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Review Article

Epidemiology of estrogen and dementia in women with Down syndrome☆

Nicole Schupf[a,b,c,d,*], Joseph H. Lee[a,b,d], Deborah Pang[e], Warren B. Zigman[e], Benjamin Tycko[f], Sharon Krinsky-McHale[e], Wayne Silverman[g]

[a] Taub Institute for Research on Alzheimer's Disease and the Aging Brain, Columbia University, New York, NY, United States
[b] G.H. Sergievsky Center, Columbia University, New York, NY, United States
[c] Departments of Neurology and Psychiatry, Columbia University Medical Center, New York, NY, United States
[d] Department of Epidemiology, Mailman School of Public Health Columbia University, New York, NY, United States
[e] Department of Psychology, NYS Institute for Basic Research in Developmental Disabilities, Staten Island, New York, NY, United States
[f] Department of Pathology & Cell Biology, College of Physicians and Surgeons, Columbia University, New York, NY, United States
[g] Kennedy Krieger Institute and Johns Hopkins University School of Medicine, Baltimore, MD, United States

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ABSTRACT

Several lines of investigation have shown a protective role for estrogen in Alzheimer's disease through a number of biological actions. This review examines studies of the role of estrogen-related factors in age at onset and risk for Alzheimer's disease in women with Down syndrome, a population at high risk for early onset of dementia. The studies are consistent in showing that early age at menopause and that low levels of endogenous bioavailable estradiol in postmenopausal women with Down syndrome are associated with earlier age at onset and overall risk for dementia. Polymorphisms in genes associated with estrogen receptor activity and in genes for estrogen biosynthesis affecting endogenous estrogen are related to age at onset and cumulative incidence of dementia, and may serve as biomarkers of risk. To date, no clinical trials of estrogen or hormone replacement therapy (ERT/HRT) have been published for women with Down syndrome. While findings from clinical trials of ERT or HRT for dementia have generally been negative among women in the neurotypical population, the short interval between menopause and onset of cognitive decline, together with a more positive balance between potential benefits and risks, suggests an opportunity to evaluate the efficacy of ERT/HRT for delaying or preventing dementia in this high risk population, although questions concerning the optimal formulation and timing of the hormone therapy are not yet resolved.

1. Introduction

Alzheimer's disease (AD) is the most frequent cause of dementia in the elderly. Clinically, AD is characterized by a progressive deterioration of cognitive and functional skills that begins during middle-age (early onset AD) or late in life (late-onset AD). AD is associated with a characteristic pattern of neuropathology, including the deposition of extracellular beta amyloid (Aβ) in neuritic plaques, intracellular accumulation of neurofibrillary tangles, neuronal loss and gross atrophy [1].

Down syndrome (DS), defined cytogenetically by trisomy 21 (in full or in part), is the most common chromosomal disorder associated with intellectual disability, occurring in approximately 1/700 live births [2]. Virtually all individuals with DS develop the characteristic pattern of neuropathology found in neurotypical adults with AD by the time they reach 40 years of age [3], with clear risk for clinical progression to AD beginning in the mid- to late 40s. Triplication and overexpression of the gene for amyloid precursor protein (*APP*), located on chromosome 21, is believed to play a significant role in the increased risk of dementia in DS which may be mediated by an increased production of Aβ peptides [4]. However, despite the nearly universal occurrence of AD pathology by age 40, there is wide variation in age at onset of dementia and in dementia related phenotypes such as levels of Aβ peptides. The average age at onset of dementia in adults with DS is between 50 and 60 years of age, with an approximate range from the late 30s to 70 years. This together with the fact that not all individuals with DS will develop dementia during their lifetime, suggests that additional genetic, biological and environmental factors may influence the rate and degree of Aβ deposition or clearance and may be important modifiers of risk that accelerate or slow disease progression [5].

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* Corresponding author at: Taub Institute for Research on Alzheimer's Disease and the Aging Brain, 630 West 168th Street, New York, NY United States.
E-mail address: ns24@cumc.columbia.edu (N. Schupf).

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2. Neuroprotective effects of estrogen

Several lines of investigation have shown a protective role for estrogen in AD through a number of biological actions [6,7]. Biologically, estrogen promotes the growth and survival of systems and processes associated with AD. Estrogen promotes the health of cholinergic neurons [8–10], increases cholinergic activity [11], has antioxidant and anti-inflammatory properties [12–14], decreases ischemic damage [15,16], promotes the nonamyloidogenic metabolism of the amyloid precursor protein [9,17–20], and protects against the toxicity of Aβ [9,21–23]. The loss of estrogen following menopause may play a role in the cognitive declines associated with AD and estrogen's protective effects have been investigated in the neurotypical population through several lines of research, although findings are not consistent. These include studies relating (a) age at menopause to cognitive decline and age at onset of dementia [24,25], (b) levels of endogenous hormones in postmenopausal women to cognitive decline and risk for dementia [26–35], (c) variants in genes involved in estrogen receptor activity and estrogen biosynthesis to risk of AD [36], and (d) studies of the beneficial effects of hormone replacement therapy on dementia risk [37,38]. Inconsistent results may be related to differences between studies in the age range of participants, the hormones assessed, whether or not study participants took hormone replacement therapy during the peri-menopausal period, and variation in adjustment for comorbid conditions and other risk factors in the analysis.

3. Menopause and risk for dementia in women with DS

Menopause is characterized by dramatic declines in estrogen levels. Women with DS have onset of menopause between 44 and 46 years of age [39–44], while the median age at menopause is around 51 years for women with neurotypical development [45]. When women with DS with onset of menopause below the median age were compared with women with DS with onset of menopause above the median age, earlier age at menopause was associated with earlier age at onset of AD and an approximately two- to three-fold increase in risk of AD [41,46,47]. Further, when cognitive function in women with DS without dementia, aged 21–57 years, was compared with cognitive function in age-matched men with DS, premenopausal women performed better than men, while postmenopausal women performed more poorly than men and showed significant declines in cognitive function [48]. These findings suggest that cognitive declines in postmenopausal women with DS are associated with reduced estrogen availability as well as with age [48].

4. Endogenous estrogen and risk for AD in women with DS

Individual differences in estrogen levels after menopause and during the period when AD is developing may play an important role in the pathogenesis of AD and influence age at onset and risk for AD. Studies in the Ts65Dn mouse model of DS found that estrogen treatment improved cognitive and cholinergic function [49,50]. Treatment with 17β estradiol for 60 days in postmenopausal female trisomic mice 11–15 months of age improved learning in a T-maze task [49]. In a related study, female trisomic mice 9–15 months of age treated with 17β estradiol for 60 days showed improved cholinergic and dendritic markers in the hippocampus and increased levels of APP in the striatum [50]. In a cross-sectional analysis, women with DS who were demented had elevated levels of serum sex hormone binding globulin (SHBG) compared with women with DS without dementia, but similar levels of total estradiol, suggesting that bioavailable estradiol is most importantly associated with cognitive decline and dementia risk [46]. In a follow-up longitudinal study in a cohort of women with DS, lower baseline levels of bioavailable estradiol were associated with a four-fold increased risk of developing AD and with an earlier age at onset [51]. These findings support the hypothesis that loss of biologically active estrogen following menopause may accelerate the development of dementia.

In postmenopausal women, body mass index (BMI) influences the level of estrone, the principal source of estrogen. Higher BMI is associated with increased levels of serum estradiol and estrone, and therefore peri- and post-menopausal obesity might have a beneficial effect on cognition [52]. In a retrospective analysis, increased body weight in women with AD was correlated with better performance on two measures of global cognitive function [53]. When estrone levels were examined in healthy postmenopausal women with DS, estrone levels were 66.9% higher in obese (BMI $\geq$ 30) compared with non-obese women with DS and 136% higher in obese than in non-obese premenopausal women with DS [52]. Among postmenopausal women with DS, obese individuals performed significantly better than non-obese individuals with DS on measures of verbal memory and on an overall measure of neuropsychological function. Among premenopausal women with DS, however, there were no similar differences in performance by obesity status [52]. Thus, higher endogenous estrogen levels after menopause, but not before, were associated with enhanced cognitive performance in women with DS who were not demented, complementing the finding that reduced endogenous levels in post-menopausal women are associated with increased risk for AD [51].

Overall, findings of studies that have examined the relationship between age at menopause or levels of endogenous estrogen and risk of dementia are more consistent in women with Down syndrome than the findings in women in the neurotypical population. One factor that may be related to differences in the consistency of findings in these two populations is that the interval between menopause and onset of dementia in women in the neurotypical population is relatively long compared with the short interval between menopause and onset of dementia in women with Down syndrome. Thus, among women in the neurotypical population, onset or changes in other risk factors during that interval may play a more important role. In addition, epidemiological studies have consistently shown that cardiovascular risk factors increase the risk of late onset Alzheimer's in the neurotypical population. History of diabetes and metabolic syndrome [54–57], stroke [58], hypertension [59], low HDL [60], smoking [59,61] and midlife central obesity [62] alone or in the aggregate have been associated with greater risk [59,63]. These cardiovascular risk factors increase with age and play an important role in risk for dementia among women in the neurotypical population, but are of lower prevalence among women with Down syndrome [64–68].

5. Genetic variants in estrogen: estrogen receptors

Prior research supports a role for genetic factors that affect the bioavailability of estrogen within the brain in modifying age at onset and risk of AD. Estrogen activity in the brain is mediated by two receptors belonging to a family of nuclear receptors, ERα and ERβ. These receptors are found in regions affected in AD, including the hippocampus, basal forebrain and amygdala [69–72]. Both ERα and ERβ appear to have a role in the preservation of cholinergic activity [73,74] and ERβ may mediate the effects of estrogen on hippocampal synaptic plasticity [75]. The neuroprotective effects of estrogen against Aβ induced toxicity appear to be mediated by ERα, which may act by blocking Aβ-induced apoptosis [23,76–78], and polymorphisms in *ESR1*, the gene coding for ERα, have been linked to risk for cognitive decline among women in the neurotypical population [10,79–87]. ERβ is expressed in the cerebral cortex, hippocampus, anterior olfactory nucleus, dorsal raphe, substantia nigra, midbrain ventral tegmental area and cerebellum [69,88], and polymorphisms in *ESR2*, the gene coding for ERβ, have been associated with cognitive impairment and risk for AD among women in the neurotypical population [10,84,89–92].

5.1. *ESR1*

Among women in the neurotypical population, two tightly linked

polymorphisms (*PvuII* and *XbaI*) in the first intron of estrogen receptor 1 (*ESR1*), the gene that encodes ERα, have been reported to influence estrogen receptor expression and risk of cognitive impairment or dementia [10,79–87]. A longitudinal cohort study of women with DS, 41–78 years of age and who were not demented at baseline, examined the relation of 5 single-nucleotide polymorphisms (SNPs) in the upstream region and the first exon/intron of the *ESR1* gene identical to or close to the intronic *Pvu*II and *Xba*I RFLP to the risk of AD [93]. Women carrying at least 1 copy of the C allele at rs2234693 and those carrying 2 copies of the C allele at rs2077647 (*PvuII*) had an almost 3-fold increase in the risk of AD compared with women who did not carry the C allele.

5.2. ESR2

Previous studies have examined the relation between polymorphisms in *ESR2* to risk of cognitive decline and onset of AD in the neurotypical population and have found a number of different SNPs that were associated with both increased and decreased risk [10,84,89–91]. In women with DS, the relation of polymorphisms in *ESR2* to the risk of AD was examined in a longitudinal study of women aged 30–71 years of age who were nondemented at baseline [94]. Evaluation of 13 SNPs in the *ESR2* gene identified two SNPs in intron 6 (rs4365213 and rs12435857), one SNP in intron 7 (rs17766755), and one SNP in intron 8 (rs4986938) that were significantly associated with increased risk of AD. Carriers of the minor alleles for these SNPs had an approximately 2-fold increase in the risk of AD. These studies of estrogen receptor variants point to the role of individual differences in estrogen receptor activity, as well as in hormone levels, in modifying the risk for AD in women with DS.

6. Polymorphisms associated with estrogen biosynthesis

Genes involved in estrogen biosynthesis or metabolism are also potential contributors to the processes associated with AD. Variants in these genes could influence the rate of memory decline, age at onset or risk of AD by altering estrogen levels over long periods of time and may serve as robust biomarkers of AD risk, since hormone levels in postmenopausal women are less likely to be informative. In the neurotypical population, variants in 3 candidate genes in the biosynthetic pathway for estradiol, *CYP17*, *CYP19* and *HSD17B1*, have been associated with differences in estrogen levels and risk for estrogen related disorders, as well as AD. However, only a few studies have examined their role among women with DS.

6.1. CYP17/CYP19

CYP17 and *CYP19* are involved in the peripheral synthesis of estrogens. Cytochrome P450 (CYP) enzymes are important for the production, bioavailability and degradation of estradiol. In women in the neurotypical population, polymorphisms in *CYP17* and *CYP19* have been associated with differences in hormone levels [95–99], age at onset of menopause [100], and increased risk of osteoporosis and breast cancer [101–108].

Several studies of women in the neurotypical population have examined the role of *CYP17* [109,110] and *CYP19* [36,111–118] in risk for AD. No association between variants in *CYP17* and risk of AD was found in a study that included both men and women [109],while one study found an association only in men [110]. Studies of the relation between variants in *CYP19* have reported positive associations that vary by sex [114–116] and interaction with other risk factors such as the presence of an *APOE E4* allele [111] or the butyrilcholinesterase (BCHE) K variant [113].

One study has examined the relation of polymorphisms in *CYP17* and *CYP19* to risk of AD in women with DS [119]. Carriers of four SNPs in *CYP17* had an earlier age at onset and over a two-fold increased risk of AD. Similarly, carriers of four SNPs in *CYP19* also had an earlier age at onset and a two-fold increased risk of AD, primarily in women without an apolipoprotein ε4 allele. In a combined analysis, postmenopausal women with DS who carried high risk alleles in both *CYP17* and *CYP19* had an almost four-fold increased risk of AD [119].

6.2. HSD17B1

The enzyme 17β-hydroxysteroid dehydrogenase 1, encoded by the *HSD17B1* gene, catalyzes the conversion of estrone to estradiol. Variants in *HSD17B1* have been associated with an increased risk for breast cancer in some [106,120,121] but not in all [122] studies of women in the neurotypical population.

Among women with DS, variants in the *HSD17B1* gene were associated with earlier onset and a two to three-fold increased risk of incident AD in women with DS homozygous for the minor allele at SNPs in intron 4 (rs676387), exon 6 (rs605059) and exon 4 in *COASY* (rs598126), and carriers of all three of the risk alleles had an almost two-fold increased risk of developing AD [123]. These candidate gene studies of estrogen receptor activity and estrogen bioavailability provide further support for the role of estrogen in influencing risk of AD in women with DS. Many of the polymorphisms tested were in noncoding (intron) chromosomal regions and are likely to serve as markers for the critical region, suggesting a need for genotyping with greater density and increased precision to identify the putative risk or protective variants.

Future studies of estrogen-related genetic variants associated with earlier onset of risk for AD in women with Down syndrome might also include additional genetic variants that have been identified to increase risk for AD in adults with DS [124–130] and consider the use of a polygenic score to provide a more complete risk assessment or examine interactions between sex and risk variants.

7. Estrogen or hormone replacement therapy

Among women in the neurotypical population, epidemiologic studies have shown that estrogen replacement therapy or hormone replacement therapy more generally (ERT/HRT) was associated with slower declines in cognitive function in postmenopausal women, particularly in verbal memory, and decreased risk of AD has also been shown in some studies [27,131–141], but others have not shown a benefit [142,143]. The association between ERT/HRT and risk of AD may vary depending on both the formulation and timing of usage [118,144]. A recent analysis of HRT use among women in the Finnish population from 1995 to 2011 found that use of estrogen plus progestogen was associated with an increased risk of AD, while long term use of estrogen alone was associated with reduced risk [145] and this difference in formulation may be related to the inconsistent results in the epidemiologic studies. The Cache County Study of women in the neurotypical population found evidence that use of HRT in the perimenopausal period protected against AD, while use of HRT among elderly women did not protect against AD unless initiated before age 63 [118,141], suggesting that there may be a critical period during which HRT provides protective effects on cognitive function, possibly early in the perimenopausal period or just after menopause [37,146–148].

Several clinical trials of ERT or HRT in women in the neurotypical population have sought to test the efficacy of ERT/HRT. The Women's Health Initiative Memory Study (WHIMS), a randomized trial of two treatment groups- one treated with estrogen alone and the other treated with combined and continuous estrogen/progesterone- reported a twofold increase in risk of AD in treated women compared with women treated with placebo [149–152]. However, participants in WHIMS were 65 years and older at the time treatment was initiated, beyond the hypothesized critical period when HRT might be beneficial [153]. Factors that could influence the efficacy of hormonal replacement treatment include dosage of estrogen/progestin, other formulations of

these hormones, schedules of administration (e.g. tonic or cyclic), or route of administration therapy [147,154,155]. For example, estrogens administrated through a transdermal route might be more effective since this more closely resembles the normal physiology and metabolism of endogenous sex hormones. Use of combined and continuous estrogen and progestin does not mirror the naturally occurring menstrual cycle and may decrease the levels and sensitivity of cerebral estrogen receptors [144]. Several trials in women in the neurotypical population that were specifically designed to test the efficacy of ERT/HRT in the recent postmenopausal period, the Kronos Early Estrogen Prevention Study (KEEPS) [156] and the Early versus Late Intervention Trial with Estradiol (ELITE), found no effect of treatment on cognitive function [156,157]. These negative findings may have been influenced by formulation and/or timing of the intervention. The KEEPS study evaluated the effects of oral conjugated equine estrogens plus cyclical micronized progesterone or transdermal estradiol plus cyclical micronized progesterone versus placebo in women who were on average 1.4 years postmenopausal [156]. The ELITE study included women within 6 years of menopause or 10+ years after menopause who were randomly assigned to oral 17b-estradiol or placebo [157].

To date, no clinical trials of HRT have been published for women with DS, despite studies showing that individual differences in endogenous estrogens influence risk for AD. While the relationship of ERT/HRT in reducing risk of AD is difficult to study in the neurotypical population because of the extended interval between menopause and onset of AD (20 years or more), women with DS have a relatively short interval between onset of menopause and risk for clinical progression of AD. This short interval between menopause and onset of cognitive decline, together with a more positive balance between potential benefits and risks, suggests an opportunity to evaluate the efficacy of ERT/HRT for delaying or preventing dementia in this high risk population and an intervention could more readily be implemented in the perimenopausal period. However, questions concerning the optimal formulation and timing of the hormone therapy are not yet resolved. Future research should also address the question of sex differences in risk of AD among adults with DS, as few studies have examined results separately for men and women. Understanding the pathways that contribute to sex differences in risk may lead to the development of more effective interventions or treatment.

Disclosure

The authors have no conflicts of interest to disclose.

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