Alzheimer's & Dementia®
THE JOURNAL OF THE ALZHEIMER'S ASSOCIATION

FEATURED ARTICLE

Menopause hormone therapy significantly alters pathophysiological biomarkers of Alzheimer's disease

Herman Depypere[1] | Andrea Vergallo[2] | Pablo Lemercier[2] | Simone Lista[2] |
Andrea Benedet[3] | Nicholas Ashton[3,4,5,6] | Enrica Cavedo[2] |
Henrik Zetterberg[3,7,8,9,10] | Kaj Blennow[3,7] | Eugeen Vanmechelen[11] |
Harald Hampel[2] | the Neurodegeneration Precision Medicine Initiative (NPMI)

[1]Department of Gynecology, Breast and Menopause Clinic, University Hospital, Coupure Menopause Centre, Ghent, Belgium

[2]Sorbonne University, Alzheimer Precision Medicine (APM), AP-HP, Pitié-Salpêtrière Hospital, Boulevard de l'hôpital, Paris, France

[3]Department of Psychiatry and Neurochemistry, Institute of Neuroscience and Physiology, the Sahlgrenska Academy, University of Gothenburg, Gothenburg, Sweden

[4]Wallenberg Centre for Molecular and Translational Medicine, Department of Psychiatry and Neurochemistry, Institute of Neuroscience and Physiology, the Sahlgrenska Academy, University of Gothenburg, Gothenburg, Sweden

[5]King's College London, Institute of Psychiatry, Psychology & Neuroscience, Maurice Wohl Clinical Neuroscience Institute, London, UK

[6]NIHR Biomedical Research Centre for Mental Health & Biomedical Research Unit for Dementia at South London & Maudsley NHS Foundation, London, UK

[7]Clinical Neurochemistry Laboratory, Sahlgrenska University Hospital, Mölndal, Sweden

[8]Department of Neurodegenerative Disease, UCL Institute of Neurology, Queen Square, London, UK

[9]UK Dementia Research Institute at UCL, London, UK

[10]Hong Kong Center for Neurodegenerative Diseases, Hong Kong, China

[11]ADx NeuroSciences, Ghent, Belgium

Correspondence
Herman Depypere, Department of Gynecology, Breast and Menopause Clinic, University Hospital, Coupure Menopause Centre, Ghent, Belgium.
Email: Herman.depypere@ugent.be

[Correction added on 21 September 2022, after first online publication: The order of the first and last names of the authors had been reversed and this has been corrected in this version.]

Abstract

Introduction: This increasing body of literature indicates that menopause hormonal replacement therapy (MHT) may substantially mitigate the risk of developing late-life cognitive decline due to progressive Alzheimer's disease (AD) pathophysiology. For the first time, we investigated the question whether MHT impacts AD biomarker-informed pathophysiological dynamics in de-novo diagnosed menopausal women.

Methods: We analyzed baseline and longitudinal differences between MHT-taking and -not women in terms of concentrations of core pathophysiological AD plasma biomarkers, validated in symptomatic and cognitively healthy individuals, including biomarkers of (1) the amyloid-β (Aβ) pathway, (2) tau pathophysiology, (3) neuronal loss, and (4) axonal damage and neurodegeneration.

Results: We report a prominent and significant treatment response at the Aβ pathway biomarker level. Women at genetic risk for AD (APOE e4 allele carriers) have particularly shown favorable results from treatment.

Discussion: To our knowledge, we present first prospective clinical evidence on effects of MHT on AD pathophysiology during menopause.

1 | INTRODUCTION

Decades of failing late-stage neuropharmacological trials and highly variable therapeutic outcomes in current healthcare suggest that merely adjusting statistical regression models for sex may not be sufficient when it comes to an appropriate understanding of the question why sex-based biological differences may account for substantially different risk rates of disease.[1–3] Evidence clearly indicates that there is an increased age-independent prevalence of Alzheimer's disease (AD) in women compared to men (average odds ratio is 1.6) and that it is consistent with sexual dimorphism in AD pathophysiology, spanning molecular pathways of brain proteinopathies, neurodegeneration, neuroinflammation, and large-scale high-order organization of the brain.[4–12] In addition, women who experience early menopause, either naturally or iatrogenic, represent the highest risk cluster within the menopause population of late-life cognitive decline and dementia.[13,14]

The higher vulnerability of perimenopausal (transition phase) and early-menopause women than men has been established by large-scale neuropsychological studies, post-mortem investigations, biomarker-based studies, data-driven multi-variate analysis, and experimental models of aging and AD. Multi-modal imaging studies corroborate the evidence of sexual dimorphism in AD biology and specifically indicate a positive association of (peri)menopause status with AD proteinopathies, neuronal loss and neurodegeneration, and cognitive outcomes.[6,15–17] In all these inter-sex comparison studies, the reported sexual dimorphism related to AD risk is clearly not significantly impacted by age, generating and supporting the hypothesis that midlife endocrinological, hormonal change patterns-rather than aging-related metabolic pathways-may drive/trigger/facilitate AD related pathophysiological events. This evidence-driven model is consistent with the established effects of sexual steroids on physiological neurodevelopment, which also account for the sexual dimorphism of global brain volume, regional gray- and white-matter density, shape, and volume of regional anatomical structures.[4,18,19]

Systematic and single-center studies provide indirect evidence of an endocrine-mediated AD risk in menopause since the chronic use of menopausal hormone therapy (MHT)-a therapeutic approach to mitigate menopause associated signs, symptoms, and complications-reduces the incidence of AD. [2,5,20]

The timing of MHT commencement is an additional significant factor concerning the AD-risk and long-term clinical outcomes.[2,5,20] Longer exposure to MHT (estrogen/progestogen) may trigger and facilitate neuroprotective pathways, as suggested by the calculated risk reduction of AD equal to 0.5% for every extra-month of steroids intake.[21,22]

While initiating MHT early during menopause seems significantly protective against development of AD, a delayed therapeutic program may less likely be effective.[5,22,23] Moreover, sub-analysis of the large-scale randomized Women's Health Initiative (WHI) clinical trial show that delayed MHT may even enhance the risk of vascular incidents and worsen an established dementia syndrome.[23–25]

In the present university-based expert outpatient menopause clinic prospective study, we recruited cognitively healthy women who had

RESEARCH IN CONTEXT

1. **Systematic Review**: Women in menopause have a 1,67 higher risk to develop Alzheimer's disease. Menopausal hormone treatment (MHT) and related timing of initiation significantly reduces the risk of AD in this population.
2. **Interpretation**: We report a prominent MHT response at the $A\beta$ pathway biomarker level, more pronounced in APOE ε 4 allele carrier women. This is the first prospective clinical evidence on the effects of MHT on Alzheimer's disease pathophysiology during menopause.
3. **Future Directions**: If corroborated, these data hold the potential to support menopause- Alzheimer's disease joint screening for timely and precision medicine interventions.

recently transitioned to menopause and met the indication criteria and were prescribed MHT (i.e., natural estrogens and progesterone).

We assessed the baseline and longitudinal concentrations of validated core pathophysiological AD plasma biomarkers, including biomarkers of (1) the amyloid-β (Aβ) pathway, (2) tau pathophysiology, (3) neuronal loss, and (4) axonal damage and neurodegeneration.

The Aβ pathway, currently known as the earliest biochemical and pathophysiological cycle occurring in the AD biological continuum by[26] analyzing Aβ peptide 42 over Aβ peptide 40 (Aβ-42/Aβ-40 ratio)[27] and protein concentrations of the β-site amyloid precursor protein cleaving enzyme 1 (also known as β-secretase 1 or BACE1).[28,29]

Plasma Aβ1-42/Aβ1-40 ratio has close concordance with amyloid-PET status.[27] BACE1 plasma concentration is hypothesized to reflect levels of gene expression of BACE1, and are associated with brain Aβ concentrations, axonal damage, and neurodegeneration biomarkers, volumetric loss in the cholinergic circuitry, and cognitive scores.[12,28,30,31]

We further implemented tau protein phosphorylated at threonine 231 (p-tau$_{231}$), a particularly early indicator of AD related tau protein phosphorylation and neurofibrillary pathology,[32] rate of hippocampal atrophy [33] and rate of regional brain atrophy, longitudinal patterns of brain networks functional decline, and indirectly reflects Aβ plaque rates of deposition when combined with Aβ1-42 in a composite value (Aβ1-42/p-tau$_{231}$ ratio). [34,35] Plasma NfL and to a lesser extent total tau (t-tau) are surrogate biomarkers of axonal damage, neurodegeneration, and neuronal loss, respectively.[28,36]

The primary objective of the present study was to investigate whether women receiving MHT show significantly different longitudinal changes of core pathophysiological AD plasma biomarkers compared with women who opted out of MHT. The second objective was to address the question whether age and the presence of at least one APOE ε4 allele may influence biomarker expression and trajectories and partially explain potential significant inter-group differences (treated vs. untreated menopausal women).

2 | MATERIALS AND METHODS

Women consulting the University-based academic expert Breast and Menopause Clinic, at the Ghent University Hospital and the Coupure Menopause Clinic in Ghent were proposed to participate in the present prospective, interventional study. The study was approved by the ethical board of the University of Ghent (Belgian registration number: B670201835724/ clinicaltrial.gov number is NCT04312399). The core eligibility criteria were the established diagnosis of menopause, the condition of drug-naïve for MHT, no medical contraindications to MHT, the preservation of normal global cognition and the absence of risk factors for acute onset of cognitive impairment (see section "Global cognition").

Additional inclusion criteria were: normal blood pressure at study baseline, normal thyroid function parameters; normal values of urea, glucose, electrolytes, ALAT, homocysteine, vitamin B12, vitamin B9, cholesterol, and triglycerides. Moreover *APOE* genotyping was performed. The use of pharmacological treatments such as antihypertensives, thyroid medication, lipid/cholesterol lowering medication, antidiabetic drugs, psychotropic medications were exclusion criteria to participate in the study. This was done to exclude comorbidity that could influence the risk of AD development. Body mass index (BMI) and adherence to the Mediterranean diet were also quantified and recorded.

2.1 | Treatment assignment

Given the multi-dimensional (medical, psychological, and social) burden of menopause on the individual experiencing it,[37] we opted to give the women the possibility to decide which treatment/control arm to be allocated in, that is, whether starting an MHT program.

MHT was prescribed in accordance with the guidelines of international societies IMS, EMAS, NAMS, and NICE.[38] Women with a history of hysterectomy or in women with a levonorgestrel-releasing intrauterine system (LNG-IUS),[39] natural oral or transdermal estrogen was prescribed. All other women were prescribed a combination of estrogen and natural progesterone. Natural progesterone was used, since it offers a well-documented protection for the endometrium,[40] is safe for the breast,[41] and does not interfere with the beneficial effects of estrogens on the serum lipid profile.[42]

Oral or transdermal route of estrogen supplementation was prescribed according to the woman's preference. If a woman opted for an oral estrogen, estradiol valerate 1 mg (Progynova 1 mg once daily) was prescribed. If a woman opted for a transdermal intake of hormones, an estrogen gel (Oestrogel two doses per day) or spray (Lenzetto two spray applications per day) was used. If, women had menopausal complaints, but after extensive counselling about the advantages and risks of MHT, opted not to take hormonal therapy, they were asked to participate in this trial as controls. Women without menopausal complaints, who met inclusion criteria for the study, were equally asked to participate in this trial as controls.

Hereafter, women who underwent a therapeutic MHT program are identified in the "MHT" arm, whereas women who opted out for any MHT treatment are identified in the "control" arm.

2.2 | Global cognition

Medical exclusion criteria were a diagnosis of mild cognitive impairment/dementia, any type of disease potentially affecting cognition in the short- or long-term, including severe cardiac comorbidities (severe congestive heart failure -NYHA III-IV-; severe arrhythmias),[43] severe psychiatric comorbidities, alcohol and/or substances abuse (excluding nicotine) according to the Diagnostic and Statistical Manual of Mental Disorders-fifth edition (DSM-V),[44] uncompensated hepatic/renal/metabolic, endocrine disorders. These clinical data were based on information provided by patient and caregiver, and all the available medical records.

All individuals had achieved the high-school education level. The neuropsychometric-based baseline inclusion criterion was a Mini Mental State Examination (MMSE), a measure of global cognition,[45] with a score below 25 out of 30 (raw values). This cutoff was used to rule out individuals who may exhibit objective cognitive impairment in one or more cognitive domains if tested with an extensive psychometric battery.[46] We did not assess MMSE at V2 since we do not expect significant changes in the global cognition status over the 6-month follow-up.

2.3 | Blood collection, pre-analytical processing, and AD plasma biomarkers assessment: Analytical protocols

Blood withdrawal was performed at V1 and V2 following the same pre-analytical protocol. BD vacutainers n#368861 (K2 EDTA as anticoagulant) were used for blood collection. All blood samples were handled in a standardized way and centrifuged at 1200 × g during 15 min. After that, the plasma was extracted, aliquoted per 1 ml, and frozen at –80°C within 1 h. Aliquoting was done in Sarstedt PP tube 1.5 ml (Cat No 72.694.105) using PP tips Greiner Cat No 741050. Six months later, participating women had another blood draw. Plasma and whole blood were subsequently stored at –80°C. The subsequent neurological plasma parameters were all determined in one run to exclude inter-assay variation.

Plasma t-tau and NfL concentrations were measured using the Single molecule array (Simoa) Tau2.0 and the NF-Light Advantage assays, respectively (Quanterix, Billerica, MA). The p-tau231 concentration was measured using an in-house Simoa assay on an HD-X Analyzer (Quanterix, Billerica, MA), as previously described.[34]

Plasma BACE1, $A\beta$1-42, and $A\beta$1-40 were measured at ADx NeuroSciences, Ghent, Belgium. The previously described amyblood assay[47] was used to measure plasma $A\beta$1-42 and $A\beta$1-40 was used to measure plasma $A\beta$1-42 and $A\beta$1-40.
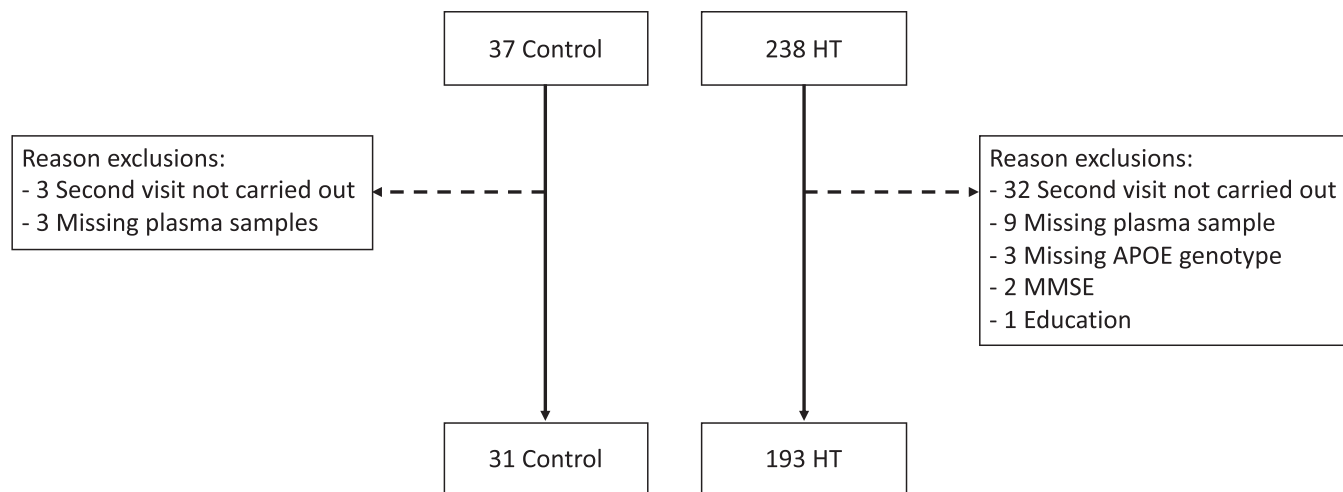
FIGURE 1 Study design overview of the study inclusion / exclusion flowchart

See Supplementary Methods for more details about the AD plasma biomarkers assessment.

2.4 | APOE genotyping

APOE variants were genotyped by sequencing at the Genetic Service Facility (GSF, www.vibgeneticservicefacility.be) of the VIB Department of Molecular Genetics, in line with previous works carried out by the same group.[48]

3 | STATISTICAL ANALYSIS

The statistical analyses were conducted on the 224 participants who had no missing data on plasma biomarkers collected at the two time-points, education, MMSE, and APOE genotype (see study flow-chart illustrated in Figure 1). The Gaussian distribution and homoskedasticity were checked visually through histograms and density plots with normal probability density function curve overlaid as well as Q-Q plots. To perform group-wise comparisons for categorical and continuous variable, we used Pearson's chi-squared test and Student's t-test, respectively.

Outliers were visually inspected for each single biomarker and not for the composite ratio values.

We used linear models (LM) to assess the potential difference of plasma biomarkers concentrations at V1 (baseline) between the two study groups (treatment vs. non-treatment). Age and APOE ε4 carrier status (presence vs. absence) were included as covariates, to rule out potential confounding effect and to better weight in on treatment effect size in case of significant results. For longitudinal analysis, we calculated the annual rate of change (ARC) as the difference in plasma concentration between the two visits (V1 and V2) divided by the delay in years.[49]

$$ARC = \frac{Concentration\ at\ V1 - Concentration\ at\ V2}{Delay\ in\ year} \quad (1)$$

We used LM to test whether the two study groups may have a different ARC. Age and APOE ε4 status were set as covariates.

To follow, we performed an additional subgroup analysis to examine whether APOE ε4 status impacts the treatment effect on plasma biomarkers. We used a LM with an interaction term between the group (MHT arm or control arm) and APOE ε4 status (APOE ε4 status*group). Eventually, we performed post-hoc analysis to breakdown significant results and capture the difference between each pair of subgroups created by the interaction term.

For all models, we reported regression coefficients (β) and standard error (SE). In addition, effect sizes were estimated using partial Cohen's f2, which represent the amount of variance of the response variables (outcome) that is explained by an explanatory variable (predictor) after accounting for other predictors in the regression model.[50] All tests were two-sided and p-values, p < .05 were considered significant in all statistical elaboration. Influent data points on model outputs were inspected through Cook's distance. When the distance is equal or higher than 1, models were refitted with a robust regression to consider the presence of influent data point.[51] Since the plasma biomarker investigated track partially independent molecular pathways, we ran separate LM for each biomarker and applied no correction of p.

Statistical analyses were performed using R software, version 4.0.5. Robust linear models, post-hoc analyses, and Cohen's f2 were carried with the libraries "MASS", "emmeans", and "effectsize", respectively, all available at http://cran.r-project.org/web/packages.

4 | RESULTS

4.1 | Group-wise comparison for socio-demographic and clinical features

V1 socio-demographic features, clinical measures and scores, APOE ε4 status are reported in Table 1. In the 224 women participating in this study 67 (29.9%) were genotyped as carriers of at least one APOE ε4 allele. The percentage of APOE ε4 carriers was not significantly

TABLE 1 Sociodemographic variables, MMSE, and APOE ε4 status at V1

	Control (n = 31)	MHT (n = 193)	Total (n = 224)	p value
Age, in years				
Mean (SD)	55.69 (4.94)	53.76 (4.63)	54.03 (4.71)	.03[a]
APOE ε4 status				
ε4-negative	21 (67.7%)	136 (70.5%)	157 (70.1%)	.76[b]
ε4-positive	10 (32.3%)	57 (29.5%)	67 (29.9%)	
APOE genotype				
ε2/ε2	0 (0.0%)	1 (0.5%)	1 (0.4%)	.83[b]
ε2/ε3	6 (19.4%)	24 (12.4%)	30 (13.4%)	
ε2/ε4	0 (0.0%)	3 (1.6%)	3 (1.3%)	
ε3/ε3	15 (48.4%)	111 (57.5%)	126 (56.2%)	
ε3/ε4	8 (25.8%)	43 (22.3%)	51 (22.8%)	
ε4/ε4	2 (6.5%)	11 (5.7%)	13 (5.8%)	
MMSE score				
Mean (SD)	29.77 (0.56)	29.52 (1.07)	29.55 (1.01)	.19[a]
Familial AD				
No	24 (77.4%)	146 (75.6%)	170 (75.9%)	.83[b]
Yes	7 (22.6%)	47 (24.4%)	54 (24.1%)	

Abbreviations: *APOE*, apolipoprotein E; Familial AD, familial history of Alzheimer's or other neurodegenerative diseases with prominent cognitive impairment, MHT, menopause hormone therapy, MMSE, Mini Mental State Examination.

[a]Student's *t*-test.

[b]Pearson's chi-squared test.

different between the control and the MHT study arms (Table 1). There was no group-wise difference in terms of MMSE scores. Women enrolled in the control group were significantly older than participants enrolled in the MHT arm ($p = .033$). No significant differences but a trend was present in education levels with the control group having lower levels ($p = .055$). The mean delay between V1 and V2 was 7.2 ± 2.4 months in the control group and 6.7 ± 1.6 months in the MHT group, with no significant between-group difference.

4.2 | Baseline and longitudinal comparison between MHT and control arms for AD biomarkers

Description of plasma biomarkers at baseline and follow-up, and the ARC are reported in Table S1. We report no significant differences for plasma concentrations of AD biomarkers result from the V1 and V2 comparison of women enrolled in the MHT arm versus untreated women. As expected, LM shows that age is positively associated with a few AD biological pathways, as indicated by the Aβ1-42/p-tau$_{231}$ ratio, BACE1, and NfL (all $p < .05$). Such an age-wise significant association faded out at the follow-up (longitudinal changes of biomarkers).

In addition, we observe an expected cross-sectional and longitudinal trend in the *APOE* ε4 positive group, exhibiting lower levels of plasma Aβ1-42 concentrations at baseline compared to the *APOE* ε4 negative group (baseline: Figure 2, $\beta = -3.18$, SE = 1.65, $p = .055$, Cohen f2 = 0.02, and longitudinal: $\beta = 4.32$, SE = 2.35, $p = .067$, Cohen f2 = 0.02).
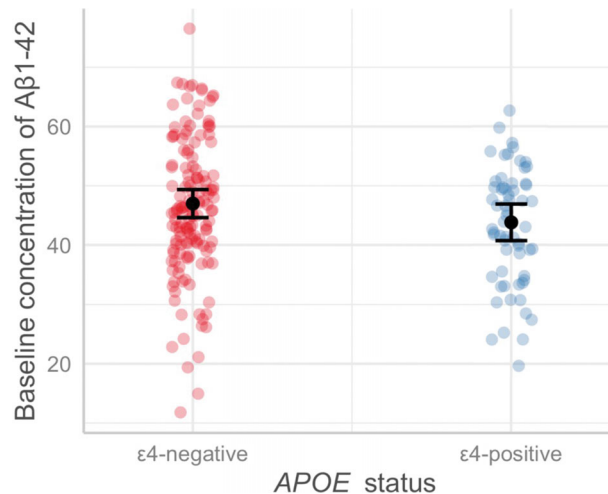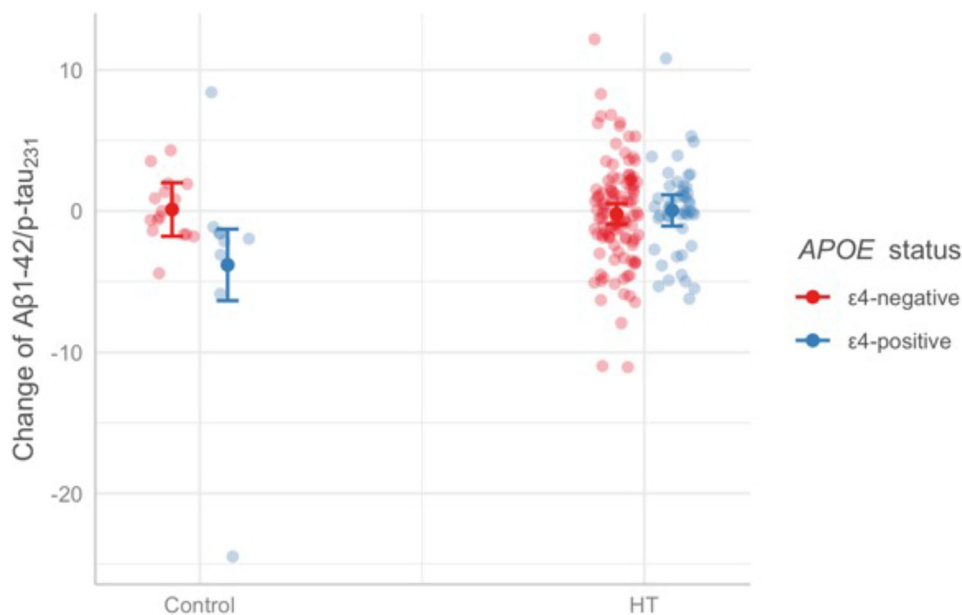

FIGURE 2 Plasma Aβ1-42 concentrations at V1 according to *APOE* ε4 allele carrier status (positive or negative). *Notes*: The values represented refer to the estimated marginal means computed based on the linear model to account for the effect of age and treatment groups. Aβ, amyloid-β; APOE, apolipoprotein E; V1, baseline visit

4.3 | Longitudinal *APOE*-wise comparison between MHT and control arms for AD biomarkers

The MHT-control groups difference for Aβ1-42/p-tau$_{231}$ ratio is significant at the longitudinal analysis. At the 6-month follow-up evaluation

FIGURE 3 Longitudinal changes of the Aβ1-42/p-tau$_{231}$ ratio according to treatment group and *APOE ε4* allele carrier status (positive or negative). *Notes*: The values represented refer to the estimated marginal means computed based on the linear model to account for the effect of age. *Post-hoc* pairwise group comparison: Control *APOE ε4*-negative - MHT *APOE ε4*-negative: $p = 0.76$, Control *APOE ε4*-negative - Control *APOE ε4*-positive: $p = 0.02$, Control *APOE ε4*-negative - MHT *APOE ε4*-positive: $p = 0.95$, MHT *APOE ε4*-negative - Control *APOE ε4*-positive: $p = 0.008$, MHT *APOE ε4*-negative - MHT *APOE ε4*-positive: $p = 0.71$, Control *APOE ε4*-positive - MHT *APOE ε4*-positive: $p = 0.007$. Aβ, amyloid-β; *APOE*, apolipoprotein E; MHT, menopause hormone therapy; p-tau$_{231}$, tau protein phosphorylated at site threonine 231

and biomarker assessment, the effect of treatment still differs according to *APOE ε4* allele status ($\beta = 4.18$, 1.74, $p = .02$, Cohen f2 = 0.03), with the pairwise subgroups comparison indicating that controls with *APOE ε4* showed greater reduction in Aβ1-42/p-tau$_{231}$ ratio levels than both MHT group individuals *APOE ε4* allele carriers and non-carriers ($p = .007$ and $p = .008$ respectively, see Figure 3 and Table S2)). Although Aβ1-42/p-tau$_{231}$ ratio does not differ between the two MHT subgroups split by *APOE ε4* status, the MHT *APOE ε4*-positive individuals exhibit a significantly greater reduction of Aβ1-42 levels than the MHT *APOE ε4*-negative individuals ($p = .03$, see Figure 4 and Table S2).

Moreover, *APOE ε4* carrier control individuals have significantly different levels of Aβ1-42/p-tau$_{231}$ ratio than non-carriers ($p = .02$, Cohen f2 = 2.65e-3, see Figure 3 and Table S2). MHT group individuals carrying at least one *APOE ε4* allele have smaller reduction of Aβ1-42 than *APOE ε4*-negative treated women (see also Figure 4). Of note, HT *APOE ε4*-positive women have a mild within-group increment of plasma Aβ1-42 over time (2.41, 95% confidence interval [CI] -1.83 to 6.65; $p = .26$), while HT *APOE ε4*-negative women show a significant longitudinal reduction of the same biomarker (-3.17, 95% CI -5.89 to 0.46, $p = .02$). The two MHT subgroups show opposite directions, albeit with slight changes, in p-tau$_{231}$ levels with either an increase or a decrease in *APOE ε4*-positive and ε4-negative women, respectively. Notably, control *APOE ε4*-positive individuals display an average higher increment rate of p-tau$_{231}$ levels than each MHT subgroups (and the control *APOE ε4*-negative individuals as well). Hence, it is conceivable to infer that the effect of MHT in *APOE ε4*-positive women is on the Aβ pathway.

5 | DISCUSSION

To our knowledge, this is the first-ever prospective longitudinal study performed with healthy, MHT-naïve women during menopause who underwent two time point assessments of an extensive panel of blood-based biomarkers charting AD pathophysiological processes, including the Aβ and tau pathways, axonal damage, neurodegeneration. We report that MHT is associated with smaller changes toward AD pathophysiology than no-therapy (control groups) and that *APOE ε4* allele carrying condition is associated with an amplified treatment outcome. Specifically, the most prominent effect of MHT on AD pathophysiological biomarkers focuses on the Aβ pathway, an early and central AD patho-biochemical cycle which defines and propagates progression in the disease continuum. Such a result is consistent with (a) the clinical features of the study cohort, cognitively healthy women with no familial history of AD; and (b) previous molecular imaging studies (Aβ-PET) reporting that women in menopause have higher rates of brain Aβ accumulation, especially in *APOE ε4* carriers.[4–12]

Our findings are also in agreement with the large-scale, randomized WHI study showing that MHT can reduce the risk of late-life dementia and indicated that the timing of MHT influences this outcome. In this sense, our study provides preliminary biological context for the WHI clinical results.[24,25] Moreover, our results are in line with structural neuroimaging studies showing that perimenopausal women not treated with MHT have significantly greater AD-vulnerable regions
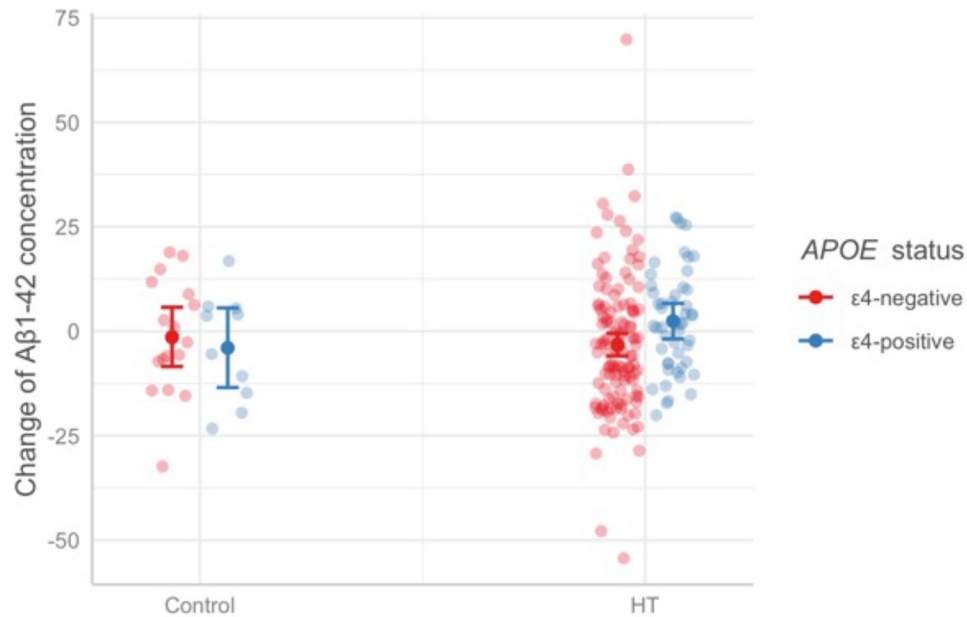
FIGURE 4 Longitudinal changes of Aβ1-42 concentrations according to the treatment group and *APOE ε4* allele carrier status (positive or negative). *Notes*: The values represented refer to the estimated marginal means computed based on the linear model to account for the effect of age. *Post-hoc* pairwise group comparison: Control *APOE ε4*-negative - MHT *APOE ε4*-negative: $p = 0.64$, Control *APOE ε4*-negative - Control *APOE ε4*-positive: $p = 0.67$, Control *APOE ε4*-negative - MHT *APOE ε4*-positive: $p = 0.37$, MHT *APOE ε4*-negative - Control *APOE ε4*-positive: $p = 0.88$, MHT *APOE ε4*-negative - MHT *APOE ε4*-positive: $p = 0.03$, Control *APOE ε4*-positive - MHT *APOE ε4*-positive: $p = 0.23$. Aβ, amyloid-β; *APOE*, apolipoprotein E; MHT, menopause hormone therapy

volumetric reduction (a surrogate marker of regional neuronal loss and neurodegeneration) over time.[17,52]

We provide preliminary evidence of an MHT-associated effect on core biomarkers of AD pathophysiology, especially the central Aβ pathway (currently the target of late-stage anti-Aβ drug developments) and mostly in females carrying the *APOE ε4* risk allele, the greatest genetic risk factor for late-onset AD.[53]

A recent study investigating sexual dimorphism in AD brain endophenotypes showed for the first time that the accumulation of soluble Aβ aggregates was higher in women than men, especially in peri-menopausal and post-menopausal women carrying the *APOE ε4* allele.[54]

The *APOE ε4* allele-wise effect we found in the MHT arm is consistent with other therapeutic approaches for AD, either symptomatic or candidate disease-modifying drugs, reported to be associated with better cognitive-functional outcomes in *APOE ε4* allele carriers.[55–57]

Clinical and animal models indicate the menopause-related risk of AD in women is non-linearly increased by the presence of the APOE ε4 allele.[53,58–60] Mouse models suggest that estrogen upregulates the APOE gene, whereas progesterone acts antagonistically to estrogen at the gene expression level. It is hypothesized that such balanced cross-talk is impaired during menopause.[59] Therefore, all these clinical-biological findings are backed by mouse models of aging and AD showing that induced estradiol deficiency is associated with cognitive worsening, synaptic decline, and AD biological signatures.[58,61–64]

Stratifying pharmacological clinical trial outcomes for female sex alongside concomitant intake of MHT may uncover specific population clusters with selective response rates to pathways-targeting drugs.[65] This reasoning may apply to late stage-development/already approved anti-Aβ treatments and developing anti-tau compounds, given the experimental and clinical evidence of a sex-APOE ε4 allele interaction effect on tau-mediated pathways related trajectories.[7,11,55]

We believe that an extensive and thorough elaboration of the limitation of this study is useful to facilitate future replication studies. Although a significant effect of MHT on AD neurobiology at 6-months is potentially clinically meaningful, data need to be handled with caution and call for studies with longer follow-up periods. Replication studies may also indicate that menopause-related and biomarker-guided dose adjustments of MHT may be beneficial and needed to maintain a stable significant effect on biomarker indicators of AD pathophysiology.

Given the multi-dimensional (medical, psychological, and social) consequences of menopause on the affected individual, we chose to give the study participants the option to decide which treatment/control arm to be allocated to, that is, whether starting a MHT program. The consequence of giving priority to this matter is represented by the absence of randomized treatment assignment, which also translates into unbalanced numbers of subgroups. On the flip side, the study enrolled more women than the number reported in the longitudinal results.

Another potential caveat of the present study is of pharmacological nature and refers to the impossibility to differentiate whether oral or transdermal estrogen as well as whether the concomitant use of progesterone yielded different effects on AD biomarkers.

Mono-centric studies have the intrinsic limitations of not adequately addressing inter-ethnical differences that may exist due to genetic polymorphism variations accounting for downstream differences in disease vulnerability and drug metabolism.

Finally, several lines of cross-disciplinary evidence have been published between menopause and the dysregulation of neuroinflammatory and neuroimmune responses,[66–68] two critical pathophysiological mechanisms occurring early in AD and involved in complex dynamic cross-links with other AD-related pathobiological changes.[66–68]

6 | CONCLUSIONS

Substantial progress in the analytical and clinical validation of blood-based biomarkers, alongside the definition of their context-of-use, have recently accelerated AD clinical diagnostic and therapy research. We provide the first prospective clinical evidence on the potential effect of MHT on core biomarkers associated to AD pathophysiology in menopause. In particular, we demonstrate a prominent response at the critical Aβ pathway biomarker level. Women at genetic risk for AD (carrying at least one APOE e4 allele) seem to be particularly benefiting from MHT.

CONFLICTS OF INTEREST

H.Z. has served at scientific advisory boards and/or as a consultant for Abbvie, Alector, Annexon, Artery Therapeutics, AZTherapies, CogRx, Denali, Eisai, Nervgen, Pinteon Therapeutics, Red Abbey Labs, Passage Bio, Roche, Samumed, Siemens Healthineers, Triplet Therapeutics, and Wave, has given lectures in symposia sponsored by Cellectricon, Fujirebio, Alzecure, Biogen, and Roche, and is a co-founder of Brain Biomarker Solutions in Gothenburg AB (BBS), which is a part of the GU Ventures Incubator Program (outside submitted work). K.B. has served as a consultant, at advisory boards, or at data monitoring committees for Abcam, Axon, Biogen, JOMDD/Shimadzu. Julius Clinical, Lilly, MagQu, Novartis, Pharmatrophix, Prothena, Roche Diagnostics, and Siemens Healthineers, and is a co-founder of Brain Biomarker Solutions in Gothenburg AB (BBS), which is a part of the GU Ventures Incubator Program, unrelated to the work presented in this paper. E.V.M. is a co-founder of ADx NeuroSciences. A.V. declares no competing financial interests related to the present article. The present study and related article have been initiated and prepared as part of an academic position at Sorbonne University, Paris, France and it reflects only and exclusively his own opinion and academic expertise on the matter. A.V. was an employee of Eisai Inc. (November 2019 - June 2021). A.V. does not receive any fees or honoraria since November 2019. Before November 2019 he had he received lecture honoraria from Roche, MagQu LLC, and Servier. S.L. received lecture honoraria from Roche and Servier. E.C. declares no competing financial interests related to the present article; her contribution to this article reflects only and exclusively his academic expertise on the matter. This work was initiated during her previous position at Sorbonne University, Paris, France. E.C. is currently an employee of Qynapse SAS. H.H. declares no competing financial interests related to the present article. He is currently an employee of Eisai Inc. The present study and related article have been initiated and prepared as part of an academic position at Sorbonne University, Paris, France and it reflects entirely and exclusively his own opinion. He serves as Senior Associate Editor for the Journal Alzheimer's & Dementia and does not receive any fees or honoraria since May 2019; before May 2019 he had received lecture fees from Servier, Biogen and Roche, research grants from Pfizer, Avid, and MSD Avenir (paid to the institution), travel funding from Eisai, Functional Neuromodulation, Axovant, Eli Lilly and company, Takeda and Zinfandel, GE-Healthcare and Oryzon Genomics, consultancy fees from Qynapse, Jung Diagnostics, Cytox Ltd., Axovant, Anavex, Takeda and Zinfandel, GE Healthcare, Oryzon Genomics, and Functional Neuromodulation, and participated in scientific advisory boards of Functional Neuromodulation, Axovant, Eisai,

REFERENCES

1. Klein SL, Flanagan KL. Sex differences in immune responses. *Nat Rev Immunol*. 2016;16(10):626-638. doi:10.1038/nri.2016.90

2. Ferretti MT, Iulita MF, Cavedo E, et al. Sex differences in Alzheimer disease – the gateway to precision medicine. *Nat Rev Neurol*. 2018;14(8):457-469. doi:10.1038/s41582-018-0032-9

3. Miller VM. Family matters: sexual dimorphism in cardiovascular disease. *Lancet (London, England)*. 2012;379(9819):873-875. doi:10.1016/S0140-6736(12)60200-1

4. Hampel H, Vergallo A, Giorgi FS, et al. Precision medicine and drug development in Alzheimer's disease: the importance of sexual dimorphism and patient stratification. *Front Neuroendocrinol*. 2018;50:31-51. doi:10.1016/j.yfrne.2018.06.001

5. Maki PM. The timing of estrogen therapy after ovariectomy—implications for neurocognitive function. *Nat Clin Pract Endocrinol Metab*. 2008;4(9):494-495. doi:10.1038/ncpendmet0901

6. Mosconi L, Rahman A, Diaz I, et al. Increased Alzheimer's risk during the menopause transition: a 3-year longitudinal brain imaging study. *PLoS One*. 2018;13(12):e0207885. doi:10.1371/journal.pone.0207885

7. Wang Y-TT, Pascoal TA, Therriault J, et al. Interactive rather than independent effect of APOE and sex potentiates tau deposition in women. *Brain Commun*. 2021;3(2):fcab126. doi:10.1093/braincomms/fcab126

8. Li X, Zhou S, Zhu W, et al. Sex difference in network topology and education correlated with sex difference in cognition during the disease process of Alzheimer. *Front Aging Neurosci*. 2021;13:639529. doi:10.3389/fnagi.2021.639529

9. Cavedo E, Chiesa PA, Houot M, et al. Sex differences in functional and molecular neuroimaging biomarkers of Alzheimer's disease in cognitively normal older adults with subjective memory complaints. *Alzheimers Dement*. 2018;14(9):1204-1215. doi:10.1016/j.jalz.2018.05.014

10. Damoiseaux JS, Seeley WW, Zhou J, et al. Gender modulates the APOE ε4 effect in healthy older adults: convergent evidence from functional brain connectivity and spinal fluid tau levels. *J Neurosci*. 2012;32(24):8254-8262. doi:10.1523/JNEUROSCI.0305-12.2012

11. Buckley RF, Mormino EC, Rabin JS, et al. Sex differences in the association of global amyloid and regional tau deposition measured by positron emission tomography in clinically normal older adults. *JAMA Neurol*. 2019;76(5):542-551. doi:10.1001/jamaneurol.2018.4693

12. Vergallo A, Houot M, Cavedo E, et al. Brain Aβ load association and sexual dimorphism of plasma BACE1 concentrations in cognitively normal individuals at risk for AD. *Alzheimers Dement*. 2019;15(10):1274-1285. doi:10.1016/j.jalz.2019.07.001

13. Ferretti MT, Santuccione-Chadha A, Hampel H. Account for sex in brain research for precision medicine. *Nature*. 2019;569(7754):40. doi:10.1038/d41586-019-01366-5

14. Nebel RA, Aggarwal NT, Barnes LL, et al. Understanding the impact of sex and gender in Alzheimer's disease: a call to action. *Alzheimers Dement*. 2018;14(9):1171-1183. doi:10.1016/j.jalz.2018.04.008

15. Mosconi L, Berti V, Quinn C, et al. Perimenopause and emergence of an Alzheimer's bioenergetic phenotype in brain and periphery. *PLoS One*. 2017;12(10):e0185926. doi:10.1371/journal.pone.0185926

16. Mosconi L, Berti V, Quinn C, et al. Sex differences in Alzheimer risk: brain imaging of endocrine vs chronologic aging. *Neurology*. 2017;89(13):1382-1390. doi:10.1212/WNL.0000000000004425

17. Schelbaum E, Loughlin L, Jett S, et al. Association of reproductive history with brain MRI biomarkers of dementia risk in midlife. *Neurology*. 2021;97(23):e2328-e2339. doi:10.1212/WNL.0000000000012941

18. Jäncke L, Mérillat S, Liem F, Hänggi J. Brain size, sex, and the aging brain. *Hum Brain Mapp*. 2015;36(1):150-169. doi:10.1002/hbm.22619

19. Williams CM, Peyre H, Toro R, Ramus F. Neuroanatomical norms in the UK Biobank: the impact of allometric scaling, sex, and age. *Hum Brain Mapp*. 2021;42(14):4623-4642. doi:10.1002/hbm.25572

20. Depypere H, Vierin A, Weyers S, Sieben A. Alzheimer's disease, apolipoprotein E and hormone replacement therapy. *Maturitas*. 2016;94:98-105. doi:10.1016/j.maturitas.2016.09.009

21. Rahman A, Schelbaum E, Hoffman K, et al. Sex-driven modifiers of Alzheimer risk: a multimodality brain imaging study. *Neurology*. 2020;95(2):e166-e178. doi:10.1212/WNL.0000000000009781

22. Brinton RD, Yao J, Yin F, Mack WJ, Cadenas E. Perimenopause as a neurological transition state. *Nat Rev Endocrinol*. 2015;11(7):393-405. doi:10.1038/nrendo.2015.82

23. Craig MC, Maki PM, Murphy DGM. The Women's Health Initiative Memory Study: findings and implications for treatment. *Lancet Neurol*. 2005;4(3):190-194. doi:10.1016/S1474-4422(05)01016-1

24. Shumaker SA, Legault C, Kuller L, et al. Conjugated equine estrogens and incidence of probable dementia and mild cognitive impairment in postmenopausal women: women's Health Initiative Memory Study. *JAMA*. 2004;291(24):2947-2958. doi:10.1001/jama.291.24.2947

25. Manson JE, Chlebowski RT, Stefanick ML, et al. Menopausal hormone therapy and health outcomes during the intervention and extended poststopping phases of the Women's Health Initiative randomized trials. *JAMA*. 2013;310(13):1353-1368. doi:10.1001/jama.2013.278040

26. Hampel H, Hardy J, Blennow K, et al. The amyloid-β pathway in Alzheimer's disease. *Mol Psychiatry*. 2021;26:5481-5503. doi:10.1038/s41380-021-01249-0

27. Janelidze S, Teunissen CE, Zetterberg H, et al. Head-to-head comparison of 8 plasma amyloid-β 42/40 assays in Alzheimer disease. *JAMA Neurol*. 2021;78(11):1375-1382. doi:10.1001/jamaneurol.2021.3180

28. Vergallo A, Lemercier P, Cavedo E, et al. Plasma β-secretase1 concentrations correlate with basal forebrain atrophy and

neurodegeneration in cognitively healthy individuals at risk for AD. *Alzheimers Dement*. 2021;17(4):629-640. doi:10.1002/alz.12228

29. Hampel H, Vassar R, De Strooper B, et al. The β-Secretase BACE1 in Alzheimer's disease. *Biol Psychiatry*. 2021;89(8):745-756. doi:10.1016/j.biopsych.2020.02.001

30. Cervellati C, Valacchi G, Zuliani G. BACE1: from biomarker to Alzheimer's disease therapeutical target. *Aging (Albany NY)*. 2021;13(9):12299-12300. 10.18632/aging.203064

31. Shen Y, Wang H, Sun Q, et al. Increased plasma beta-secretase 1 may predict conversion to Alzheimer's disease dementia in individuals with mild cognitive impairment. *Biol Psychiatry*. 2018;83(5):447-455. doi:10.1016/j.biopsych.2017.02.007

32. Buerger K, Ewers M, Pirttilä T, et al. CSF phosphorylated tau protein correlates with neocortical neurofibrillary pathology in Alzheimer's disease. *Brain*. 2006;129(Pt 11):3035-3041. doi:10.1093/brain/awl269

33. Hampel H, Bürger K, Pruessner JC, et al. Correlation of cerebrospinal fluid levels of tau protein phosphorylated at threonine 231 with rates of hippocampal atrophy in Alzheimer disease. *Arch Neurol*. 2005;62(5):770-773. doi:10.1001/archneur.62.5.770

34. Ashton NJ, Pascoal TA, Karikari TK, et al. Plasma p-tau231: a new biomarker for incipient Alzheimer's disease pathology. *Acta Neuropathol*. 2021;141(5):709-724. doi:10.1007/s00401-021-02275-6

35. Suárez-Calvet M, Karikari TK, Ashton NJ, et al. Novel tau biomarkers phosphorylated at T181, T217 or T231 rise in the initial stages of the preclinical Alzheimer's continuum when only subtle changes in Aβ pathology are detected. *EMBO Mol Med*. 2020;12(12):e12921. 10.15252/emmm.202012921

36. Ashton NJ, Janelidze S, Al Khleifat A, et al. A multicentre validation study of the diagnostic value of plasma neurofilament light. *Nat Commun*. 2021;12(1):3400. doi:10.1038/s41467-021-23620-z

37. Monteleone P, Mascagni G, Giannini A, Genazzani AR, Simoncini T. Symptoms of menopause - global prevalence, physiology and implications. *Nat Rev Endocrinol*. 2018;14(4):199-215. doi:10.1038/nrendo.2017.180

38. Baber RJ, Panay N, Fenton A. 2016 IMS recommendations on women's midlife health and menopause hormone therapy. *Climacteric*. 2016;19(2):109-150. doi:10.3109/13697137.2015.1129166

39. Depypere HT, Hillard T, Erkkola R, et al. A 60-month non-comparative study on bleeding profiles with the levonorgestrel intrauterine system from the late transition period to estrogen supplemented menopause. *Eur J Obstet Gynecol Reprod Biol*. 2010;153(2):176-180. doi:10.1016/j.ejogrb.2010.08.017

40. Furness S, Roberts H, Marjoribanks J, Lethaby A. Hormone therapy in postmenopausal women and risk of endometrial hyperplasia. *Cochrane Database Syst Rev*. 2012;2012(8):CD000402. doi:10.1002/14651858.CD000402.pub4

41. Fournier A, Berrino F, Clavel-Chapelon F. Unequal risks for breast cancer associated with different hormone replacement therapies: results from the E3N cohort study. *Breast Cancer Res Treat*. 2008;107(1):103-111. doi:10.1007/s10549-007-9523-x

42. Effects of estrogen or estrogen/progestin regimens on heart disease risk factors in postmenopausal women. The Postmenopausal Estrogen/Progestin Interventions (PEPI) Trial. The Writing Group for the PEPI Trial. *JAMA*. 1995;273(3):199-208.

43. Yancy CW, Jessup M, Bozkurt B, et al. 2013 ACCF/AHA guideline for the management of heart failure: executive summary: a report of the American College of Cardiology Foundation/American Heart Association Task Force on practice guidelines. *Circulation*. 2013;128(16):1810-1852. doi:10.1161/CIR.0b013e31829e8807

44. Weinstein AM, Gujral S, Butters MA, et al. Diagnostic precision in the detection of mild cognitive impairment: a comparison of two approaches. *Am J Geriatr Psychiatry Off J Am Assoc Geriatr Psychiatry*. 2022;30(1):54-64. doi:10.1016/j.jagp.2021.04.004

45. Folstein MF, Folstein SE, McHugh PR. Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res*. 1975;12(3):189-198. doi:10.1016/0022-3956(75)90026-6

46. Arevalo-Rodriguez I, Smailagic N, Roqué-Figuls M, et al. Mini-Mental State Examination (MMSE) for the early detection of dementia in people with mild cognitive impairment (MCI). *Cochrane Database Syst Rev*. 2021;7(7):CD010783. doi:10.1002/14651858.CD010783.pub3

47. Thijssen EH, Verberk IMW, Vanbrabant J, et al. Highly specific and ultrasensitive plasma test detects Abeta(1-42) and Abeta(1-40) in Alzheimer's disease. *Sci Rep*. 2021;11(1):9736. doi:10.1038/s41598-021-89004-x

48. Adamczuk K, De Weer A-S, Nelissen N, et al. Polymorphism of brain derived neurotrophic factor influences β amyloid load in cognitively intact apolipoprotein E ε4 carriers. *NeuroImage Clin*. 2013;2:512-520. doi:10.1016/j.nicl.2013.04.001

49. Garcia TP, Marder K. Statistical approaches to longitudinal data analysis in neurodegenerative diseases: Huntington's disease as a model. *Curr Neurol Neurosci Rep*. 2017;17(2):14. doi:10.1007/s11910-017-0723-4

50. Cohen J, Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Academic Press; 1977:1-17. doi:10.1016/B978-0-12-179060-8.50006-2

51. Faraway JJ. *Extending the Linear Model with R : Generalized Linear, Mixed Effects and Nonparametric Regression Models /Julian J. Faraway*. 2nd ed.. CRC Press; 2016.

52. Than S, Moran C, Beare R, et al. Interactions between age, sex, menopause, and brain structure at midlife: a UK Biobank Study. *J Clin Endocrinol Metab*. 2021;106(2):410-420. doi:10.1210/clinem/dgaa847

53. Zhao N, Liu C-C, Qiao W, Bu G. Apolipoprotein E, receptors, and modulation of Alzheimer's disease. *Biol Psychiatry*. 2018;83(4):347-357. doi:10.1016/j.biopsych.2017.03.003

54. Mosconi L, Berti V, Dyke J, et al. Menopause impacts human brain structure, connectivity, energy metabolism, and amyloid-beta deposition. *Sci Rep*. 2021;11(1):10867. doi:10.1038/s41598-021-90084-y

55. Tolar M, Abushakra S, Hey JA, Porsteinsson A, Sabbagh M. Aducanumab, gantenerumab, BAN2401, and ALZ-801-the first wave of amyloid-targeting drugs for Alzheimer's disease with potential for near term approval. *Alzheimers Res Ther*. 2020;12(1):95. doi:10.1186/s13195-020-00663-w

56. Wattmo C, Wallin AK, Londos E, Minthon L. Predictors of long-term cognitive outcome in Alzheimer's disease. *Alzheimers Res Ther*. 2011;3(4):23. doi:10.1186/alzrt85

57. Cummings J, Lee G, Zhong K, Fonseca J, Taghva K. Alzheimer's disease drug development pipeline: 2021. *Alzheimer's Dement (New York, N Y)*. 2021;7(1):e12179. doi:10.1002/trc2.12179

58. Zhao W, Hou Y, Song X, et al. Estrogen deficiency induces mitochondrial damage prior to emergence of cognitive deficits in a postmenopausal mouse model. *Front Aging Neurosci*. 2021;13:713819. doi:10.3389/fnagi.2021.713819

59. Ratnakumar A, Zimmerman SE, Jordan BA, Mar JC. Estrogen activates Alzheimer's disease genes. *Alzheimer's Dement (New York, N Y)*. 2019;5:906-917. doi:10.1016/j.trci.2019.09.004

60. Hou X, Adeosun SO, Zhang Q, et al. Differential contributions of ApoE4 and female sex to BACE1 activity and expression mediate Aβ deposition and learning and memory in mouse models of Alzheimer's disease. *Front Aging Neurosci*. 2015;7:207. doi:10.3389/fnagi.2015.00207

61. Hao J, Rapp PR, Janssen WGM, et al. Interactive effects of age and estrogen on cognition and pyramidal neurons in monkey prefrontal cortex. *Proc Natl Acad Sci U S A*. 2007;104(27):11465-11470. doi:10.1073/pnas.0704757104

62. Qin Y, An D, Xu W, et al. Estradiol replacement at the critical period protects hippocampal neural stem cells to improve cognition in

APP/PS1 mice. *Front Aging Neurosci*. 2020;12:240. doi:10.3389/fnagi.2020.00240

63. Bailey ME, Wang ACJ, Hao J, et al. Interactive effects of age and estrogen on cortical neurons: implications for cognitive aging. *Neuroscience*. 2011;191:148-158. doi:10.1016/j.neuroscience.2011.05.045

64. Candeias E, Duarte AI, Sebastião I, et al. Middle-aged diabetic females and males present distinct susceptibility to Alzheimer disease-like pathology. *Mol Neurobiol*. 2017;54(8):6471-6489. doi:10.1007/s12035-016-0155-1

65. Martinkova J, Quevenco F-C, Karcher H, et al. Proportion of women and reporting of outcomes by sex in clinical trials for Alzheimer disease: a systematic review and meta-analysis. *JAMA Netw open*. 2021;4(9):e2124124. doi:10.1001/jamanetworkopen.2021.24124

66. Mishra A, Brinton RD. Inflammation: bridging age, menopause and APOEε4 genotype to Alzheimer's disease. *Front Aging Neurosci*. 2018;10:312. doi:10.3389/fnagi.2018.00312

67. Wang Y, Mishra A, Brinton RD. Transitions in metabolic and immune systems from pre-menopause to post-menopause: implications for age-associated neurodegenerative diseases. *F1000Research*. 2020;9. 10.12688/f1000research.21599.1

68. Hampel H, Caraci F, Cuello AC, et al. A path toward precision medicine for neuroinflammatory mechanisms in Alzheimer's disease. *Front Immunol*. 2020;11:456. doi:10.3389/fimmu.2020.00456

69. Hampel H, Cummings J, Blennow K, Gao P, Jack CRJ, Vergallo A. Developing the ATX(N) classification for use across the Alzheimer disease continuum. *Nat Rev Neurol*. 2021;17(9):580-589. doi:10.1038/s41582-021-00520-w

70. Hampel H, O'Bryant SE, Molinuevo JL, et al. Blood-based biomarkers for Alzheimer disease: mapping the road to the clinic. *Nat Rev Neurol*. 2018;14(11):639-652. doi:10.1038/s41582-018-0079-7

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Depypere H, Vergallo A, Lemercier P, et al. Menopause hormone therapy significantly alters pathophysiological biomarkers of Alzheimer's disease. *Alzheimer's Dement*. 2022;1-11. https://doi.org/10.1002/alz.12759