole-brain voxel-based pattern classifiers (such as mean diffusivity and fractional anisotropy) in studies aimed to discriminate MCI individuals who progress and convert to AD dementia and those who remain stable over a follow-up of 1 to 3 years (93–96). DTI measures, however, are more prone to multicenter variability than classical volumetric MRI sequences (97). Despite higher multicenter variability, DTI

detected predementia stages of AD with a moderately higher accuracy than volumetric MRI in a multicenter setting using machine learning algorithms (98).

Longitudinal DTI studies are still rare, indeed, individuals with MCI and AD dementia showed declining integrity of intracortically projecting fiber tracts (99–101). One study has reported a moderate effect of treatment with a cholinesterase inhibitor on fiber tract integrity in AD dementia patients (102).

According to the currently available scientific evidence, DTI will be mainly used in secondary prevention trials to predict AD dementia in individuals with MCI. Currently, evidence demonstrating the potential use of DTI to predict cognitive decline and dementia in cognitively healthy elderly individuals is not sufficient for primary prevention trials. On theoretical grounds, based on the early involvement of axonal and dendritic integrity in AD pathology, such a use seems possible but requires multicenter DTI studies to be conducted in preclinical AD. The use of DTI metrics as a surrogate of fiber tract integrity for clinical trials seems questionable to date given the high vulnerability of DTI measures to scanner drift effects over time compared to classical volumetric MRI data. Future studies are needed to further clarify this issue.

In addition to DTI metrics, tractography of diffusion-weighted imaging (DWI) represents a challenging method to study white matter organization in AD prevention trials population.

Given the dense axonal organization of white matter tissues, water molecules will be more likely to diffuse along rather than across them. Hence, by sequentially piecing together discrete estimates of the brain's water diffusion, one might reconstruct continuous trajectory that follows the subjacent axonal organization. Using this approach, recent tractography studies identified an extended Papez circuit interconnecting essential areas dedicated to memory, emotion, and behavior (103). Indeed, axonal damage is associated with pathological behavioral manifestation (104, 105) and lead to drastic changes in the water diffusion properties that will affect the tractography reconstructions (106). Preliminary evidences have already associated discrete damage to these connections with early behavioral markers in AD (107, 108) and other dementia disorders (109). However, whether some of these anatomical changes occurred before the appearance of any behavioral signs is still unknown. It still needs to be shown if diffusion imaging tractography applied to pre-symptomatic populations may reveal exciting new footprints, which have the potential to model and predict the conversion from cognitive normality to the prodromal symptomatic stages of AD.

Utility of imaging platforms for AD prevention trials

Harmonization of image acquisition and analysis protocols is mandatory for increased statistical power and smaller sample sizes in AD prevention trials. Hence, following the seminal ADNI initiative (<http://adni.loni.usc.edu>), multiple regional imaging platforms have been set up (110, 111) either in the context of specific multicenter studies or as a service to any study such as the CATI multicenter neuroimaging platform (<http://cati-neuroimaging.com>), the neuGRID4you (<https://neugrid4you.eu>), the CBRAIN (<http://mcin-cnim.ca/neuroimagingtechnologies/cbrain/>), the LONI (<https://ida.loni.usc.edu/login.jsp>).

The service model aims at lowering the cost of imaging technology (<http://www.eurobioimaging.eu/>). The first objective of these platforms is the harmonization of a network of imaging facilities, data collection, rigorous quality control and standard analysis procedures. ADNI protocols are largely embedded in this kind of activity since they have become a standard (112). The second objective is the emergence of a broader spectrum of potential biomarkers, which can stem from new imaging modalities or from “head-to-head” evaluations of new analytic methods. Finally, these platforms generate normative values for determining trial sample size and for the future clinical use of biomarkers. With regard to the challenges ahead, it is eagerly required to create a superarching organization in charge of globally synchronizing this network of platforms to proceed further with the advent of standard protocols and data sharing. It is all the more crucial that a big data perspective is probably mandatory to generate the ultimate models required for the acceptance of imaging biomarkers as surrogate endpoints.

Molecular Imaging Markers: PET FDG, Amyloid, Tau, Neuroinflammation

Positron emission tomography (PET) provides specific imaging biomarkers for early detection and diagnosis and longitudinal assessment of molecular and functional changes associated with disease progression and therapeutic interventions. An increasing number of 18F-labeled tracers are now available for use at clinical sites, not requiring an on-site cyclotron and thus turning brain PET scans into a widely applicable routine tool in dementia research. This will provide detailed insight into human pathophysiology and the effects of early interventions that until recently could only be studied in experimental animals. In this section we will address current use of molecular markers for amyloid and tau, provide an update on FDG as a functional marker, and provide an outlook on new markers for neuroinflammation and transmitters.

Amyloid-PET imaging

Several tracers with similar properties (113), including 18F-florbetapir, 18F-florbetaben, and 18F-flutemetamol, are now being included into observational studies and intervention trials. Their visual analysis in a binary fashion as amyloid positive or negative has been thoroughly validated by post-mortem pathological assessment in AD (Figure 3 shows an example of PET amyloid uptake in controls and AD) (114). Although results are promising, methods for quantitative analysis have not yet reached the same degree of standardization, and more research is needed to understand inter-individual and longitudinal changes.

Several important prevention trials on autosomal-dominant AD (ADAD) and late-onset AD (LOAD) incorporating PET amyloid are currently on going (Table 1). The role of PET amyloid in the studies investigating the effect of monoclonal anti-amyloid antibodies varies from that of a primary outcome measure (one arm of DIAN-TU), to secondary outcome measure (API), to screening tool necessary to meet inclusion criteria (A4). In the A4 study, eligible participants must show evidence of elevated amyloid on both a semi-quantitative SUVr measurement and a qualitative binary visual read of a florbetapir PET scan. Amyloid PET is also being utilized as an exploratory outcome measure in A4, along with Tau PET (T807) in a subset of participants in the A4 study. A4 will also include an observational cohort with a group of participants who fell just below the threshold for amyloid eligibility

for A4 to determine the factors that predict rapid amyloid accumulation, as these individuals may be ideal candidates for future secondary prevention trials aimed at slowing the production of amyloid-beta.

Tau-PET imaging

In addition to amyloid-beta, deposits of hyperphosphorylated tau are the other main defining neuropathologic feature of AD. Until recently measurement of brain tau deposition has not been possible during life. Several PET ligands highly selective for tau deposits have now been applied to imaging of individuals along the AD spectrum, from cognitively normal to AD dementia. Initial experience with these ligands at a small number of centers (115, 116) indicates that binding is detected in the anatomic areas expected from AD pathology according to the ordinal Braak staging scheme (Figure 3). Thus, binding is observed in medial temporal areas in most cognitively normal older individuals, in additional limbic and neocortical regions among individuals with established AD-like cognitive impairment, and in more widespread neocortical regions among those with AD dementia. While within-subject longitudinal change in tau ligand binding has not yet been reported, the initial experience at the Massachusetts General Hospital in over 200 subjects using 18F-T807 PET suggests that the characteristics of this PET measure are potentially well suited for use in AD prevention trials. This new technology could potentially be used in clinical trials both to stage AD pathology and as a therapeutic endpoint.

FDG-PET imaging

While tracers for amyloid-beta and tau provide images of key pathological protein deposits, 18F-2-fluoro-2-deoxy-D-glucose (FDG) has already been used over many years as a functional marker of cortical synaptic dysfunction for diagnosis (117) and in clinical trials (118). Considerable progress has been made in recent years to derive quantitative biomarkers from FDG scans (119), while further standardization of analysis methods and longitudinal characterization of reference samples is still ongoing.

When applied to Mild Cognitive Impairment (MCI), FDG PET provides a good predictor of progression within the next 2 years (120), while markers of amyloid-beta and tau tend to become positive up to 20 years before actual onset of dementia. Recent studies comparing FDG and amyloid PET have revealed a substantial proportion of patients with amnesic MCI who have impaired FDG uptake while amyloid scans are negative (121). Contrary to the uniform sequential model of disease progression they show a relatively high rate of progression to dementia, and further research is required to clarify which type of dementia they actually suffer from. Considerable heterogeneity of AD subtypes and progression rates is well known from retrospective pathological studies (122), and longitudinal multimodal imaging studies including FDG are expected to provide better predictors and thus improve the efficacy of early intervention studies.

Inflammation- and receptor-PET imaging

Neurodegenerative diseases, including AD, are associated with activation of microglia. This leads to increased mitochondrial expression of the 18-kDa translocator protein (TSPO), which can be imaged using (R)-[11C]PK11195. Recent studies (123, 124) have partially

confirmed earlier findings of increased cortical binding potential in AD, but this increase could not be detected in individual patients and was much weaker than the signal on amyloid PET (125). In addition, (R)-[11C]PK11195 was not able to separate clinically stable prodromal AD patients from those who progressed to dementia, and there was no correlation with cognitive function.

More recently, many new TSPO ligands have been developed (126), and TSPO has also been identified as a potential drug target (127). In particular, studies using [11C]PBR28 have shown a signal that correlates with cognitive performance (128), providing a means for detecting changes early in the disease process. However, a major disadvantage of many new TSPO ligands is that, due to genetic polymorphism (129), a subpopulation of subjects will not show binding. There is a need for TSPO ligands that provide high signal, but are insensitive to this polymorphism. In addition, PET ligands for other molecular targets related to neuroinflammation, e.g. monoamine oxidase B located in astrocytes (130), are being investigated. AD is associated with failure of cholinergic neurotransmission, but its relation to clinical symptoms and disease progression is still poorly understood. Thus, ongoing research into development of suitable PET tracers (131) may allow future studies on the relation between pathological protein deposition and their functional interactions and consequences.

Value of multimodal imaging in prevention trials

With regard to preventive strategies of AD, in vivo multi-modal neuroimaging biomarkers may play an important role with regard to early and reliable detection of subjects at risk and to allow measuring of success/improve understanding of failure of therapeutic concepts. In this context, multimodal neuroimaging approaches are expected to be advocated on the basis of several important facts: (i) neurodegeneration in AD cannot be reduced to a singular pathological process in the brain. A number of different neuropathologies are known to be crucially involved in the development of this disorder and the causal interaction between these pathologies is not yet fully understood; (ii) it is well accepted that the onset of development/appearance of the mentioned pathologies in the brain may occur subsequently not simultaneously. Consequently, the presence/detectability of these pathologies depends on the stage of disease; (iii) it has been demonstrated that the temporal development of these different pathologies over time is neither linear, nor parallel to each other (132–134).

These facts explain the potential of multimodal imaging approaches. Several of the characteristic forms of neuropathology known to be involved in AD such as protein aggregation (A β and tau), synaptic dysfunction, inflammation and neuronal loss/brain atrophy can be captured using in vivo imaging procedures. However, not a single one out of these pathologies is fully specific for AD (i.e. they can be found in other forms of neurodegeneration as well). Thus, in recent guidelines on the diagnosis of AD, improved diagnostic certainty or increased risk for underlying AD has been proposed for a combination of different disease biomarkers (32). These guidelines divide between markers of A β peptides aggregation pathology (including amyloid PET imaging) and markers of neuronal injury (including structural/volumetric MRI and FDG-PET imaging). The authors suggest that cumulative evidence obtained by biomarkers out of these two categories

increases the probability for ongoing AD even in preclinical stages. This directly applies to the detection of subjects at risk for AD, e.g. in prevention trials.

It is well accepted that amyloid-pathology may be detectable in the brain of subjects suffering from AD long before clinical symptoms occur and, possibly, also ahead of detectable neuronal injury. However, little is known so far about the time to symptomatic onset in amyloid-positive subjects without cognitive deficits. Furthermore, it has been demonstrated that amyloid-deposition seems to reach a plateau in later stages of AD, whereas markers of neuronal injury seem to better mirror the continued progression of cognitive decline. Consequently, only a multimodal combination of information on amyloid-pathology and neuronal injury may allow a reliable *in vivo* disease staging, particularly ahead of clinical disease onset.

Generally, the classification of disease biomarkers into only 2 categories may represent an oversimplification (135). Depending on the type of prevention approach, higher resolutions of disease stages may be possible and the spectrum may be completed with other available imaging biomarkers, e.g. of tau-aggregation, inflammation, connectivity or receptor status (136–139).

With regard to therapy monitoring or measuring success of any prevention methods, any one-dimensional biomarker assessment may fall short. With regard to the dynamic non-linear and non-parallel natural courses of the different neurodegenerative pathologies over time, relevant changes may be overlooked and inter-patient differences may be interpreted incorrectly. Furthermore, interventions may influence single parameters without effect on other pathologies, e.g. inhibit amyloid-aggregation pathology without slowing down the ongoing cascade of neuronal injury.

The recent introduction of PET/MR technology may represent the ideal tool for multimodal imaging approaches, particularly in longitudinal prevention trials. The systematic combination of complementary MRI and PET-methods may offer a number of advantages leading to the optimal diagnostic assessment and disease quantification with the least possible burden for the patient (Figure 4). Suitable PET/MR examination work-flow protocols have already been published for the assessment of neurodegenerative disorders (140). In short, such protocols may allow for acquisition of data in high quality (motion and partial volume corrected), providing information on neuronal dysfunction, protein aggregation pathology and atrophy and at the same time exclude non-neurodegenerative diseases in a single patient visit.

In summary, multimodal imaging assessment of different types of neuropathology might be designated as the method of choice for a reliable and specific detection and quantification of AD *in vivo*, and, thus, represent the approach of choice for prevention strategies.

Established and potential CSF biomarkers

At present, there are three gold standard (“core feasible”) CSF biomarkers for AD molecular pathology: total tau protein (T-tau) that reflects the intensity of neuronal/axonal degeneration, hyperphosphorylated tau protein (P-tau) that probably reflects neurofibrillary

tangle pathology and the 42 amino-acid-long form of amyloid β ($A\beta_{1-42}$) that is inversely correlated with $A\beta$ pathology in the brain (low lumbar CSF levels reflect sequestration of the peptide in the brain parenchyma) (141). The biomarkers detect AD with an overall accuracy of 85–95% in both dementia and MCI stages of AD and appear to switch to pathological levels 10–20 years before the first symptoms become recognizable (142). Recently revised diagnostic criteria for AD suggest that biomarkers for both tau and $A\beta$ pathology should be positive if an AD diagnosis is to be made (27). Here, CSF provides a biomarker source covering both these aspects and the assays for T-tau, P-tau and $A\beta_{1-42}$ are currently undergoing standardization for such use; the most important international standardization efforts being the Alzheimer's Association Quality Control program for CSF biomarkers (143, 144), the Alzheimer's Association Global Biomarkers Standardization Consortium (GBSC) (145) and the International Federation of Clinical Chemistry and Laboratory Medicine (IFCC) Working Group for CSF Proteins (WG-CSF) (145). Standard operating procedures (SOPs) for CSF sampling and storage have been published (141). As an outcome from the IFCC WG-CSF and the GBSC, the Single-Reaction Monitoring (SRM) mass spectrometry candidate Reference Measurement Procedures (RMP) for $A\beta_{1-42}$ has been published (146), and certified reference material is being developed. These will be used to harmonize measurements between assay formats and to assure longitudinal stability and minimize batch-to-batch variations, and thereby serve as the basis for the introduction of uniform cut-off values and a more general use of CSF biomarkers in clinical routine and trials. Updates on the work within the GBSC are available at: http://www.alz.org/research/funding/global_biomarker_consortium.asp.

Recent data show that it is possible to identify longitudinal changes in CSF $A\beta_{1-42}$, T-tau and P-tau in cognitively healthy controls followed with multiple lumbar punctures over several years (147–149), but most studies (with exceptions (147)) show that CSF AD biomarkers are essentially stable in symptomatic AD (150–152). This biomarker stability may be useful in clinical trials to help identify effects of interventions, both on the intended biological target, such as altered $A\beta$ metabolism in response to an anti- $A\beta$ treatment (18). One of the truly longitudinal studies of cognitively normal individuals with repeated CSF samples suggests that $A\beta_{1-42}$ and T-tau changes occur in parallel and predict upcoming cognitive symptoms better than absolute baseline levels (149). CSF measurements may track trajectories of specific $A\beta$ and APP metabolites (153–156), and down-stream effects on secondary phenomena, such as reduced axonal degeneration in response to a disease-modifying drug as measured by CSF tau levels (157, 158). So far, unfortunately, these changes have not predicted clinical benefit of any anti-AD drug (159).

In addition to T-tau, some CSF biomarkers reflecting neuronal and axonal damage, including visinin-like protein 1 (160) and heart-type fatty acid-binding protein (H-FABP) (161) show a clear increase in AD and correlates with CSF t-tau. Further, a number of novel biomarkers that should be relevant to the disease process in AD are under development. These include markers of synaptic degeneration (e.g. the dendritic protein neurogranin (162)), microglial activation (e.g. chitinase-3-like protein 1, CHI3L1, also called YKL-40 (163)) and protein homeostasis/lysosomal dysfunction (e.g. lysosomal-associated membrane proteins 1 and 2, LAMP-1 and LAMP-2 (164)). An overview of CSF biomarkers and their interpretation in the scenario of AD prevention trials is reported in Table 2.

There is also a critical need for biomarkers to identify co-morbidities, including blood-brain barrier dysfunction, cerebrovascular disease, and Lewy body and TDP-43 pathologies, that could resemble or aggravate AD.

Evolving blood biomarkers

The identification of blood-based biomarkers that have utility in clinical trials for AD is of great importance (165), as they have been recently included as secondary outcome measures in many ongoing trials (Table 1). Blood-based biomarkers and biomarker profiles have been shown to be highly accurate in detecting and discriminating amongst neurodegenerative diseases (19, 166–169) and may serve as a cost-effective first step in a multi-stage screening process for clinical trials (17). As an example, Kiddle (166) and colleagues recently cross-validated the link between 9 markers from previously published studies and AD-related phenotypes across independent cohorts using an independent assay platform (SOMAscan proteomic technology). Recently, O’Bryant and colleagues (168) also cross-validated a serum-based biomarker profile using an independent assay platform (Meso Scale Discovery; 21-protein profile AUC=0.96; 8-protein profile AUC=0.95), across species (mice and humans) and tissues (serum and brain tissue). The proteomic profile approach was also able to extend further and accurately discriminate AD from Parkinson’s disease (168). If demonstrated effective in primary care settings, these blood-based profiles for detection of AD could provide access to clinical trials far beyond what is currently available through specialty clinic settings (168). Additionally, blood-based approaches have been shown capable of detecting A β burden (170, 171). Using data from the Australian Imaging, Biomarkers and Lifestyle (AIBL) cohort, a plasma proteomic signature consisting of chemokine 13, IgM-1, PPY, VCAM-1, IL-17, A β 42, age, ApoE genotype and CDR sum of boxes yielded an AUC=0.88 in AIBL and an AUC=0.85 when applied to the ADNI cohort. The existence of a blood-based screener for A β positivity would provide a cost-effective means of screening patients into trials requiring A β positivity on PET scans (17, 170).

Preliminary work also suggests that blood-based profiles can identify patients at risk for progression from MCI to AD (172,173) as well as from cognitively normal towards some level of cognitive impairment (174, 175). Along these lines, recent work identified a 10-protein (plasma) algorithm (TTR, clusterin, cystatinC, A1AcidG, ICAM1, CC4, pigment epithelium-derived factor, A1At, RANTES, ApoC3) that when combined with ApoE genotype predicted progression from MCI to AD with an optimal accuracy of 87% (sensitivity = 0.85, specificity = 0.88) (172). Mapstone and colleagues (174) also provided preliminary data suggesting that a set of 10 lipids can predict progression from control to MCI/AD over a 2–3 year period. Kivipelto and colleagues (37) generated a risk score from the Cardiovascular Risk Factors, Aging and Dementia (CAIDE) study consisting of ApoE genotype, total cholesterol, systolic and diastolic blood pressure, demographics (age, education, gender), and lifestyle (smoking status, Body Mass Index [BMI], physical inactivity) factors that predicted increased risk for dementia over a 20-year period. Each of these methods has potential use in the identification and selection of patients into novel preventative and therapeutic clinical trials. Blood-based biomarkers can be also employed for patient stratification in trials. For example ApoE ϵ 4 which is the strongest risk factor for AD and correlates well with CSF A β 1–42 levels and increased amyloid burden and has been

used for patient stratification into clinical trials (e.g. ClinicalTrials.gov; identifiers: NCT00574132 and NCT00575055). Recent data also suggests serum/plasma ApoE protein levels are lower among ApoE carriers (169) and that plasma ApoE levels correlate with amyloid PET (176). Therefore, serum/plasma ApoE protein and ApoE genotype may be useful in patient stratification for trials (165). Crenshaw and colleagues (177) generated a patient stratification algorithm based on ApoE $\epsilon 4$ genotype and the TOMM40 gene. Risk stratification per this algorithm assigns all ApoE $\epsilon 2/\epsilon 2$ and $\epsilon 2/\epsilon 3$ carriers to the low risk group with all ApoE $\epsilon 4$ carriers then assigned to the high risk group. Next, for all non-ApoE $\epsilon 2$ carriers, risk stratification varied by TOMM40 genotype and age. This risk stratification scheme was designed for a preventative trial targeting Pioglitazone for the prevention of cognitive loss (177). Moreover, prior work has suggested that blood-based biomarkers can be utilized for the identification of AD-based endophenotypes (17, 167, 178) with additional work needed to determine if these endophenotypes can predict which groups of patients are more likely to respond to specific interventions (165). Recent findings presented at the Alzheimer's Association International Conference (AAIC) suggest this is a promising line of investigation. As has been pointed out previously, additional work is needed regarding harmonization of methods for this work to progress (17, 179) with the first guidelines for pre-analytical methods now available (180).

Genetic tests and risk factors for Alzheimer's disease

AD occurrence and evolution, as for most complex chronic diseases, result from the interactions between environmental factors and an individual susceptibility. The very first genetic determinants have been described for rare hereditary early onset clinical forms almost 25 years ago: the A β precursor protein gene (APP), the presenilin 1 (PSEN1) and the presenilin 2 (PSEN2). These three loci were rapidly followed by the discovery of strong and consistent associations of the apolipoprotein E (ApoE) isoforms with late-onset AD. Then, it is only during the last five years, and thanks to large-scale international collaborations such as the AlzGene database (<http://www.alzgene.org>) (181) and high throughput genotyping progresses, that the deciphering of the genetic susceptibility to sporadic AD has rapidly progressed, leading to the identification of 20 confirmed loci, and of 16 putative others (182). The population attributable risk/preventive fractions of each of these loci vary from 27.1% for the ApoE $\epsilon 4$ allele to less than 2% (Table 3). This allows for the establishment of a more precise picture of the genetic susceptibility background associated with the occurrence of late-onset AD, adding to the list of biomarkers a new tool, useful for AD diagnosis and prognosis.

However, the use of this information in current clinical practice still remains limited. In the dominant early onset hereditary forms, when a causal mutation can be identified (in half of these early onset forms), presymptomatic genetic testing could be performed following the protocols issued from the Huntington disease experience by the World Federation of Neurology (183). In late-onset AD, despite a high attributable fraction, the ApoE $\epsilon 4$ allele is not recommended for diagnosis because of its low sensitivity and specificity. Conversely, in clinical and translational studies, genomic biomarkers are of the utmost interest. For instance, when studying AD cases, ApoE $\epsilon 4$ allele is now a common risk factor to systematically register, adjust and stratify on, as age, gender and educational level. Today, it

is a major requirement to collect DNA in any clinical study or drug trial and the decreased costs of sequencing offer a unique opportunity to access the genetic susceptibility information of each enrolled individual.

The characterization of the 40 known susceptibility locus genotypes constitutes a major biomarker that can be usefully added to CSF biological measurements and PET imaging. This information helps to stratify the heterogeneity of AD clinical forms and identify specific subgroups with different disease evolution and therapeutical answers. This pharmacogenomics stratification based on the potential biological pathways underpinned by the specific genetic background of each patient, helps to better understand the possible mechanism of action of drugs. In primary and secondary AD prevention trials including asymptomatic patients, the identification of this genetic susceptibility allows to select individuals with the highest risk and the very best chances to benefit from these preventive approaches, improving the statistical power of such studies.

The access to genomics information plays also a major role in the discussions about the efficiency of active and passive anti-A β immunotherapies in AD treatment (184). Genomics offer the best opportunity to identify presymptomatic individuals with AD causal mutations or at very high risk of developing AD to better appreciate the potential curative interest of these drugs at a stage where the resilience of cognitive functions is still possible. Thus, the DIAN-TU consortium has initiated a phase II/III randomized, double-blind, placebo-controlled multi-center study of two potential disease modifying therapies in presymptomatic mutation carriers and their non-carrier siblings; a prevention trial is also conducted in 300 symptom-free individuals 30 years of age and older from a large Colombian family with a mutant gene (PSEN1 E280A) and another one in volunteers aged 60 to 75, homozygous for the ApoE ϵ 4, without cognitive impairment is in preparation (35). Considering the increasing knowledge and dissemination of these biomarkers based on genetic information, ethical concerns must be carefully taken into account, especially as direct-to-consumer tests develop for diseases as AD where no therapeutic solution is available yet.

Novel Advances and Research Frontiers : High-field MRI, and neurophysiological EEG-MEG markers

High-field of MRI such as (3T and higher) and ultra-high fields (7T and higher) as well as EEG-MEG techniques push further the possibilities of developing new biomarkers able to select and to monitor the disease in primary prevention trials.

High-fields of MRI: 3T MRI is widely available for clinical trials and the number of ultra-highfield 7T scanners is increasing rapidly as well, with about 40 7T scanners for humans currently installed worldwide (185).

An important contribution of high-field MRI to AD biomarkers is the possibility to measure hippocampal subregions. Indeed, hippocampal subparts show distinct vulnerability to the AD pathological process, as demonstrated by neuropathological studies (186). Such measurements are usually based on T2-, T2*- or proton-density-weighted sequences with

high in-plane resolution (about 200 μm –500 μm). At 3T/4T, it is possible to detect atrophy in different hippocampal subfields, such as CA1 and the subiculum (187, 188). 7T MRI provides higher contrasts, increased signal-to-noise ratio and higher spatial resolution, which dramatically improve the visualization of hippocampal subregions. This makes it possible to quantify the atrophy of distinct hippocampal layers associated with AD, such as the stratum pyramidale and the strata radiatum, lacunosum and moleculare (SRLM), and not only subfields (189–191). These measures have the potential to provide more sensitive and specific biomarkers than global hippocampal volumetry but require further validation in larger samples.

Another important area of research is the detection of amyloid plaques using high-fields MRI. Such detection has been demonstrated in transgenic mouse models of AD (192, 193), as well as in non-transgenic mouse lemur primates in which plaques are more similar to those formed in humans (194). In vivo detection in humans of amyloid plaques by high-fields MRI is an important challenge for the upcoming years and might open promising scenario in prevention AD trials.

Ultra-high-field MRI also improves the assessment of vascular burden associated with AD. Cerebral microbleeds are often found in patients with AD and are likely to be due to frequent association between AD and cerebral amyloid angiopathy. 7T MRI, using T2*-weighted sequences or susceptibility weighted imaging (SWI), provides increased sensitivity to detect cerebral microbleeds (195, 196). 7T can also improve in vivo detection of microinfarcts. A recent 7T study reported an increased number of microinfarcts in AD patients compared to controls 197 while another study reported no difference (198).

Electroencephalography (EEG) and magneto encephalography (MEG) modalities (199, 200) are complementary techniques to high-field MRI due to their ability to detect the dynamic behavior of neuronal assembly circuits in the brain and to provide non-invasive time-dependent capabilities with sub-millisecond precision, especially in regard to cortical structures. Two main EEG/MEG biomarker approaches have emerged in using these techniques in AD research—evaluation of localized measures and inter-area connectivity indices (201). Localized neurodynamics biomarkers, such as band power or signal strength/phase, can characterize the change of the dynamic state of a brain area either through spontaneous brain oscillations or event-related activity (202). Evidence points to abnormal slowing of faster alpha and beta cortical rhythms especially in posterior regions and increase of slower delta- and theta-band activity in AD (203). Short- and long-range connectivity estimates, on the other hand, offer high sensitivity to evaluate the integrity of brain pathways or reduction of central cholinergic inputs, if employed properly (204). EEG/MEG connectivity biomarkers have revealed the existence of an entire new class of approaches able to manifest, for example, impaired functional synchrony in the upper alpha and beta bands in AD (205), and declining global synchronization in all frequency bands (206). While the full potential of EEG (207) and MEG (208) biomarkers to characterize degenerative brain changes for primary AD prevention has yet to be realized, a substantial number of studies have demonstrated results compatible with secondary prevention trial strategy. Although numerous studies have investigated the feasibility of EEG/MEG biomarkers in varying degrees, they still could be considered an emerging approach in AD

trials, and especially in prevention trials, due to the complexity and multidimensionality of the observed dynamic signals, as well as the need to achieve a converging consensus among studies for better understanding of the disease pathology and its time-dependent aspects.

Regulatory Requirements and evolving challenges

As there is now consensus that effective therapies for AD have to start very early in the disease process after the many failures of development programs, European Medicines Agency (EMA) and food and drug administration (FDA) are reacting to these changes. FDA and EMA suggest potential approaches to clinical trial design and execution that allow for regulatory flexibility and innovation (209, 210). It is outlined that clinical diagnosis of early cognitive impairment might be coupled with specific appropriate biomarkers reflecting in vivo evidence of AD pathology. New diagnostic criteria addressing these issues have been established and are under validation by various working groups (18, 26, 27, 211, 212). Most biomarkers include brain A β and Tau load, as measured by PET and CSF levels of A β and tau proteins (22, 213), however, there is a clear move to update the amyloid hypothesis and to look for new biomarkers for the different disease stages (214, 215).

However, adequate standardization and validation of these biomarkers for regulatory purposes is still lacking as described by Noel-Storr and colleagues (2013) (216). As far as the CSF biomarkers are concerned, it was recently reported that the overall variability of data coming from a total of 84 laboratories remains too high to allow the validation of universal biomarker cut-off values for its intended use (217), which underpins the urgent need for better harmonization and standardization of these methods.

The use of biomarkers as endpoints in earlier stages of drug development is well established for regulators, and there are examples to approve medicinal products on the basis of their effects on validated surrogate markers, eg, anti-hypertensives, or cholesterol-lowering products. However, these examples have been considered as validated surrogate markers as they allow substitution for a clinically relevant endpoint. In their validation a link between a treatment-induced change in the biomarker and long-term outcome of the relevant clinical measure was undoubtedly established. Therefore the regulatory requirements on biomarkers used as endpoints in clinical trials are high as outlined earlier (210). In consequence EU regulators help applicants in their research and development by issuing opinions on the acceptability of using such biomarkers or a distinct methodology in clinical trials. Since 2011, EMA's Committee for Medicinal Products for Human Use (CHMP) has adopted and published several qualification opinions for use in the development of medicines for AD. In these qualification opinions biomarkers are accepted for identification and selection of patients at the pre-dementia stage of the disease as well as for selection of patients for clinical trials in mild and moderate AD. In September 2013, a qualification opinion for a novel model of disease progression and trial evaluation in mild and moderate AD was adopted by CHMP. The simulation tool is intended to provide a quantitative rationale for the selection of study design and inclusion criteria for the recruitment of patients.

The EMA guideline on the clinical investigation of medicines for the treatment of AD will be updated on the basis of new knowledge obtained from the validation of the new

diagnostic criteria, the use of biomarkers in clinical evaluation and other recent trends in research and development. A first draft will be available soon, in a 2-day workshop later this year the draft will be presented and discussed with the involved stakeholders. The final guidance should help regulators and industry to decide on the most appropriate study design for the distinct stages of AD, particularly in its early preclinical/prodromal stage.

Conclusions & perspective on a decade-long initiative on prevention

The discovery-validation of a broad spectrum of interventions, including pharmacologic, behavioral and life-style treatments, remains a crucial global public policy objective (218–222). Although a series of clinical trials for treating AD dementia have failed during the last two decades, these setbacks have not deterred the confidence of investigators in pursuing the strategic goal of acquiring disease-modifying treatments, which would ameliorate the progression of neurodegeneration with the eventual aim of preventing the onset of symptoms. The optimism of the scientific community, regarding the technical feasibility of discovering strategies to slow or halt neurodegenerative process is conditional, predicated by the availability of adequate resources and our capabilities to surmount the major barriers that are hindering progress of research on prevention. In this scenario, as emerged from the current review, the role of neuroimaging and biological markers is crucial. In particular, they are involved in the future development of technologies algorithms identifying the better combination able to detect accurately the early stages of disease or the prognosis in asymptomatic people at elevated risk. Moreover, they could be essential to select sample of prevention trials and, ultimately, they might be employed as surrogate measure to assess drugs treatment efficacy.

Some of the critical challenges need to be addressed in order to accelerate the pace of Research and Development (R&D) of interventions for prevention.

The first challenge refers to the development of new paradigms and conceptual models for R&D on therapies. The sequential failure of clinical trials based on prevailing theories on dementia along with emerging new knowledge about the complexity of the biology underlying the disease has created the need to re-assess our assumptions about its etiology and the adoption of new paradigms for therapy development. At the present, there is growing consensus that AD is a heterogeneous disorder, a syndrome rather than a disease, with polygenic origins where multiple putative risk factors influence the prolonged progression of neurodegenerative processes. These biological features will require radically different thinking and new approaches to therapy development. In particular, the adoption of concepts from ‘systems theory’ might be well suited for guiding the formulation of new conceptual models for teasing out the complexities of this disease.

The second challenge addresses the issue of developing technologies to accurately detect individuals at elevated risk – among asymptomatic populations. Indeed emerging knowledge showed that the cellular and molecular mechanisms leading to neurodegeneration start decades prior the onset of clinical symptoms of AD. For this reason, prospective prevention trials in the future will require the employment of treatments in the earlier asymptomatic or prodromal phases of neurodegeneration. Presently, crucial rate-limiting factors, which

hinder the launch of true prevention trials are: (i) the lack of well-validated technologies for identification of asymptomatic people at elevated risk for the disease; (ii) the need for a reliable measure of disease progression – i.e. a surrogate marker allowing for precise tracking of one or more biological indices of the neurodegenerative process.

The third critical challenge to consider is the need for novel original therapeutic targets, new molecules and paradigms for efficacy validation. In this context, the strategic goal is to enrich the drug discovery pipeline by investigating a wide array of options for therapy development. Notably, this issue may have been exasperated by the limitations of current theories, conceptual models, or even ideas about the pathogenesis of AD and dementia disorders, which have provided a dominant framework and paradigm for drug discovery-development efforts thus far.

Finally, taking into account all the above issues, novel/different regulatory requirements for demonstrating efficacy based on revised guidelines or definitions of outcomes measurements are also required.

In conclusion, the major challenge to contend with will be the development of R&D resources for a multinational prevention initiative. The convergence of several unique features of AD (e.g. heterogeneity, complex polygenic etiology, and prolonged asymptomatic pre-clinical phase of neurodegeneration) highlights the need for very large cohorts of well-characterized cohorts from various genetic/cultural backgrounds as potential volunteers for both: a) longitudinal epidemiological studies to discover and/or validate putative risk factors and b) clinical studies for prospective validation of potential preventive interventions. A massive international longitudinal database on health aging and pre-dementia or at risk populations, as a shared R&D resource, is an essential infrastructure to address the future needs of a major prevention initiative. Along with a 'Big-Data', the field of therapy development will require novel computational capabilities to not only sort out the complex interactions among multiple etiologic factors but also to discover and validate technologies for the early and accurate detection of the disease (220–222).

In spite of many great strides in understanding AD, the lack of effective interventions for chronic brain disorders along with the rapid expansion of the aging population at risk for dementia pose an ever-increasing threat to the solvency of healthcare systems worldwide. The scope and magnitude of this global health-economic crisis demands a commensurate response; fortunately, many countries have begun to develop national plans to address the scientific, social, economic, and political challenges posed by dementia. There are several parallel efforts that reflect the global concerns and international efforts to formulate strategies for overcoming these challenges - e.g. the Organization for Economic Co-operation and Development (OECD) Expert Conferences/G-8 Dementia Summit/Post G-8 Legacy Meeting (218–221, 223). However, the open question remains whether these prospective plans for action will convince policy-makers worldwide to make the necessary financial commitments to significantly increase R&D resources for prevention.

The first 'call to arms' for a global mobilization of all necessary resources to address the looming crisis due to the exponential increases in the prevalence of dementia was made in a

1992 editorial (224). In 1997, nearly two decades ago, in a Congressional Testimony on the ‘Prospects of Prevention’, the Alzheimer’s Association (available at <http://www.alz.org/>) made the case for a radical shift in therapy development towards a strategy of ‘Prevention’ (225). In 2009, once again, there was a call to launch a major international initiative called The Campaign to Prevent Alzheimer’s Disease by 2020 (PAD2020) (available at <http://www.pad2020.org/>) (226). Nearly a quarter of a century after the first plea for action, the worldwide scientific community is well poised to make a quantum advance towards the strategic objectives of preventing dementia. The earlier calls for adoption of alternative paradigms to focus for therapies towards prevention were considered untenable goals. To date, however, there is an overwhelming optimism in the field with respects to the prospects of developing disease modifying intervention to delay the onset of disabling symptoms; and eventually to prevent (218, 226). The prevailing consensus is that current symptomatic treatments are woefully inadequate, indicating an urgent need to re-focusing R&D paradigms towards disease-modifying interventions.

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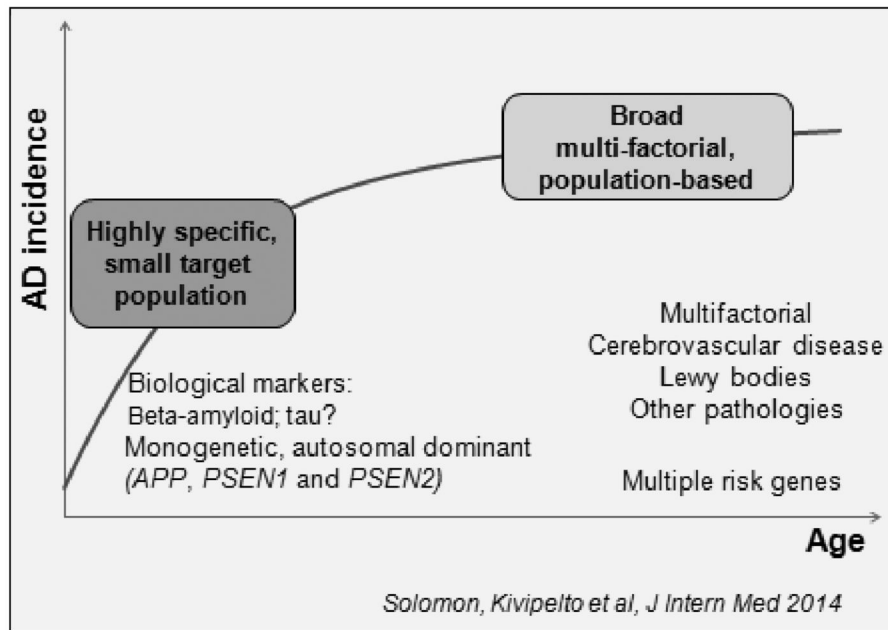


Figure 1.

Prevention approaches. The range of prevention approaches include one targeting highly specific populations (biomarker evidence for AD pathology) with specific targeted interventions (e.g. anti-amyloid). Another approach is broad, multi-factorial, population-based, and non-specific. Both approaches are needed and we should probably work more in the 'area between' these approaches, combining potential treatments and interventions and to various at-risk populations. (With permission, Solomon et al 2014) (24)

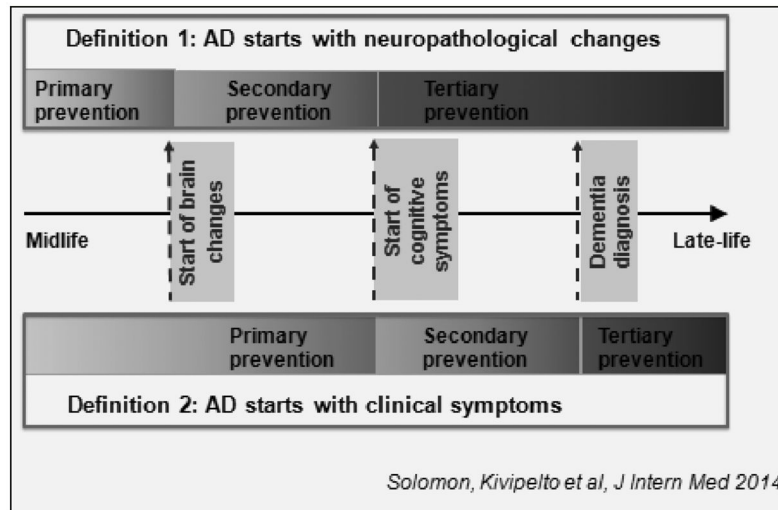


Figure 2. How disease definition affects prevention. The figure illustrates how two alternative definitions of AD (i.e., definition 1, disease defined as starting with neuropathological changes, and, definition 2, disease starting with clinical symptoms) lead to different definitions of primary, secondary and tertiary prevention. The differences between the definitions may blur distinctions between prevention and treatment strategies. For example, if Abeta-PET positivity is considered and accepted as diagnostic for AD (i.e., pre-clinical AD) then treating such a sample would be an example of secondary prevention rather than primary (237). Alternatively, if Abeta-PET positivity is considered a risk for the future development of cognitive impairment and Alzheimer pathology then treatment would be considered as primary prevention (238, 239). These frameworks show that it is difficult to define pure primary vs secondary prevention. (With permission, Solomon et al 2014) (24)

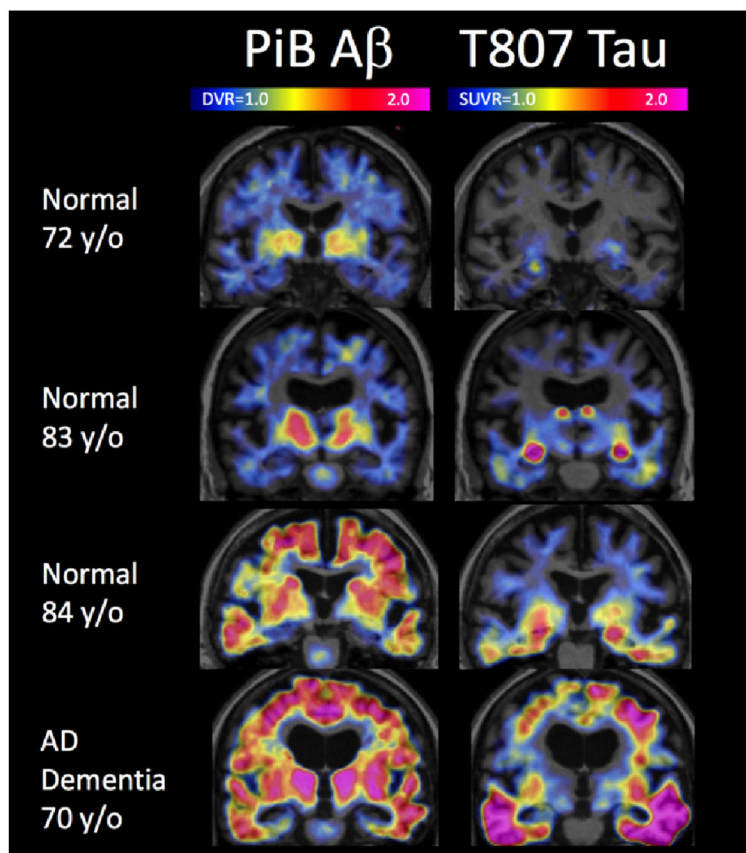


Figure 3. Positron Emission Tomography Staging of AD pathology. Coronal Positron Emission Tomography images (overlaid with structural Magnetic Resonance) of PiB A β (left column) and T807 Tau (right column) acquired from 3 normal individuals (top 3 rows) and a patient with AD dementia (bottom row). Low levels of amyloid are seen in the top 2 cases and high levels in the bottom 2. T807 binding is particularly striking in medial temporal lobe in the middle 2 normal cases, possibly corresponding to Braak Stage III/IV, but is more intense and widespread in the AD dementia case, which is consistent with Braak V/VI

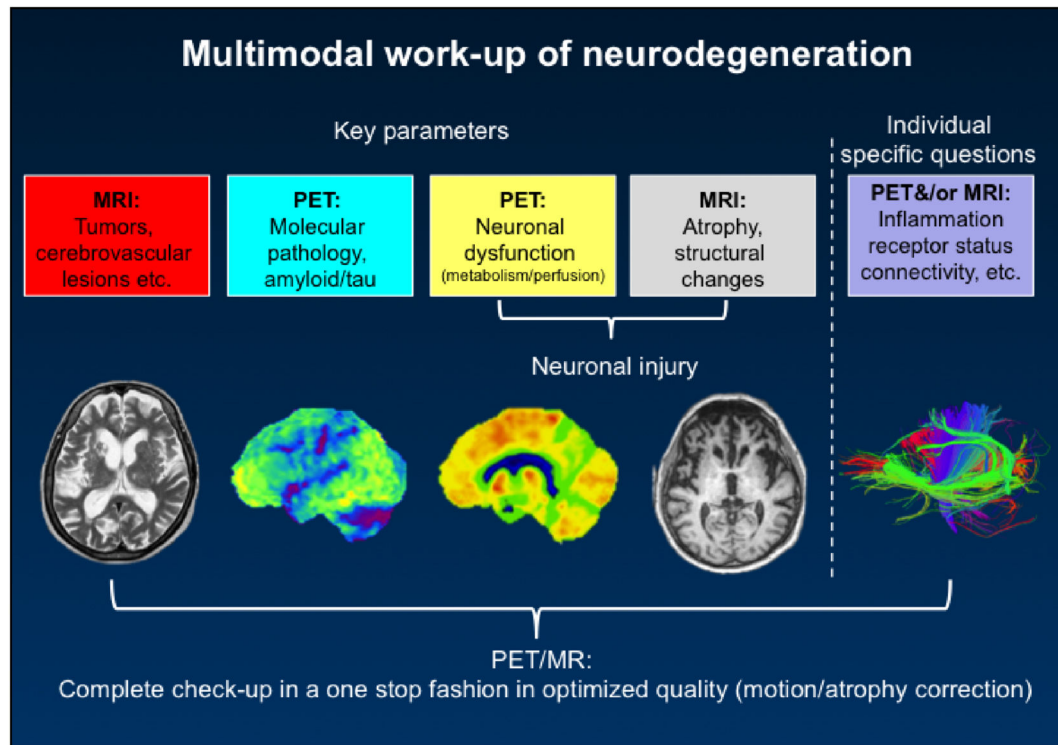


Figure 4. Multimodal work-up of neurodegeneration, opportunities for combined Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI)

Table 1

Biological and imaging markers currently used in prevention trials

Primary Prevention							
Study (clinical Trials.gov Identifier)	Status	Sample	Intervention	Markers of Incl/Excl criteria	Stratification	Biomarkers as Secondary Outcome	
MAPT NCT00672685	(recruitment completed)	Frail elderly	Omega-3 Fatty Acids and/or Multi-domain Intervention			MRI atrophy FDG-PET	Disease modification (227)
SimBio NCT01142336	(recruiting)	Asymptomatic	Simvastatin			CSF Aβ42, t-tau, p-tau181 and BDNF	Disease modification
Secondary Prevention							
Study (clinical Trials.gov Identifier)	Status	Sample	Intervention	Markers of Incl/Excl criteria	Stratification	Biomarkers of Outcome	Use
API NCT01998841	Phase II (recruiting)	Asymptomatic	Crenezumab	PSEN1 E280A	PSEN1 E280A	MRI atrophy rate FDG-PET amyloid PET	Disease modification (33, 35)
DIAN-TTU NCT01760005	Phase II/III Trial (ongoing recruiting)	Asymptomatic	Gantenerumab, Solane zumab, LY2886721	PS1 PS2 carriers	PS1 PS2 carriers	MRI (cortical thickness) FDG-PET amyloid PET	Disease modification (28)
PREVENT-Alzheimer	To be approved	Asymptomatic family history of AD	Naproxen, Nasal Insulin			MRI rate of atrophy	Disease modification
TOMMORROW NCT01931566	Phase III (recruiting)	Asymptomatic	Pioglitazone	TOMM40-523 and ApoE ε4			
AD-A4 Trial NCT02008357	Phase III (recruiting)	Asymptomatic	Solanezumab	Positive amyloid PET		volumetric MRI SUVR CSF Abeta42 and Tau levels	Disease modification (29, 30)
NCT00597376	Exploratory (completed)	Memory Complaints	Cerefolin NAC			Plasma Aβ42/40 ratio	Memory complaints
Tertiary Prevention							
Study (clinical Trials.gov Identifier)	Status	Sample	Intervention	Markers of Incl/Excl criteria	Stratification	Biomarkers of Outcome	Use
NCT01055392	Phase II (completed)	aMCI	Lithium			CSF Aβ42, total Tau, p-Tau	Target Engagement (228)
NCT00438568	Phase II (completed)	aMCI	Intranasal Insulin			CSF Aβ42, total Tau, p-Tau, 18-FDG-PET "Plasma biological markers"	Disease modification (229)
NCT01595646	Phase II (active, not enrolling)	aMCI	Intranasal Insulin			Plasma Biomarkers of AD (Aβ39, Aβ40, Aβ42), Tau (total and phosphorylated)	Disease modification
NCT01072812	Phase I (Unknown)	aMCI	Posiphen tartrate			Plasma and CSF APP, Aβ40, Aβ42, AChE, BChE	

Primary Prevention									
Study (clinical Trials.gov Identifier)	Status	Sample	Intervention	Markers of Incl/Excl criteria	Stratification	Biomarkers as Secondary Outcome	Indication	Ref	
NCT01811381	Phase II (recruiting)	aMCI	Curcumin and Yoga			Clusterin, CRP, NT-proBNP, ApoE, Aβ, VCAM1, BDNF, IL6, IL1b, IL1ra, TNFα, osteopontin.			
InDDEX study NCT00000174	Phase IIIb Trial (completed)	MCI	Rivastigmine			Hippocampal and Whole brain atrophy rate, ventricular dilatation rate	Disease modification	(230)	
NCT00620191	Phase II Completed	MCI	Metformin			18-FDG-PET Plasma Aβ42	Disease modification		
NCT00236574	Phase III Trial (completed)	MCI	Galantamine			Brain and Hippocampal rate of atrophy	Disease modification		
NCT00000173	Phase III Trial (completed)	MCI	Donepezil and Vitamine E			Brain, Hippocampal, ERC rates of atrophy, ventricular dilatation rate	Disease modification	(67)	
NCT00267163	Phase IV Trial (completed)	age-associated memory impairment	Donepezil			Change in brain hypometabolism and MRI	Disease modification		
Hippocampus Study	completed	Prodromal AD	Donepezil			Hippocampal rate of atrophy	Disease modification	(231)	
NCT01600859	Phase I Trial (completed September 2013)	MCI due to AD	E2609			Positive biomarker for amyloid β	Target Engagement		
NCT01561430	Phase II Trial (completed August 2013)	MCI due to AD	LY2886721			Positive amyloid PET	Target Engagement		
NCT00890890	Phase II Trial (completed July 2013)	Prodromal AD	BMS-708163 (Avagacestat)			CSF Aβ40, Aβ42, total Tau, p-Tau and plasma Aβ40, Aβ42	Disease modification		
NCT01953601	Phase III Trial (ongoing recruiting)	Prodromal AD	MK-8931			Positive [18F]flutemetamol PET	Disease modification Target Engagement		
NCT01224106	Phase III Trial (ongoing not recruiting)	Prodromal AD	Gantenerumab (RO4909832)			amyloid PET	Disease modification		
NCT01767311	Phase II Trial (recruiting)	MCI due to AD	BAN2401			Hippocampal rate of atrophy, amyloid PET	Disease modification		
NCT01677572	Phase I Trial (recruiting)	Prodromal	BIIB037			MRI, Change in 18F-AV-45 PET scan	Safety Disease modification		

Phase I trials on healthy volunteers and study with a sample size <30 were excluded. Abbreviations: MCI, Mild Cognitive Impairment; aMCI, amnesic MCI; AD, Alzheimer's Disease; A, amyloid-β; P-tau, phosphorylated tau; T-tau, total tau; MRI, Magnetic Resonance Imaging; 18-FDG-PET, 18F-2-fluoro-2-deoxy-D-glucose positron emission tomography

Table 2

Cerebrospinal fluid biomarkers in prevention trials

Application	Method	Biomarkers	Interpretation
Identification of individuals with AD pathology	CSF samples from individuals analyzed during the screening period for enrolment into a clinical trial	A β 42, T-tau, P-tau	Low A β 42 is indicative of cortical AD A β deposition, and is likely the first CSF biomarker that become positive. The combination of low CSF A β 42 together with high T-tau and P-tau is indicative of AD, and may thus be used for enrichment of early AD in the trial.
Theragnostics	CSF samples taken before study initiation and at time-points during the trial including end-of-study	A β 42, A β 40, sAPP β	The amyloid biomarkers may provide evidence of target engagement of an anti-Ab drug candidate, e.g. a BACE1 inhibitor.
		P-tau	A change towards normalization in CSF P-tau may provide evidence of an effect of a drug candidate on tau phosphorylation state or tangle formation.
		T-tau, H-FABP, VLP-1	Downstream biomarkers, e.g. T-tau, may provide evidence of an effect of a drug candidate on the on the intensity of neuronal degeneration. Biomarkers not directly involved in AD pathogenesis, e.g. H-FABP and VLP-1, may give complementary information to T-tau.
		Synaptic proteins	A change in synaptic biomarkers, e.g. neurogranin, may provide evidence of an effect of a drug candidate on synaptic function and degeneration.
		Inflammation and microglial activity	A change in CSF biomarkers reflecting microglial activity, e.g. YKL-40, may additional evidence of downstream drug effects.

Abbreviations: Ab, amyloid-b AD, Alzheimer disease BACE1, b-site APP cleaving enzyme 1 CSF, cerebrospinal fluid H-FABP, Heart fatty acid-binding protein MRI, magnetic resonance imaging PET, positron emission tomography P-tau, phosphorylated tau sAPP, soluble amyloid precursor protein extracellular domain T-tau, total tau VLP-1, visinin-like protein-1

Table 3

Population attributable/preventive fractions of AD loci (182)

SNP	Gene	MAF	PAF(%)	Effect type
$\epsilon 4$ allele	<i>ApoE</i>	0.123	27.3	risk
rs6733839	BIN1	0.366	8.1	risk
rs10792832	PICALM	0.365	5.3	preventive
rs9331896	CLU	0.398	5.3	preventive
rs35349669	INPP5D	0.462	4.6	risk
rs983392	MS4A6A	0.406	4.2	preventive
rs6656401	CR1	0.191	3.7	risk
rs1476679	ZCWPW1	0.293	3.2	preventive
rs9271192	HLA	0.277	3.2	risk
rs11771145	EPHA1	0.350	3.1	preventive
rs28834970	PTK2B	0.358	3.1	risk
rs2718058	NME8	0.368	2.9	preventive
rs4147929	ABCA7	0.162	2.8	risk
rs190982	MEF2C	0.389	2.7	preventive
rs10838725	CELF1	0.312	2.4	risk
rs10948363	CD2AP	0.255	2.3	risk
rs10498633	SLC24A4/RIN3	0.212	1.5	preventive
rs17125944	FERMT2	0.079	1.5	risk
rs11218343	SORL1	0.044	1.1	preventive
rs7274581	CASS4	0.088	1.1	preventive