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## Smoking and increased Alzheimer's disease risk: A review of potential mechanisms

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### Abstract

**Background**—Cigarette smoking has been linked with both increased and decreased risk for Alzheimer's disease (AD). This is relevant for the US military because the prevalence of smoking in the military is approximately 11% higher than in civilians.

**Methods**—Systematic review of published studies on the association between smoking and increased risk for AD, and preclinical and human literature on the relationships between smoking, nicotine exposure and AD-related neuropathology. Original data from comparisons of smoking and never-smoking cognitively normal elders on *in vivo* amyloid imaging are also presented.

**Results**—Overall, the literature indicates that former/active smoking is related to a significantly increased risk for AD. Cigarette smoke/smoking is associated with AD neuropathology in preclinical models and humans. Smoking-related cerebral oxidative stress is a potential mechanism promoting AD pathophysiology and increased risk for AD.

**Conclusions**—A reduction in the incidence of smoking will likely reduce the future prevalence of AD.

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#### Potential conflicts of interest

Drs. Durazzo, Mattsson, and Weiner have no conflicts of interest to report.

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## 1. Background

### 1.1. Cigarette smoking prevalence, mortality, and morbidity

In this review, “smoking” refers to chronic smoking of tobacco in the form of cigarettes. Approximately 2 billion people worldwide use tobacco products, mostly in the form of cigarettes, with tobacco smoking-related diseases resulting in at least 4 million global deaths per year.<sup>1</sup> There are an estimated 44 million active-smokers in the US,<sup>2</sup> however, the actual prevalence of smoking in the US may be underestimated, particularly in younger adults and females.<sup>3</sup> In the US, smoking-related disease accounts for about 1 in every 5 deaths, which equates to over 440,000 annual deaths, and smoking-related morbidity results in annual direct health care expenditures and productivity loss of \$193 billion.<sup>2,4</sup> The greatest smoking-related mortality is increasingly apparent among economically disadvantaged groups, which, in the US, includes a disproportionate number of ethnic minorities.<sup>5, 6</sup> Over the past 5 years, the prevalence of adult smokers in the US has remained constant, and the ratio of former to never smokers (quit ratio) has not changed since 1998.<sup>7</sup> In 2009, the US Food and Drug Administration (FDA) enacted the Family Smoking Prevention and Tobacco Control Act (TCA) to regulate the manufacture, distribution and marketing of tobacco products to protect the public from smoking-related mortality and morbidity (Public Law 111-31; [www.fda.gov/TobaccoControlAct](http://www.fda.gov/TobaccoControlAct)). However, despite the implementation of the TCA, millions of Americans continue to smoke.

Smoking prevalence in active duty US Armed Services personnel is approximately 31%<sup>8</sup>, and is estimated at 35% in active duty personnel with high combat exposure,<sup>9</sup> which are 11% and 15% higher, respectively, than in the general U.S. population. Smoking among US military personnel is associated with lower productivity and levels of physical fitness, as well as increased risk for injury during training, and impaired rate of wound healing (see<sup>8, 10, 11</sup> for review); consequently, smoking lowers combat readiness of our active duty personnel.<sup>11</sup> Smoking is among the strongest predictors of premature discharge from the military, and is related to over \$130 million in annual excess training costs (see<sup>10, 11</sup> for review). As of 2006, it was estimated that tobacco use costs military approximately \$564 million per year from the associated adverse health consequences (e.g., lower productivity and levels of physical fitness) and treatment of tobacco-related diseases (see<sup>8, 11, 12</sup> for review).

Cardiovascular disease (CVD), chronic obstructive pulmonary diseases (COPD), and various forms of cancer are the leading causes of smoking-related mortality in the US.<sup>13</sup> Sustained smoking cessation is associated with significantly decreased risk for these conditions,<sup>13</sup> indicating that several adverse health consequences related to smoking are modifiable. It is now apparent that smoking-related morbidity extends beyond CVD, COPD, stroke, and cancer, and includes brain neurobiological and neurocognitive abnormalities (e.g., hippocampal volume loss, learning and memory deficits) that are not solely attributable to the foregoing medical conditions, and some abnormalities show significant progression over time.<sup>14–17</sup> Importantly, some of these smoking-related neurobiological abnormalities may represent risk factors for Alzheimer’s disease.<sup>18–21</sup> Correspondingly, there is now substantial epidemiological evidence from meta-analyses and cohort-based

studies that indicates smoking is associated with significantly increased risk for Alzheimer's disease pathophysiology and associated dementia.<sup>22–24</sup>

This review will focus on the epidemiological evidence for smoking as a risk factor for late-onset/sporadic AD-dementia (AD), as well as provide a comprehensive review of the potential mechanisms by which smoking promotes increased AD risk. Original and novel data is presented from comparisons of cognitively-normal elder smokers and non-smokers on regional brain  $\beta$ -amyloid deposition, via florbetapir F-18 positron emission tomography (PET; see section 7). A synopsis is provided following each major subsection or section, and an inclusive summary (section 8) and conclusions (section 9) are provided after the review of the literature and presentation of original data.

## 2. Alzheimer's disease

Alzheimer's disease is the most common cause of dementia, and late-onset AD (i.e., onset at 65 years of age) is the predominant form (> 90% of AD cases).<sup>25, 26</sup> Over 35 million individuals worldwide are estimated to suffer from AD, and this number is projected to nearly double by 2030 due to increasing life expectancy.<sup>26</sup> In 2012, an estimated 5.2 million Americans over the age of 65 (i.e., 1 in 8) had AD, resulting in approximately \$200 billion in health care-related costs.<sup>25</sup> Recent research criteria recognizes that AD is an insidious process, which begins with extended asymptomatic preclinical stages that may last for several decades before dementia symptomatology is exhibited.<sup>27</sup> As the AD-related neuropathological abnormalities accumulate over time during the preclinical stages, there is a transition from normal neurobiological and neurocognitive function into mild cognitive impairment (MCI), which is most frequently typified by AD-like pathophysiology and clinically significant memory deficits.<sup>28, 29</sup> MCI patients are at high risk for conversion to AD, with 50–70% converting to dementia within 5–7 years after MCI onset.<sup>29</sup> The increasing incidence of AD has promoted extensive research into delineating the risk factors associated with the development and progression of this neurodegenerative disease.<sup>30</sup> Despite this major multidisciplinary research effort, the mechanisms associated with the onset and progression of late-onset AD are not definitively established, and both preclinical and human clinical trials on AD-pathology/progression-modifying medications have yielded disappointing results.<sup>27, 31</sup>

### 2.1. AD pathophysiology and neuropathology

Two of the hallmark neuropathological findings in AD are extracellular amyloid and neuritic plaques and intracellular neurofibrillary tangles.<sup>32</sup> Amyloid plaques are primarily formed by aggregation of insoluble  $\beta$ -amyloid ( $A\beta$ ) peptides, while neuritic plaques are composed of insoluble  $A\beta$  peptides, degenerated neurites (dendrites, axons and/or telodendria), and some contain hyperphosphorylated tau proteins (p-tau).<sup>32</sup> Neurofibrillary pathology (pretangles, neuropil threads, neurofibrillary tangles) is primarily composed intracellular p-tau protein aggregates.<sup>32, 33</sup> Insoluble argyrophilic neuropil threads and neurofibrillary tangles develop in the dendrites and cell body, respectively.<sup>34</sup> Aging and APOE genotype ( $\epsilon 4 > \epsilon 3 > \epsilon 2$ ) are independently associated with increased cerebral  $A\beta$  deposition,<sup>35–37</sup> and may interact where  $A\beta$  deposition, beginning the early 40's, is greater with increasing age in APOE  $\epsilon 4$

carriers.<sup>38</sup> Aging is also related to cerebral p-tau accumulation and neurofibrillary tangle density.<sup>34, 36, 39</sup>

The current predominant hypothesis (although not universally accepted; for review see<sup>40–44</sup>) for the development of AD indicates that pathological A $\beta$  metabolism is the primary event promoting plaque formation, followed by wide spread cortical tau pathology, inflammation, synaptic degradation, and neuronal loss (see<sup>32, 40, 45</sup> for review). Brain amyloid deposition is indicated to be necessary, but not sufficient to promote the clinical symptomatology demonstrated in MCI and AD.<sup>27</sup> The pivotal role of A $\beta$  in the development and progression of AD is supported by the genetic link between hereditary/familial AD and mutations in either the gene encoding for the amyloid precursor protein, or in the genes encoding for amyloid precursor protein (APP)-processing enzymes (presenilin 1 and 2).<sup>46</sup> A $\beta$  deposition and plaque formation is indicated to begin as early as 20 years (i.e., during middle-age) before the onset of AD symptoms.<sup>46–49</sup> Cerebral amyloid and neuritic plaque development follows a predictable pattern of progression, beginning with diffuse amyloid plaques in the inferior/basal temporal neocortex, spreading to the hippocampus and entorhinal cortex, and ultimately widely distributed amyloid and neuritic plaques are present throughout the neocortex.<sup>34</sup> In AD, amyloid deposition is not exclusively relegated to brain parenchyma, but can also found, in variable levels, in leptomeningeal and intracortical arteries, arterioles, capillaries, venuoles, and veins.<sup>50, 51</sup> Significant vascular amyloid deposition is referred to as cerebral amyloid angiopathy (CAA)<sup>52</sup> and is primarily composed of the A $\beta$ <sub>1–40</sub> isoform.<sup>53</sup> Vasculature in the occipital lobe and cerebellum tend to show the greatest level of CAA.<sup>54</sup>

The AD amyloidogenic process begins with the proteolysis of the transmembrane protein APP. If APP is cleaved by  $\alpha$ -secretase, extracellular soluble sAPP $\alpha$  is produced and A $\beta$  peptide formation is inhibited.<sup>55</sup> In contrast, A $\beta$  peptides are created from the sequential cleavage of APP by  $\beta$ -and- $\gamma$ -secretases;  $\beta$ -secretase initially cleaves APP to yield extracellular soluble APP (sAPP $\beta$ ) and an intracellular carboxyl terminal fragment ( $\beta$ -CTF), which is subsequently cleaved by  $\gamma$ -secretase producing A $\beta$  peptides of different lengths.<sup>55, 56</sup> A $\beta$ <sub>1–40</sub> and A $\beta$ <sub>1–42</sub> are major isoforms<sup>57</sup> and these may aggregate to produce dimers, trimers, oligomers, protofibrils, and insoluble fibrils (which is a fundamental A $\beta$  component of amyloid and neuritic plaques).<sup>58</sup> A $\beta$ <sub>1–42</sub> is considered the greater pathological isoform due to its strong association with atrophic neurites, reactive astrocytosis, and activated microglia.<sup>59</sup> The redox potential (i.e., ability to acquire electrons) of the primary A $\beta$  species (A  $\beta$ <sub>1–42</sub>  $\gg$  A $\beta$ <sub>1–40</sub>) is consistent with their level of neurotoxicity, and redox-active transition metals (e.g., iron and copper) known to increase reactive oxygen species free radical levels bind with high affinity to all A $\beta$  isoforms.<sup>60</sup> It is also established that soluble and oligomeric intracellular A $\beta$  and extracellular neuritic formation are associated with a chronic neuroinflammatory process marked by activated microglia and reactive astrocytes.<sup>61, 62</sup> The insertion of A $\beta$ <sub>1–42</sub> oligomers into the phospholipid bilayer serves as a source of oxidative stress via increased concentrations of reactive oxygen and nitrogen species free radicals, which damage cell membranes and other micro-and-macro-cellular components, via lipid peroxidation.<sup>55</sup> However, it has also been proposed that some A $\beta$  isoforms may serve as anti-oxidants, and A $\beta$  production represents a compensatory response to mitigate pre-existing chronic oxidative stress (see<sup>42, 131, 200</sup> for review). The level of

soluble A $\beta$  oligomers, not amyloid or neuritic plaque load, shows a stronger association with cognitive decline and hyperphosphorylated tau concentration, in animal models and humans [see<sup>55, 58</sup> for review].

Neurofibrillary tangles show a different regional pattern of development and temporal appearance than A $\beta$  deposition and neuritic plaque formation.<sup>36</sup> In AD, neurofibrillary tangles first appear in the brainstem and transentorhinal cortex, before A $\beta$  deposition, spreading to the entorhinal cortex and hippocampus, and finally showing diffuse distribution throughout the neocortex.<sup>34</sup> Specifically, neurofibrillary tangles localized in the locus coeruleus and entorhinal cortex is common in adults 30–40 years of age, and precedes the appearance of significant amyloid deposition and neuritic plaques in these regions.<sup>39</sup> Widespread neurofibrillary tangles in neocortical regions are typically not prominent until high amyloid or neuritic plaques levels are present,<sup>32</sup> and recent research suggests that medial temporal lobe tangle formation is also independently related to age.<sup>63</sup> Currently, there is extensive debate regarding whether the development and progression of A $\beta$  and tau protein pathologies in AD are interrelated or represent independent pathophysiological processes.<sup>34, 64</sup>

### 3. Risk factors for AD: role of smoking

While the mechanisms responsible for the inception and progression of late-onset AD are not established, increasing age and inheritance of the  $\epsilon 4$  allele of the apolipoprotein APOE gene are the strongest and most consistently replicated risk factors for the development of AD.<sup>25, 65, 66</sup> Specifically, the risk for AD doubles every 5 years between ages of 60–90 years,<sup>66</sup> and AD risk for those with one copy of the APOE  $\epsilon 4$  allele is increased by 3–5 times and inheritance of two copies (i.e., APOE  $\epsilon 4$  homozygotes) is associated with a 12-fold increased risk.<sup>67</sup> Aging and APOE genotype may interact with other potential genetic and/or modifiable environmental risk factors to increase AD-related pathophysiology and risk for AD.<sup>38, 68–70</sup> CVD, cerebrovascular disease, moderate-to-severe traumatic brain injury, and race may also be risk factors for AD.<sup>25, 71</sup> An increasing number of investigations have focused on the identification of risk factors for AD that are “modifiable”, that is, conditions/behaviors that can be effectively treated/alterd to reduce their prevalence during the asymptomatic preclinical stage,<sup>72</sup> which will promote a significant decrease in the prevalence of AD.<sup>68</sup> However, there is considerable debate on the strength of the association between AD and potentially modifiable risk factors.<sup>65, 68</sup>

#### 3.1. Modifiable risk factors for AD: smoking

Cognitive engagement, diet/nutritional supplement intake, physical activity level, type-2 diabetes, alcohol consumption level, mood disorders, hypertension, hypercholesterolemia, and smoking have been proposed as modifiable risk factors for AD.<sup>65, 68, 73, 74</sup> In 2011, a multidisciplinary panel convened by the National Institutes of Health (NIH) reviewed the cohort studies and randomized controlled trials conducted from 1984–2009 on the foregoing potential risk factors, and concluded “insufficient evidence exists to draw firm conclusions on the association of any modifiable risk factors with risk of AD.”<sup>65</sup> However, for smoking, the panel’s rigorous review criteria resulted the consideration of a very limited number studies, and their conclusions were fundamentally based on a single meta-analysis<sup>75</sup> of 19

prospective cohort studies published up to 2005, and two cohort studies published in 2006<sup>76</sup> and 2007.<sup>77</sup> While the panel's conclusions for many of these modifiable risk factors are likely applicable to the present day, there is substantial additional data that suggests smoking is a significant risk factor for AD. Specifically, a conclusive and authoritative meta-analysis conducted by Cataldo and colleagues<sup>22</sup> in 2010, on 43 international case-controlled and cohort studies published from 1984 – 2009, revealed that tobacco industry affiliation (e.g., study funding provided by the tobacco company, study author(s) currently/previ-ously employed by tobacco industry) was robustly related to the direction and magnitude of smoking as a risk factor for AD. In case-controlled studies with a tobacco industry affiliation, smoking was associated with a significantly decreased risk for AD [odds ratio (OR) pooled = 0.86; 95% CI = 0.75–0.98], but studies with no tobacco industry affiliation showed no association between smoking and risk of AD. Cohort studies with a tobacco industry affiliation demonstrated a significantly decreased risk for AD (pooled OR = 0.60; 95% CI = 0.27–1.32), while those with no tobacco industry affiliation showed a significantly increased risk for AD (pooled OR = 1.45; 95% CI = 1.16–1.80). Some studies in this meta-analysis reported that risk for development of AD was greater only in smokers who were not APOE ε4 carriers.<sup>78–81</sup> After concurrently controlling for study design, quality (based on impact factor of journal), secular trend, and tobacco industry affiliation and year of publication, Cataldo et al., found that active or former lifetime smoking was a significant risk factor for AD (relative risk = 1.72; 95% CI 1.33–2.12). Although the year of publication was included as a covariate in their primary analyses, the authors acknowledge that this variable may be systematically related to studies reporting a reduction in AD risk for smokers, since all the industry-affiliated/sponsored reviews were published in 1994 or earlier; this may also be attributable to the fact that the tobacco industry ceased funding support for reviews on smoking-related risk for AD after 1994.

In the non-tobacco industry affiliated cohort studies reviewed by Cataldo and colleagues, there were generally consistent findings for smoking exposure variables (i.e., pack years, a measure of cigarette smoking dose and duration) for AD risk, but mixed results were apparent for former smoking status as risk factor for AD. With respect to exposure, Ott and colleagues<sup>78</sup> reported that risk of AD was significantly increased for active-smokers with < 20 pack-years (OR = 2.5; 95% CI = 1.1–5.5), as well as for those with > 20 (OR = 3.0; 95% CI = 1.2–5.4); a corresponding increased risk for AD was observed in former-smokers with < 20 pack-years (OR = 1.5; 95% CI = 1.0–2.5), and > 20 (OR = 2.1; 95% CI = 1.2–3.7). In a combined group of active and former-smokers, Tyas et al.,<sup>82</sup> found that smokers with 27–41 (OR = 2.55; 95% CI = 1.22–5.58), and 41–56 (OR = 2.92; 95% CI = 1.37–6.53) pack years, had significantly greater risk of AD compared to those with < 27 pack-years; however, those with > 56 pack years showed no statistically significant increased risk for AD (OR = 1.37; 95% CI = 0.53–3.44), which was attributed to a strong survivor bias. Juan and colleagues<sup>83</sup> applied the same pack-year groupings as Tyas et al., in a separate cohort, and obtained highly similar results. Reitz et al.,<sup>77</sup> reported active-smokers with > 20 pack-years had a significantly increased risk of AD than active-smokers with < 20 pack-years (hazard ratio = 1.82; 95% CI = 1.26–2.57). Regarding former smoking status, Launer et al.,<sup>84</sup> observed increased risk for AD in male (relative risk = 1.97; 95% CI = 0.92–4.22), but not in female (relative risk = 1.08; 95% CI = 0.73–1.61) former-smokers. Merchant et al.,<sup>79</sup> and Reitz et



al.,<sup>77</sup> reported former-smokers risk for AD was not statistically different from never-smokers, while in Aggarwal et al.,<sup>76</sup> former-smokers, who were APOE  $\epsilon$ 4 carriers had a significantly lower risk of AD relative to never-smokers (OR = 0.27; 95% CI = 0.08–0.93). Notably, greater pack-years were associated with increased mortality in controls and AD,<sup>82</sup> and the onset of AD occurred at a significantly younger age in former-smokers<sup>78</sup> and active-smokers<sup>78, 79, 85</sup> compared to never-smokers.

Subsequent to the meta-analysis by Cataldo and colleagues, a large Finnish cohort study<sup>23</sup> reported that individuals who smoked during midlife, and were APOE  $\epsilon$ 4 carriers, demonstrated a markedly increased risk for AD (OR = 6.56; 95% CI = 1.80–23.94).<sup>23</sup> Additionally, a large US cohort study found individuals who smoked more than two packs/day, had a significantly increased risk for AD (hazard ratio = 2.57; 95% CI = 1.63–4.03).<sup>24</sup> Finally, Barnes and Yaffe<sup>68</sup> estimated the influence of the prevalence of several modifiable AD risk factors on AD prevalence. Smoking was projected to account for 574,000 (11%) of AD cases in the US and 4.7 million (14%) cases worldwide. A 10% reduction in the total number of smokers in the US and worldwide was projected to decrease the prevalence of AD cases by 51,000 and 412,000, respectively.

For all of the above case-controlled and cohort studies, there was considerable variability in the sample sizes, the duration that participants were followed (for cohort studies), and the covariates (e.g., APOE genotype, alcohol consumption, sex, biomedical risk factors) acquired and/or controlled for in statistical analyses. Survivor bias has been indicated to promote an underestimation of the smoking-related risk for AD in both case-controlled and cohort studies.<sup>86–90</sup> Specifically, elders who die prematurely from smoking-related diseases are a major source of attrition; this reduces the proportion of smokers who may have ultimately developed AD if they had a normal lifespan, creates attrition in cohort-studies, and those who do survive are biased toward healthier individuals.<sup>90</sup> The findings regarding former smoking status as an AD risk factor must be interpreted with caution because some studies were not consistent or explicit about the typical level of cigarette consumption or duration of smoking cessation.<sup>91</sup> Additionally, the association of other forms of tobacco consumption (e.g., pipe, cigars, cigarillos, smokeless tobacco) and risk for AD was not specifically considered in previous case-controlled and cohort studies.

### 3.2. Synopsis

The cumulative body of data from international cohort studies, with no affiliation to the tobacco industry, indicates that smoking during lifetime is associated with at least a 1.7 times (70%) greater risk for AD, and the risk markedly increases with greater cumulative cigarette exposure. The relationship between smoking status, exposure, and AD risk may be mediated or moderated by APOE genotype. The magnitude of risk for AD associated with smoking is likely to be underestimated in both case-controlled and cohort studies due to attrition/survivor bias from smoking-related mortality and morbidity. Smoking is associated with earlier onset of AD, and estimated to account for 4.7 million AD cases worldwide. In the following section, we review the neurocognitive and neurobiological consequences of smoking.



## 4. Neurocognitive and neurobiological consequences of smoking

The vast majority of research investigating the effects of smoking on the human body has focused on the cardiac, pulmonary functions, and vascular systems, as well as on its carcinogenic properties, primarily in the elderly (i.e., > 65 years of age).<sup>92–95</sup> However, outside of cerebrovascular risk factors for stroke, comparatively little research has been devoted to effects of chronic smoking on the brain and its functions, particularly in young/middle-aged adults (i.e., 25–65 years of age).<sup>14, 16</sup> Over the past 12 years there has been an emergence of studies specifically focusing on the neurocognitive and neurobiological effects of smoking in multiple populations. The findings from these studies suggest that smoking, in those without a history of clinically significant psychiatric and biomedical conditions, with a history of a neuropsychiatric disorder (e.g., schizophrenia, alcohol/substance use disorder), and with a history of mild traumatic brain injury, is associated with adverse effects on brain neurobiology and function. Smoking is highly prevalent in these populations in both civilians and US veterans and active duty military personnel.<sup>9, 96</sup> The findings for smokers in these populations is highly relevant because pattern of neurobiological and neurocognitive abnormalities observed in the above populations (see below) are congruent with multiple aspects of the neuropathological and neurocognitive abnormalities that characterize the recently proposed “preclinical” stages of AD,<sup>27, 49</sup> as well as MCI.<sup>97–99</sup> See<sup>15, 16</sup> for comprehensive reviews on the effects of smoking on neurobiology and neurocognition in other neuropsychiatric conditions (e.g., schizophrenia).

### 4.1. Smoking in “healthy” non-clinical cohorts

Smoking in adolescents-to-young adults (i.e., 17–21 years of age), young-to-middle-aged adults (i.e., 25–60), and elders (< 65 years of age) without a history of clinically significant biomedical or psychiatric conditions, is associated with significant neurocognitive and/or neurobiological abnormalities. Adolescent-to-young adult active-smokers showed inferior performance relative to never smokers on measures of attention, learning and memory, processing speed and impulse control (see<sup>14</sup> for review). Young-to-middle-aged adult active-smokers, compared to never-smokers, showed poorer performance on multiple neurocognitive domains, predominantly on measures of executive functions, processing speed, and learning and memory.<sup>14, 100, 101</sup> Young-to-middle-aged active-smokers also demonstrated abnormalities in regional cortical, hippocampal, subcortical morphology (volumes and cortical thickness),<sup>16, 19, 102–106</sup> biochemistry (markers of neuronal integrity and cell membrane turn-over/synthesis),<sup>107, 108</sup> white matter (WM) microstructural integrity,<sup>109</sup> and cortical perfusion.<sup>15</sup> In these studies, the neurobiological abnormalities were apparent in anterior brain regions (e.g., orbitofrontal cortex, dorsolateral prefrontal cortex, anterior cingulate cortex, insula), which are cortical components of the brain reward/executive oversight system (BREOS) that is involved in the inception, development, and persistence of all addictive disorders.<sup>18, 110</sup> The neurobiological abnormalities demonstrated by young-to-middle-aged neurobiological were also apparent in regions that show significant atrophy (e.g., hippocampus, posterior cingulate, precuneus) and/or glucose metabolism deficits in MCI and/or early stage AD.<sup>111, 112</sup> In several studies, pack years were related to the level of neurobiological<sup>102–105</sup> or neurocognitive<sup>14, 101</sup> abnormalities observed. In elders, active-smokers, relative to never-smokers, demonstrated poorer

performance in cross-sectional studies, and a greater rate of decline in longitudinal studies in the domains of executive functions, processing speed, and learning and memory (see<sup>14</sup> for review). In some studies, former-smokers across adulthood performed intermediate to active and never-smokers.<sup>14</sup> Early longitudinal computer tomography studies of elders reported that active-smokers showed a greater rate of global brain atrophy relative to never-smokers.<sup>14</sup> More recent MRI studies with elder cohorts reported active smokers showed lower gray matter density in posterior cingulate gyrus and precuneus bilaterally, right thalamus and right precentral gyrus<sup>21</sup> and those with any history of smoking demonstrated greater rate of atrophy over 2-years in anterior frontal, temporal, posterior cingulate, and posterior parietal regions.

#### 4.1. Smoking in alcohol use disorders (AUD)

Smoking is the most prevalent comorbid condition in those with an AUD.<sup>96</sup> For the past 10 years, we have applied multimodality magnetic resonance neuroimaging methods and comprehensive neurocognitive assessment to investigate the effects of smoking and hazardous alcohol consumption on the brain and its functions in young-to-elderly adults (25–69 years of age) seeking treatment for alcohol use disorders (trsAUD). The majority of our trsAUD participants are US Armed Services veterans. At 1–4 weeks of abstinence from alcohol, smoking trsAUD consistently demonstrated significantly greater abnormalities than non-smoking trsAUD on magnetic resonance-derived measures of brain structure, neuronal integrity, and perfusion, primarily in the frontal and temporal lobes (including the hippocampus), as well as poorer performance on measures of learning and memory, cognitive efficiency, executive functions, processing speed, and fine motor skills.<sup>110, 113–118</sup> Smoking trsAUD also showed significantly less recovery than non-smoking trsAUD in: a) brain metabolite markers of neuronal integrity and cell membrane turnover/synthesis in the frontal and medial temporal lobes, frontal gray matter (GM) perfusion and microstructural integrity in the frontal, temporal and parietal white matter (WM), as well as in neurocognition, over 1-month of abstinence,<sup>119–122</sup> and b) multiple domains of neurocognition over 1<sup>123</sup> and 9–12 months of abstinence.<sup>124</sup> Recently, we also observed that smoking trsAUD relative to non-smoking trsAUD had thinner cortex and lower N-acetylaspartate levels (marker of neuronal integrity), in anterior frontal and temporal regions at entry into treatment.<sup>125</sup> Recent analyses also indicated that smoking trsAUD showed greater age-related volume loss than non-smoking trsAUD in the anterior frontal regions and the insula, as well as poorer performance with increasing age on measures of learning and memory, cognitive efficiency, executive functions, processing speed, and fine motor skills at 1-month of abstinence.<sup>103, 126</sup> In several of these studies, greater smoking exposure (i.e., lifetime years of smoking or pack-years) were related to greater neurobiological and/or neurocognitive abnormalities in cross-sectional studies or poorer recovery in longitudinal studies.<sup>103, 113–115, 120, 124, 126, 127</sup> Level of nicotine dependence in these studies showed weak or no association with neurobiological and neurocognitive measures.

#### 4.2. Smoking in mild traumatic brain injury

In those with a mild traumatic brain injury (TBI), we observed that active-smokers demonstrated significantly poorer recovery than never-smokers over 6 months post injury on measures of processing speed, visuospatial learning and memory, visuospatial skills and

global neurocognition. Similar to AUD cohorts, greater smoking exposure (i.e., lifetime years of smoking or pack-years) was robustly related to less improvement on measures of visuospatial learning, visuospatial memory, working memory, visuospatial skills, and global cognition.<sup>128</sup>

#### 4.4. Synopsis

Smoking in non-clinical and clinical populations is strongly related to multiple neurocognitive and neurobiological abnormalities. Many of the neurocognitive (e.g., learning and memory, executive function, processing speed deficits) and neurobiological (e.g., hippocampal and lateral temporal volume loss, regional cortical thinning and decreased markers of neuronal integrity) demonstrated by non-clinical smokers and smokers with AUD are observed in the recently proposed preclinical stages of AD as well as in MCI. The progressive nature of regional atrophy and neurocognitive decline observed in elder smokers is also consistent with risk factors associated with progression from MCI to AD.<sup>18, 20, 29, 30</sup> The neurobiological and neurocognitive abnormalities observed in late adolescents through middle-aged adult smokers are highly relevant for the US Armed Services, given the majority of active duty personnel are between the ages of 18 and 50, and the increased prevalence of smoking relative to civilians in the corresponding age range.<sup>9</sup> The neurobiological and neurocognitive sequelae associated with mild TBI and AUD/hazardous alcohol consumption may be exacerbated by smoking, and impaired recovery from these conditions is associated with smoking. These findings are of considerable import to all branches of the military because personnel engaged in combat operations are at significantly increased risk for mild TBI and AUD/hazardous alcohol consumption.<sup>129, 130</sup>

A primary pathophysiological mechanism that is hypothesized to contribute to the neurobiological and neurocognitive abnormalities observed in smokers is cerebral oxidative stress (OxS).<sup>14, 17</sup> Correspondingly, OxS may serve as a factor promoting the greater risk for AD observed in smokers, which is addressed in the following section.

## 5. Smoking-related neuropathology: the role of oxidative stress

### 5.1. Oxidative stress (OxS)

OxS is established by detection of damage to brain and other organ system tissue that is caused by reactive oxygen species (ROS), or more broadly by damage from ROS, reactive nitrogen species (RNS), and other oxidizing agents.<sup>60, 131, 132</sup> Increased levels of free radical species (i.e., ROS and RNS) and oxidants occurs from an imbalance between the generation of these compounds via endogenous (i.e., normal cell metabolism) and/or exogenous sources (e.g., smoking), and their chemical reduction by antioxidants/radical scavengers.<sup>60, 133, 134</sup> Irrespective of the source, increased free radical concentrations are directly associated with oxidative damage to membrane lipids, proteins, carbohydrates, DNA and RNA of neuronal, glial, and vascular tissue of the brain.<sup>133, 135–141</sup>

Cytokines, which include chemokines, interferons, interleukins, growth factors, and tissue necrosis factors (TNF), are a major component of a highly complex system that controls immune and inflammatory responses in the peripheral and central nervous systems.<sup>142</sup> Oxidative damage from free radical or other oxidants may trigger inflammation via a

cytokine-mediated immune response<sup>143</sup> that involves release of anti-inflammatory and proinflammatory cytokines (e.g., TNF $\alpha$ , IL-1, IL-6) by peripheral and central nervous system cells (e.g., microglia and astrocytes).<sup>142</sup> Elevated proinflammatory cytokine levels are associated with cerebral OxS and apoptosis through generation of ROS and other inflammatory mediators in the brain (and peripheral organ systems) by immune cells, microglia and astrocytes.<sup>142, 144, 145</sup> Therefore, OxS and inflammation often occur in tandem in many diseases/disorders, including AD, smoking and substance/alcohol use disorders.<sup>14, 55, 62, 146–149</sup>

The brain is highly susceptible to OxS caused by free radicals and other oxidizing agents due to its high metabolism and energy demand, and vulnerability of membrane phospholipids that are rich in polyunsaturated fatty acids, to peroxidation by radical species.<sup>150–154</sup> The anterior frontal lobe, medial and lateral temporal lobe,<sup>155, 156</sup> and hippocampus are particularly vulnerable to OxS-mediated cellular damage.<sup>60</sup> See<sup>143, 148, 157, 158</sup> for details on OxS-mediated cell damage, apoptosis, and neurodegeneration. Smoking-induced OxS, via increased ROS and RNS levels, is also robustly related to increased risk for atherosclerosis, chronic obstructive pulmonary disease, and carcinogenesis in humans.<sup>132, 133, 141, 159–163</sup>

## 5.2. Cigarette smoke/combustion products and OxS

Cigarette smoke is a complex admixture of approximately 5000 combustion products (including nicotine), which contains a high number of cytotoxic and carcinogenic compounds.<sup>164</sup> The gas and particulate phases of cigarette smoke have extremely high concentrations of short-and-long-lived ROS, RNS, and other oxidizing agents.<sup>92, 133</sup> In addition to increased free radical concentrations, smoking is associated with markedly elevated carboxyhemoglobin levels,<sup>165</sup> altered mitochondrial respiratory chain function,<sup>166</sup> and induction of proinflammatory cytokine release by peripheral and CNS glial cells,<sup>167</sup> which collectively promote significant cerebral OxS.

**5.2.1. In vitro and animal studies**—Giunta and colleagues<sup>168</sup> demonstrated that *in vitro* exposure of microglia (BV-2) to cigarette smoke condensate promoted significantly increased release of TNF- $\alpha$  and IL-1B proinflammatory cytokines. Barr and colleagues<sup>169</sup> reported nicotine administration to rat mesencephalic cells induced high ROS levels and activated NF- $\kappa$ B (involved in inflammation, innate immunity, development, apoptosis, and antiapoptosis). In a series of studies by Anbarasi and colleagues, rats were exposed to daily cigarette smoke for 12 weeks. Homogenized brain tissue showed consistent evidence of OxS (i.e., lipid peroxidation,<sup>170</sup> increased creatine kinase,<sup>171</sup> and increased apoptotic markers<sup>172</sup>), as well as OxS and dysfunction specifically in mitochondria<sup>173</sup> (i.e., lipid peroxidation, diminished oxidative phosphorylation). Rueff-Barroso et al.,<sup>174</sup> reported that mice exposed to daily cigarette smoke for 15 weeks demonstrated significant OxS in homogenized whole brain tissue as indicated by elevated malondialdehyde level, a marker of lipid peroxidation. Ho et al.,<sup>175</sup> found that rats exposed to daily cigarette smoke for approximately 8 weeks showed significantly increased levels of 8-hydroxyguanine, a marker of oxidative damage to RNA and DNA nucleosides, in the dentate and CA3 subfields of the hippocampus.<sup>175</sup> Khanna et al.,<sup>147</sup> reported rats exposed to cigarette smoke 5 days/week for

6 weeks exhibited significantly increased brain IFN- $\gamma$  and TNF- $\alpha$  proinflammatory cytokine levels, as well as upregulation of the expression of multiple cytokine genes (e.g., TNF- $\alpha$ , IL1- $\alpha$ , IL1- $\beta$ , Th17). Das and colleagues<sup>176</sup> observed that rats treated with intraperitoneal nicotine for 7 days showed significant lipid peroxidation and protein oxidation in mitochondria from cortical, diencephalic, and cerebellar tissue.

**5.2.2. Human studies**—Sonnen et al.,<sup>177</sup> conducted post-mortem comparisons of human smokers and never-smokers ( $87 \pm 6$  years of age) without significant AD or microvascular pathology. Active-smokers showed significantly higher cortical F<sub>4</sub>-neuroprostanes, a measure of neuronal free radical-mediated lipid peroxidation, but groups were not different on measures of cerebellar lipid peroxidation. Additionally, numerous human studies have shown elevated markers of OxS (e.g., F<sub>2</sub>-isoprostanes, hydroxycholesterols, C-reactive protein) in the serum or plasma of smokers.<sup>132, 178–184</sup>

### 5.3. Cigarette smoke/combustion products and antioxidant depletion

The combined activity of enzyme-based (e.g., superoxide dismutase, catalase, glutathione reductase) and non-enzyme-based (e.g., glutathione and vitamins A, C, and E) anti-oxidants and radical scavengers are responsible for managing the levels of free radicals and other oxidants in the brain.<sup>151, 185</sup> Acute exposure to radical species and oxidizing agents promotes an adaptive increase in the production of enzyme-based anti-oxidant to mitigate oxidative damage.<sup>151</sup> Deficiencies in the production and/or maintenance of optimal levels of these antioxidant compounds can result in significantly increased radical and oxidant concentrations (via endogenous and/or exogenous sources), which promotes OxS.<sup>151, 157, 158, 186, 187</sup> Glutathione is the dominant anti-oxidant in the human brain with regional concentrations from 0.8 to 5.0 mM,<sup>188–190</sup> and oxidized forms represent less than 1% of the total glutathione level.<sup>191</sup> Glutathione is critically involved in the chemical reduction of ROS and hydrogen peroxide, and in maintenance of other antioxidants (e.g., vitamins A, C and E) in their chemically reduced functional forms.<sup>135, 153, 191–193</sup> Decreased central and peripheral glutathione concentration is a longstanding and accepted proxy for OxS.<sup>134, 153, 186, 187, 193–195</sup>

**5.3.1. Animal studies**—*In vivo* chronic cigarette smoke exposure to rats was associated with significantly decreased enzyme-based free radical and non-enzyme-based radical scavenger concentrations in brain homogenates.<sup>151, 196</sup> Chronic cigarette smoke exposure was specifically associated with significantly decreased glutathione level in rodent brains.<sup>151, 170, 197</sup> Das et al.,<sup>176</sup> reported that intraperitoneal nicotine administration over 7 days in rats, along with OxS (see section 5.2.1), significantly decreased multiple enzyme-based radical scavenger levels in brain mitochondria.

**5.3.2. Human studies**—In humans, smoking was related to significantly reduced glutathione level in plasma/serum across race and sex,<sup>135, 178, 179, 181, 197–200</sup> as well as decreased serum superoxide dismutase and vitamin C.<sup>178, 179</sup> Smoking was also shown to directly decreases glutathione production via alterations of its synthetic pathway,<sup>135, 181</sup> and dietary differences did not account for reduced glutathione levels.<sup>178, 198</sup> The decreased glutathione and other anti-oxidant concentrations in smokers are postulated to result from

the amplified demand to detoxify (i.e., chemically reduce) the chronically high ROS and RNS levels delivered in cigarette smoke.<sup>151, 178, 198, 201</sup>

#### 5.4. Oxidative stress, amyloidogenic pathway, and tau phosphorylation

A $\beta$  isoforms are indicated to promote OxS in brain tissue and AD-related disease progression (see section 2.1)<sup>55</sup> However, cerebral OxS has also been hypothesized to be involved in the initiation of AD pathophysiological process, rather than strictly emerging as a physiological consequence of existing amyloid-or-tau-based neuropathology.<sup>131, 202–204</sup> More specifically, *in vitro* studies of various brain cell types reported OxS induced by exogenous agents (e.g., hydrogen peroxide) is associated with increased  $\beta$ -secretase cleavage of APP, under mild and toxic OxS conditions, and amplified OxS does not increase  $\beta$ -secretase levels in cells lacking presenilins or APP.<sup>205, 206</sup> Additionally, *in vitro* and *in vivo* preclinical models have demonstrated that OxS is promotes abnormal tau phosphorylation in the brain (see<sup>42, 149, 204</sup> for review) Therefore, smoking-related OxS may serve as a fundamental mechanism contributing to the neurobiological abnormalities (e.g., brain atrophy, regional cortical thinning) observed in smokers in clinical and non-clinical cohorts,<sup>14, 17</sup> as well as for increased risk for development of A $\beta$  and tau pathology.<sup>77, 82, 131, 168, 175, 207, 208</sup>

#### 5.5. Synopsis

The *in vitro* and animal and literature clearly demonstrates a causal relationship between *in vivo* chronic cigarette smoke/condensate and nicotine exposure and cerebral OxS; cigarette smoke/condensate, nicotine, and increased proinflammatory cytokines (via activation of immune cells, microglia and astrocytes) promote high concentrations of ROS, RNS, and other oxidants. Animal models also showed cigarette smoke and nicotine exposure was causally linked to significant cerebral anti-oxidant depletion. The factors promoting cerebral OxS and antioxidant depletion in animal models are hypothesized to be operational, *in vivo*, in the human brain<sup>132, 151, 168, 177</sup> and evidence of free radical-mediated damage was demonstrated post-mortem in the human brain.<sup>177</sup> Taken together, the existing literature indicates that smoking and pure nicotine: a) serves as an exogenous source of high concentrations of ROS, RNS, and other oxidizing compounds; b) up-regulates activity and release of proinflammatory cytokines by peripheral and central nervous systems, which promotes immune system-mediated discharge of additional free radicals and oxidizing compounds; c) depletes enzyme-and-non-enzyme-based antioxidants secondary to increased demand for the chemical reduction of high radical concentrations (from cigarette smoke and proinflammatory cytokine signaling), and inhibits the production of glutathione, the primary antioxidant in the human brain. The combination of these conditions serves to place the brain and other organ systems of smokers under a state of chronic OxS. Importantly, OxS is associated with increased  $\beta$ -secretase cleavage of APP as well as tau phosphorylation; therefore, smoking-related OxS may serve as a fundamental mechanism initiating the AD-pathophysiological process promoting increased risk for the development of AD.



## 6. Smoking and nicotine: relationships to AD pathophysiology

As previously summarized in section 5, cerebral OxS has been implicated in the initiation of AD neuropathology, rather than strictly developing as a physiological consequence of existing and/or progressing amyloid-or-tau-based pathophysiology.<sup>42, 131, 202, 203</sup> Smoking is strongly associated with cerebral OxS (see section 5), and OxS promotes increased  $\beta$ -secretase cleavage of APP and abnormal tau phosphorylation. Thus, smoking-related OxS may directly facilitate the amyloidogenic pathway involved in A $\beta$  oligomers production and extracellular fibrillar A $\beta$  aggregation,<sup>168</sup> as well as abnormal tau phosphorylation, which is the basis of neurofibrillary tangle pathology.

Nicotine is a main constituent of the particulate phase of cigarette smoke, and is principally responsible for promoting physiological dependence on all forms of tobacco.<sup>209</sup> Nicotine consumption has been suggested to be protective against AD neuropathology via activation of nicotinic acetylcholine receptors (nAChR).<sup>210, 211</sup> Both smoking and pure nicotine significantly upregulate the number of inotropic  $\alpha 4\beta 2$  and  $\alpha 7$  nAChR subtypes of, but the sensitivity of these receptors is diminished.<sup>212, 213</sup> Nicotine binding at nAChRs influences neurotransmitter release, signal transduction, gene transcription, and cell survival, apoptosis, and plasticity;  $\alpha 7$  nAChRs appear to be centrally involved in survival, apoptotic, and plastic mechanisms.<sup>213, 214</sup> A significant loss of neurons and/or synapses expressing nAChRs is apparent in early AD, and A $\beta$  aggregation is frequently pronounced at nAChRs.<sup>215</sup>

### 6.1. Smoking and smoke exposure

**6.1.1. In vitro and animal studies**—*In vitro* studies by Giunta and colleagues<sup>168</sup> showed that cigarette smoke condensate (i.e., the particulate component of tobacco smoke) increased A $\beta_{1-40}$  and A $\beta_{1-42}$  levels in a concentration-dependent manner in cells transfected with human APP (SweAPP N2a cells). In addition to elevated markers of OxS (see Section 5.2.1.) in cigarette smoke exposed rats, Ho et al.,<sup>175</sup> reported these rats concurrently demonstrated significantly increased  $\beta$ -sAPP, but not  $\alpha$ -sAPP, levels in homogenized hippocampal tissue and markedly increased A $\beta$  accumulation in the CA3 and dentate subfields of the hippocampus. The smoke exposed rats also showed significantly increased hippocampal hyperphosphorylated tau, but not total tau levels. Moreno-Gonzalez and colleagues<sup>208</sup> exposed 3-month-old APP/presenilin1 (PS1) transgenic mice to high (one cigarette over 60 minutes) or low (half of a cigarette over 30 minutes) dosage cigarette smoke 5 days/week for 4 months. The high-dosage group showed levels of cotinine, the primary metabolite of nicotine, that were physiologically consistent with human smokers. Both high-and-low-dosage groups begin to develop neuritic plaques at 5–6 months of age. The high-dosage group demonstrated a significantly greater number of A $\beta$  deposits and fibrillar neuritic plaques, increased density of activated microglia and reactive astrocytes, and positive hyperphosphorylated tau staining in the majority of the cerebral cortex and hippocampus relative the low-dosage group and controls.

**6.1.2. Post-mortem human studies**—In a large human autopsy sample, Tyas and colleagues<sup>82</sup> observed across elder dementia and non-dementia groups, that active-smokers and former-smokers demonstrated significantly higher neuritic plaque burden in the cerebral



cortex and hippocampus than never-smokers, but no differences were apparent between groups on cortical or hippocampal neurofibrillary tangle count. Furthermore, the risk for CERAD neuropathologically defined AD was more than double for active (OR = 2.64; 95% CI = 0.54–12.88) and former (OR = 2.62; 95% CI = 0.80–11.57) smokers relative to never-smokers. Conversely, in a hospital-based autopsy sample (pre-existing biomedical and neurodegenerative conditions were not considered), Ulrich et al.,<sup>216</sup> observed in a group of female never/former-smokers, relative to active-smokers, had a lower average density of neuritic plaques in a composite of the hippocampus, entorhinal cortex, and neocortex, but showed a trend for a higher density of neurofibrillary tangles. There were no differences between male smokers and non-smokers in plaque or neurofibrillary tangle density. In smokers for both sexes, higher pack years were significantly correlated with greater neurofibrillary tangle density, but not with neuritic plaque density. Sabbagh et al.,<sup>85</sup> found no differences in neuritic plaques or neurofibrillary tangle density specifically in the mid-frontal cortex (the only region examined) between never, former and active smokers with AD. Hellstrom-Lindahl et al.,<sup>210</sup> observed that soluble and insoluble  $A\beta_{1-40}$  and  $A\beta_{1-42}$  levels were significantly lower in homogenates of frontal and temporal cortex, but not the hippocampus, in cognitively-normal active-smokers compared to never-smokers. In the same study, active-smoker AD cases had lower insoluble and soluble  $A\beta_{1-40}$  and  $A\beta_{1-42}$  in the frontal cortex than never-smoker AD, but in the temporal cortex and hippocampus, only insoluble and soluble  $A\beta_{1-40}$  levels were significantly lower in active-smoker AD. Perry and colleagues<sup>217</sup> reported non-demented elders who had smoked within 10 years of (smokers) death had lower mean neuritic plaque level in the hippocampus, entorhinal cortex and neocortex than those who had quit smoking more than 10 years before death (non-smokers); a never-smoker group was not available for comparison. No group differences were observed for neurofibrillary tangles in any region, and APOE genotype did not mediate the finding for neuritic plaque or neurofibrillary tangle burden in group comparisons on smoking status; however, irrespective of smoking status, APOE  $\epsilon 4$  carriers had lower mean neocortical neuritic plaque density than non-carriers, which appeared to be driven by the low density in the small number of smoker APOE  $\epsilon 4$  carriers ( $n = 4$ ). In a subsequent study by the same lab, Court et al.<sup>218</sup> found non-demented elders who smoked most of their lives/smoked within 15 years of death showed lower entorhinal cortex levels of total and diffuse  $A\beta$  deposits and insoluble  $A\beta_{1-42}$  relative to elders who never smoked/quit smoking at least 25 years before death. Higher pack-years were related to lower entorhinal cortex soluble  $A\beta_{1-42}$  level. Groups did not differ on hyperphosphorylated tau density.

**6.1.3. Synopsis**—The *in vitro* and animal studies showed cigarette smoke condensate and cigarette smoke exposure consistently facilitated the amyloidogenic pathway, as well as causally increased tau hyperphosphorylation. Specifically, chronic cigarette smoke exposure in normal and AD model transgenic animals was causally related to significantly increased sAPP $\beta$  level,  $A\beta$  deposition, neuritic plaque burden, as well as increased hyperphosphorylated tau levels in the cerebral cortex and hippocampus. Cigarette smoke condensate exposure to cells transfected with human APP produced increased  $A\beta_{1-40}$  and  $A\beta_{1-42}$  levels in a concentration-dependent manner. Markers of increased OxS were concurrently observed in several of studies demonstrating amyloidogenic pathway facilitation and tau accumulation. In contrast, human autopsy studies yielded mixed findings

regarding the association between smoking and AD neuropathology. The interpretation of these studies is obfuscated by inconsistencies in the assignment of smoking status (e.g., never-smokers and former-smokers with variable lengths of smoking cessation combined into a single group), small sample sizes in some studies, inconsistent consideration of potential sex effects, and survivor bias. In the large-sample study<sup>82</sup> with clear assignment of never/former/active-smokers, significantly greater brain A $\beta$ -related neuropathology was observed in active-smokers and former-smokers, compared to never-smokers. Conversely, in small sample sized studies comparing groups of non-smokers (e.g., combined never and long-term abstinent former smoker) and smokers (combined active or smoked within 15 years of death), smokers showed significantly lower levels of A $\beta$ -related neuropathology. One of the studies<sup>217</sup> reporting smokers showed lower neuritic plaque density reported irrespective of smoking status, APOE  $\epsilon$ 4 carriers had lower mean neocortical neuritic plaque density than non-carriers, which is contrary to typically observed effect of APOE  $\epsilon$ 4 genotype on plaque density in humans.<sup>66</sup> Despite the methodological limitations and inconsistent results across the human post-mortem studies, these findings, combined with the animal and *in vitro* data suggest: a) at a minimum, smoking is not protective of AD-related pathophysiological processes, and smoking may facilitate the development of regional A $\beta$  and tau pathology; b) increased OxS is a robust candidate mechanism contributing to the initiation of the AD pathophysiological process in smokers.

## 6.2. Nicotine, nicotinic acetylcholine receptor agonists and antagonists, and AD pathophysiology

**6.2.1. In vitro and animal studies**—Hellstrom-Lindahl et al.<sup>219</sup> reported that nicotine or epibatidine (a non-selective nAChR agonist) treatment of the human neuroblastoma cells (SH-SY5Y) caused increased levels of levels of p-tau and total tau. Additionally nicotine, epibatidine or A $\beta$ <sub>1-42</sub> (as a ligand for nAChRs) administration induced tau phosphorylation in neuroblastoma cells (SK-N-MC) and in hippocampal synaptosomes. In rats, subcutaneous nicotine administration over 2 weeks decreased soluble APP peptides,<sup>220, 221</sup> but increased levels of total sAPP in the cerebrospinal fluid (CSF).<sup>221</sup> Over 6 weeks, rats administered intraventricular A $\beta$ <sub>1-40</sub> and A $\beta$ <sub>1-42</sub> with concurrent subcutaneous nicotine showed lower levels of A $\beta$ <sub>1-40</sub> and  $\beta$ -secretase in the hippocampal CA1 subfield, better memory, and greater hippocampal long-term potentiation compared to rats administered A $\beta$ <sub>1-40</sub> and A $\beta$ <sub>1-42</sub> alone.<sup>222</sup> In transgenic mice (expressing Swedish human APP), those administered nicotine in drinking water showed a significant reduction of neuritic plaques and insoluble A $\beta$ <sub>1-40</sub> and A $\beta$ <sub>1-42</sub> levels, but no changes in soluble A $\beta$ <sub>1-40</sub> and A $\beta$ <sub>1-42</sub> levels, in the cerebral cortex, compared to sucrose treated mice.<sup>211</sup> Transgenic mice (expressing human A $\beta$  precursor protein and PS1 genes) that were administered cotinine, the primary metabolite of nicotine, via oral gavage for 3.5 months, showed lower insoluble A $\beta$ <sub>1-42</sub> in the cortex and A $\beta$ <sub>1-40</sub> in the hippocampus than control transgenic mice; no differences between treated and control animals were observed for soluble A $\beta$ <sub>1-42</sub> and A $\beta$ <sub>1-40</sub> levels in the cortex or hippocampus; decreased A $\beta$ <sub>1-42</sub> oligomerization was also observed *in vitro*.<sup>223</sup> Conversely, a study employing transgenic mice (3xTg-AD; expressing combination of Swedish human APP and tau<sub>P30H</sub>) that were administered nicotine in drinking water for 5 months showed no increase in soluble or insoluble A $\beta$ <sub>1-42</sub> and A $\beta$ <sub>1-40</sub> levels in the hippocampus compared to control transgenic mice; however, the nicotine treated mice exhibited a significant

increase of hippocampal tau phosphorylation and aggregation; the increased hippocampal tau aggregation and phosphorylation were related to an age-dependent decreased density of  $\alpha 7$  nAChRs in both the nicotine treated and untreated mice.<sup>224</sup> Additionally, *in vitro* exposure of mature mouse brain mitochondria to nicotine produced no increase in free radical concentration or corresponding evidence of lipid peroxidation.<sup>225</sup>

**6.2.2. Post-mortem human study**—In a human autopsy study, the effect of several nAChRs agonists (but not nicotine) and antagonists on <sup>11</sup>C-Pittsburgh compound B binding (PiB; shows high affinity binding to fibrillar A $\beta$ <sup>226</sup>) were evaluated in frontal lobe homogenates of elder controls and AD. The smoking status of AD and control cases was not provided. The  $\alpha 7$  nAChR agonists varenicline and JN403, but not the  $\alpha 4\beta 2$  nAChR agonist cytisine, increased PiB binding in both AD and controls. This effect was abolished by the  $\alpha 7$  nAChR antagonists  $\alpha$ -bungarotoxin, mecamylamine, and methyllycaconitine, but not by the  $\alpha 4\beta 2$  antagonist dihydro- $\beta$ -erythroidine. Increased PIB binding promoted by varenicline and JN403 was significantly inhibited by pre-incubation with the amyloid ligand, BF-227. The acetylcholinesterase inhibitor and allosteric nAChR modulator galantamine, and the N-methyl-D-aspartate receptor blocker memantine did not significantly influence PiB binding levels in AD cases.<sup>227</sup>

**6.2.3. Synopsis**—The rodent studies on the effect of chronic nicotine administration on A $\beta$  deposition and isoforms yielded inconsistent results; nicotine administration in transgenic and non-transgenic animals produced significant reductions of neuritic plaques and insoluble A $\beta_{1-40}$  and A $\beta_{1-42}$  levels in brain tissue in some studies, or nicotine caused no increase in soluble or insoluble A $\beta_{1-42}$  and A $\beta_{1-40}$  levels in others. Regardless of the use of different species and genetic modifications, variable routes of nicotine administration, and different assay and quantitation methods in rodent studies, nicotine did not alter soluble A $\beta_{1-40}$  and A $\beta_{1-42}$  concentrations in the cortex or hippocampus. This finding is relevant to humans because soluble A $\beta$  oligomer levels, but not fibrillar A $\beta$ -containing compounds, show consistent associations with cognitive decline and tau hyperphosphorylation.<sup>55</sup> In humans,  $\alpha 7$  nAChR agonists, but not  $\alpha 4\beta 2$  nAChR agonists, increased PiB binding in post-mortem frontal lobe homogenates of elder controls and AD. Additionally, chronic nicotine administration to adolescent rats evoked cell damage and loss throughout the brain, and with selectively greater effects in the female hippocampus.<sup>228, 229</sup> The interpretation of the effects of nicotine on A $\beta$ -related neuropathology in animals and humans is further complicated by the following: a) AD is associated with a significant reduction in acetylcholinergic neurons, synapses, and nAChR expression; b) active smoking/nicotine consumption is associated with upregulated nAChR numbers; c) neuritic plaque and A $\beta$  accumulation show strong co-localization at nAChRs;<sup>230</sup> d) APOE  $\epsilon 4$  carriers with carriers with AD may possess fewer nAChR binding regions.<sup>78</sup> Therefore, it is clear that the interplay between nicotine/ cholinergic agonists at nAChRs, particularly  $\alpha 7$  nAChRs, and A $\beta$  deposition is complex and incompletely understood.<sup>6, 227, 230</sup> In contrast to A $\beta$ , animal and *in vitro* models showed administration of nicotine and nAChR agonists consistently induced tau aggregation and hyperphosphorylation. Overall, the findings across animal and human studies do not provide consistent evidence that nicotine and other  $\alpha 7$  nAChR agonists are protective against A $\beta$  production and deposition. Notably, preclinical data indicated nicotine and nAChR agonists

reliably produced tau hyperphosphorylation. Given nicotine exposure *in vitro* and *in vivo* induces cerebral OxS in animal models, which is related to abnormal tau phosphorylation, the above reported associations observed between nicotine exposure and increased tau phosphorylation may be explained by nicotine-induced OxS.

## 7. Comparison of elders with and without a history of smoking on cerebral A $\beta$ deposition: Florbetapir positron emission tomography

### 7.1. Background and subjects

To our knowledge, there are no published *in vivo* human studies that specifically investigated the influence of smoking status on neuroimaging markers of A $\beta$  deposition in cognitively-normal elders. Accordingly, we compared a large cross-sectional sample of cognitively-normal elder control participants from the Alzheimer's Disease Neuroimaging Initiative (ADNI) who were never-smokers (n = 154; 75  $\pm$  7 years of age; 17  $\pm$  3 years of education), to those with at least 1-year of smoking during lifetime (smokers; n = 109; 76  $\pm$  5 years of age; 16  $\pm$  3 years of education; pack-years = 26  $\pm$  21), on cortical A $\beta$  deposition, via florbetapir F-18 PET. Twelve smokers (11%) were active-smokers at the time of study; former-smokers (n = 97) quit smoking 34  $\pm$  15 (min = 1, max = 34; median = 37) years before study. Smokers (former and current smokers combined) and never-smokers were equivalent on: age, education, allowed current and historical biomedical conditions, and frequency of sex, APOE  $\epsilon$ 4 carriers, antihypertensive, statins and cholesterol absorption blockers, and COPD medication use. Smokers and non-smokers did not differ on plasma triglyceride and cholesterol levels, the Modified Hachinski score (measure of cerebrovascular risk factors) or WM hypointensity volume based on T1-weighted MRI. Smokers had a significantly higher frequency of history of alcohol misuse (p < .05), which is consistent with findings from middle-aged cohorts.<sup>14</sup>

### 7.2. florbetapir F-18 PET and statistical analyses

Florbetapir shows high affinity and specific binding to fibrillar A $\beta$  deposits in neuritic plaques,<sup>231</sup> and is strongly correlated with the level of neuritic plaque binding demonstrated by PiB.<sup>232</sup> Mean florbetapir retention was calculated for prefrontal, anterior/posterior cingulate, lateral parietal, and lateral temporal gray matter (GM), and each region was standardized to the whole cerebellar retention. A composite measure was calculated by taking the average of the four cortical regions and dividing by whole cerebellar florbetapir retention [see (adni.loni.usc.edu/research/pet-analysis/) for details on formation florbetapir quantitation and formation of GM regions of interest]. Human fibrillar A $\beta$  deposition, as measured by PET ligands, is highly related to age beginning in the 5<sup>th</sup> decade of life, and suggested to follow a sigmoid curve through old age.<sup>30</sup> APOE genotype is also strongly related to fibrillar A $\beta$  deposition, with APOE  $\epsilon$ 4 carriers typically showing greater deposition than non-carriers, particularly with increasing age.<sup>38, 233</sup> Since history of smoking in cognitively-normal elders is associated with greater regional brain atrophy, and other neurobiological abnormalities in the anterior and posterior cingulate, and anterior frontal, posterior parietal and lateral temporal lobes (see section 4.3), we predicted smokers demonstrate greater florbetapir retention than non-smokers across these regions. A composite GM florbetapir retention value of 1.11 is designated as an "amyloid-positive"

cutoff, based on levels demonstrated by individuals who completed a florbetapir PET scan within 12 months of death that showed probable AD at autopsy (see [adni.loni.usc.edu/research/pet-analysis/](http://adni.loni.usc.edu/research/pet-analysis/)). We predicted a greater frequency of smokers have  $\geq 1.11$  composite GM retention values. Multivariate analysis of covariance (MANCOVA) tested for differences between smokers and never-smokers in prefrontal, anterior/posterior cingulate, lateral parietal, and lateral temporal gray matter GM and composite florbetapir retention, controlling for APOE  $\epsilon 4$  carrier status, age, sex, education, and history of alcohol misuse. Effect sizes (ES) for mean differences between smokers and non-smokers on regional florbetapir uptake were calculated with Cohen's  $d$ . The small number of active-smokers ( $n = 12$ ) had numerically higher florbetapir uptake in all regions than former-smokers (data not shown), but these differences were not statistically significant, so active and former-smokers were combined into one group. The proportion of smokers and never-smokers that were  $\geq 1.11$  versus  $< 1.11$  for composite GM florbetapir were compared with chi-square. Associations between smoking exposure variables (i.e., pack-years, years of smoking cessation) and regional florbetapir uptake were examined with partial correlations controlling for age, sex and APOE  $\epsilon 4$  carrier status.

### 7.3. Results

MANCOVA yielded a significant omnibus effect for smoking status (active/former smoker vs. never-smoker) [ $F(5, 252) = 2.75, p = .019$ ]. There were no significant interactions among smoking status and covariates. Follow-up t-tests (two-tailed,  $p \leq .025$  considered statistically significant) indicated smokers showed greater florbetapir retention than never-smokers in the cingulate, temporal, parietal and composite GM (all  $p < .018$ ; see Figure 1), with a trend in the frontal GM ( $p = .065$ ). A significantly higher proportion of smokers (44 of 109; 40%) than never-smokers (39/154; 25%) had florbetapir retention values  $\geq 1.11$  for the composite GM (two-tailed  $\chi^2 = 6.69; p = .01$ ). Virtually identical results were obtained for the above analyses when only former-smokers ( $n = 97$ ) were compared to never-smokers. In smokers, there were no significant associations between cigarette exposure variables (i.e., pack-years, lifetime years of smoking, years of smoking cessation) and florbetapir retention in any region.

### 7.4. Discussion

The significantly higher regional florbetapir retention in this large sample of cognitively-normal, elders with a history of smoking indicated they had greater fibrillar A $\beta$  deposition in the cingulate, temporal, parietal and composite cortical GM. The greater *in vivo* florbetapir retention in these cognitively normal elder smokers is novel and congruent with *in vitro*, animal, and human postmortem studies that reported cigarette smoke exposure/smoking was associated with significantly increased A $\beta$ -based neuropathology (see section 5.2). A significantly higher proportion of smokers (40%) than never-smokers (25%) had composite GM retention values that fell into the range demonstrated by those with histologically confirmed AD. Human post-mortem studies have reported that approximately 30% of cognitively intact elders exhibit levels of amyloid deposition observed in AD cases.<sup>48, 234</sup> This suggests the proportion of smokers in this cohort that demonstrated elevated amyloid deposition is 10% beyond that expected in the general population of cognitively-normal elders. Additionally, research criteria<sup>27</sup> have been recently proposed to stage and

operationalize the severity of the neuropathological correlates of preclinical AD in cognitively-normal individuals; the stages are as follows: no indications of elevated amyloid and neuronal injury biomarkers or “subtle” cognitive decline (Stage 0), elevated amyloid biomarkers only (Stage 1), elevated amyloid and neuronal injury biomarkers (Stage 2), elevated amyloid, neuronal injury biomarkers, and subtle cognitive decline (Stage 3). Based on the florbetapir findings alone, approximately 33% of the entire cognitively-normal elder cohort would have been classified as Stage 1 preclinical AD; however, when smoking status was considered, 40% of smokers versus 25% of never-smokers would be classified as Stage 1, after controlling for APOE4 genotype and other relevant covariates. This highlights the importance of consideration of the potential effects of smoking status on AD-related pathophysiology. Smokers and never-smokers from this cognitively-normal cohort will be compared on markers of structural, metabolic, OxS, and neurocognition in future analyses in order to more accurately determine the number of individuals exhibiting criteria for the various preclinical AD stages.

The 11% active-smokers in this cohort is consistent with the estimated prevalence of 10% active-smokers in those 60 years of age in the general US population.<sup>2</sup> It is noteworthy that 89% of smokers were former-smokers, with a wide range of duration of smoking cessation. The lack of differences between smokers and never-smokers on CVD and cerebrovascular disease risk factors (e.g., triglyceride and cholesterol levels, Modified Hachinski score, use of antihypertensive medications) may be related to the fact that 89% of the smokers were former smokers, or potentially to survivor bias in the smoker cohort. Nevertheless, despite  $34 \pm 15$  years of smoking cessation, former-smokers demonstrated significantly greater florbetapir retention in the cingulate, temporal, parietal, and composite GM. In the entire smoker sample, and in former-smokers alone, there were no significant associations between cigarette exposure variables and regional florbetapir retention. These findings suggest that other premorbid and/or comorbid factors not considered in this report may have partially contributed to the greater regional florbetapir retention observed in smokers, or the amyloid deposition in this cohort has been stable for many years. Given the increased rate of amyloid accumulation, via PET neuroimaging, is associated with increased risk for cognitive decline in cognitively-normal elders, as well as conversion from MCI to AD,<sup>235, 236</sup> longitudinal tracking of this cohort of smokers and never-smokers may advance our understanding of the factors related to the increasing dementia incidence in the rapidly growing numbers of oldest-old (i.e., 90 years of age) in the US.<sup>237</sup>

## 8. Summary

1. The cumulative body of research considered in this review strongly indicates that a history of smoking (i.e., former and active) is a significant and modifiable risk factor for AD, and increasing smoking exposure is related to greater risk. Smoking is associated with earlier onset of AD symptomatology, and is estimated to account for 4.7 million AD cases worldwide. In the US, smoking is associated with at least a 10 year reduction in life expectancy,<sup>238</sup> which will decrease the numbers of elder smokers participating in both case-controlled and cohort studies, and creates a survivor bias due to premature death. In other words, the study of smoking-related risk of AD in elders will be inescapably biased toward the healthiest smokers -



individuals who survived or did not experience significant smoking-related morbidity.<sup>89, 90</sup> Further, Chang and colleagues<sup>90</sup> clearly demonstrated how competing risk due to death (i.e., a smoker dies of another cause before manifesting AD) may obscure the association between smoking and risk for AD. The development of common clinically significant smoking-related morbidity (e.g., CVD, COPD, cancer, multiple cerebrovascular accidents) may be exclusionary in some studies or limit the functional ability and/or motivation of individuals to participate in longitudinal studies. This may also create a selection bias where the characteristics of study participants free from these conditions are not representative of the general population comparably aged smokers. Taken together, the actual magnitude of risk for AD associated with smoking is likely underestimated due to survivor bias.

2. Chronic exposure to cigarette smoke and nicotine is consistently and causally linked to OxS *in vitro* and in animal models, and is associated with OxS and corresponding cerebral cellular damage in post-mortem human studies. The animal models employed a wide variety of smoke exposure levels and durations, which should be considered when interpreting the findings from these studies. OxS is related to increased activity of the proteolytic pathway responsible for generating A $\beta$  isoforms, as well as abnormal tau phosphorylation. Therefore, exogenous sources of OxS may facilitate the onset of AD pathophysiology/neuropathology, rather than simply emerge as a physiological consequence of existing amyloid or tau pathology. Given the strong association between cigarette smoke exposure and increased brain OxS, smoking in humans may serve as a fundamental mechanism promoting development of AD pathophysiology and neuropathology. This assertion is supported by: 1) *in vitro* data demonstrating chronic cigarette smoke condensate exposure and nicotine to various cell types is causally related to increased cerebral A $\beta$  isoforms and hyperphosphorylated tau concentrations, 2) animal data showing cigarette smoke exposure causally increases brain fibrillar A $\beta$  deposition and nicotine administration promoted hyperphosphorylated tau levels; 3) human data from large-sample size post-mortem studies, and our novel *in vivo* PET neuroimaging findings (see section 7) showing that cognitively-normal former/active smoking is robustly associated with significantly increased cortical fibrillar amyloid deposition (former/active smokers and never-smokers were also equivalent on cerebrovascular risk factors in our cohort). Taken together, smoking-related OxS may increase the risk of AD through the initiation and progression of the core amyloid and tau pathologies that are hypothesized to lead to neurodegeneration, cell death, and neurocognitive decline.
3. Pure nicotine administration *in vitro* and in animal models yielded variable findings for A $\beta$  pathology, but consistent results for tau pathology. In humans, we are not aware of any published *in vivo* or post-mortem studies on the effects of pure nicotine consumption on AD pathophysiology. In animals, chronic nicotine was shown to significantly decrease neuritic plaques and insoluble A $\beta$ <sub>1-40</sub> and A $\beta$ <sub>1-42</sub> levels in the cortex or hippocampus, but did not alter soluble A $\beta$ <sub>1-40</sub> and A $\beta$ <sub>1-42</sub> concentrations in these regions. The findings for the soluble A $\beta$  isoforms are



significant for humans because soluble A $\beta$  oligomer levels may be more strongly related to cognitive decline and tau hyperphosphorylation than fibrillar A $\beta$ -containing compounds. *In vitro* exposure of nicotine and nicotine agonists causally increased p-tau and total tau levels, and in animals, chronic nicotine administration causally and significantly increased hippocampal tau aggregation and phosphorylation. The animal research reviewed employed a wide variety of animal types (e.g., mice, rats, transgenic animals), and routes of nicotine administration and dosages, which may have contributed to the variability of the findings in these preclinical studies. In humans,  $\alpha 7$  nAChR agonists increased PiB binding (shows high affinity binding to fibrillar amyloid), post-mortem, in frontal lobe homogenates of elder AD and controls. Currently, the combined findings from animal and human studies do not provide consistent evidence that nicotine and other  $\alpha 7$  nAChR agonists are protective against A $\beta$  deposition. Importantly, *in vitro* and animal models showed administration of nicotine and nAChR agonists consistently and causally induced tau hyperphosphorylation and aggregation. The association between nicotine administration and abnormal tau phosphorylation is consistent with nicotine serving as a source of OxS.

4. Smoking in clinical and non-clinical cohorts across adulthood is strongly related to multiple neurobiological and neurocognitive abnormalities (see section 4). In humans, smoking in multiple clinical conditions, and in cognitively-normal young-to-middle-aged adults and elders, is consistently associated with biomarkers of compromised neuronal integrity and degeneration (e.g., regional volume loss, cortical thinning, decreased N-acetylaspartate levels) and neurocognitive deficiencies. Smoking-related deficiencies in learning/memory, processing speed and executive skills, as well as regional brain structural abnormalities may show progression over time in middle-aged-to-elder adults. In cognitively-normal elders, several of the reviewed post-mortem studies indicated smokers showed significant A $\beta$  deposition and increased tau pathology. Additionally, we observed that cognitively-normal elder controls with a history of smoking demonstrated significantly higher retention of florbetapir, a marker of fibrillar A $\beta$  deposition, in multiple brain regions. Taken together, several of these neurobiological and neurocognitive abnormalities exhibited by cognitively-normal middle-aged and elder adults are components of the recently proposed preclinical stages of AD (see section 7.4 for description of pathology associated with each stage).<sup>27, 49</sup> It is important to recognize that some of the neurobiological and neurocognitive abnormalities demonstrated may also be, least partially, related to unrecognized genetic and/or premorbid/comorbid factors, rather than solely to the effects of smoking.<sup>14, 110, 128</sup>
5. The relationship between midlife smoking and risk for AD may also be influenced by potential differences between smokers and non-smokers on brain reserve, cognitive reserve,<sup>239</sup> other unrecognized genetic and/or premorbid/comorbid factors, as well as other modifiable factors such as diet, physical activity, and cognitive engagement.<sup>14, 68</sup> Smoking is associated with increased risk for CVD<sup>13</sup> and cerebrovascular disease;<sup>167, 240</sup> OxS is suggested as a mechanism for both

CVD and cerebrovascular disease.<sup>92, 141</sup> Since individuals with AD frequently manifest evidence of cerebrovascular pathology (e.g., WM hyperintensities/lesions, subcortical nuclei lesions),<sup>241, 242</sup> smoking-related OxS also potentially contributes to increased risk for AD via CVD/cerebrovascular disease (i.e., atherosclerosis and associated vascular dysfunction),<sup>68, 71</sup> rather than exclusively through the facilitation of the amyloidogenic pathway. However, compromised cerebrovascular function may also be related to cerebral amyloid angiopathy, which is more severe and wide-spread across the brain in APOE ε4 carriers.<sup>52</sup> The *in vitro* and preclinical animal findings, reviewed in this report, indicate that both cigarette smoke condensate and smoke exposure causally facilitates the amyloid and tau pathology, and healthy young/middle-aged adults exhibit significant neurobiological and neurocognitive abnormalities that are apparent in the preclinical stages of AD (see Section 4.3). Therefore, smoking-related subclinical or clinically significant CVD and/or cerebrovascular diseases may contribute to, but likely do not completely account for, the link between midlife smoking and increased risk for AD.

6. Approximately 31% of active military personnel are active smokers, which is 11% higher than in the general U.S. population, and cigarette use approaches 35% in personnel with high combat exposure. Smoking in active duty personnel is clearly linked to decreased combat readiness and diminished general health.<sup>8, 11, 243</sup> TBI and post-traumatic stress disorders (PTSD) are prevalent conditions in active duty personnel serving in Iraq and Afghanistan, and increasing evidence suggests these conditions increase the risk for AD.<sup>244</sup> Smoking is a highly comorbid condition in both TBI<sup>128</sup>, PTSD,<sup>201</sup> and other anxiety disorders;<sup>260</sup> consequently, it is imperative to consider the potential mediating or moderating effect of smoking status on the association between TBI, PTSD and risk for AD in future case-controlled or cohort studies. The smoking-related neurobiological and neurocognitive abnormalities observed in non-clinical cohorts of late adolescents through middle-aged adults are highly relevant for the US Armed Services, given the majority of active duty personnel are between the ages of 18 and 50. Additionally, the neurobiological and/or neurocognitive sequelae associated with both mild TBI and hazardous alcohol consumption appears to be exacerbated by smoking, and diminished recovery from these conditions is associated with smoking. These findings are of critical import for active duty personnel engaged in combat operations because of their significantly increased risk for mild TBI and hazardous levels of alcohol consumption. The Department of Defense (DoD) clearly recognizes the adverse effects of smoking on the well-being of active duty personnel,<sup>9</sup> and has promoted the “Quit Tobacco. Make Everyone Proud” public-education campaign. Also, the Code of Federal Regulations, Title 32, Part 85, specifically outlines DoD policies to prevent smoking and encourage cessation, which dictates that each armed service develop its own health-promotion plans.<sup>8</sup> However, the efficacy of such programs and policies have been questioned, and, unfortunately, there currently appears to be many logistical and political issues that

obstruct the enactment of more stringent tobacco control in the US Armed Services.<sup>8, 10–12, 243</sup>

#### 7. Future research opportunities

- Currently, the interplay between APOE genotype and smoking on risk for AD is unclear and requires further prospective cohort-based research.
- Additional prospective longitudinal studies with former smokers that are fully characterized on smoking exposure variables, cessation periods, diet, and exercise is necessary to better understand the association between former smoking status/smoking cessation and risk for AD.
- The association between smoking and risk for MCI has received little attention,<sup>245, 246</sup> and warrants future research because MCI is considered to be the prodromal stage of AD.<sup>28, 247</sup>
- Longitudinal in vivo measurements of multiple biomarkers of brain A $\beta$  burden, tau, and oxidative stress in smokers and non-smokers during middle-age (i.e., 30–60 years of age) will promote a better understanding how smoking relates to the onset and trajectory of AD pathophysiology and neuropathology. The interplay between nicotine/cholinergic agonists at nAChRs, and A $\beta$ -and-tau-related neuropathology is clearly multifaceted, and additional prospective research needed to clarify their effects on AD-related neuropathology and utility as potential disease-modifying agents. These research objectives may be accomplished via florbetapir for fibrillar amyloid, new PET tracers for tau,<sup>248</sup> and with magnetic resonance spectroscopy (MRS) of glutathione concentration, an established marker of oxidative stress.<sup>249</sup> Alternately, concurrent measurement of CSF concentrations A $\beta$  and tau isoforms combined with CSF isoprostanoids, a measure of ROS-mediated OxS (i.e., lipid peroxidation; see<sup>141, 154, 250</sup> for review), may also provide parallel information. Additionally, examination of the association between smoking and soluble A $\beta$  oligomers (e.g., A $\beta$  trimers, A $\beta$ \*56) may be informative as recent research has reported the strong relationships between these oligomers and age, neurocognition, neuritic plaque load, and soluble tau levels.<sup>58, 251</sup>

## 9. Conclusions

- The cumulative body of research to date indicates that previous and active smoking is associated with a significantly increased risk for AD, and previous research reporting that smoking was related to a significantly decreased risk for AD appears to be highly confounded by selection/survivor bias and affiliation with the tobacco industry. Correspondingly, in humans, there is no current or compelling evidence demonstrating that smoking or pure nicotine confers any protection from the development of AD pathophysiology, or is associated with decreased risk for AD.

- Late-onset AD is characterized by an extended preclinical stage, and smoking has been associated with earlier onset of AD symptomatology. We hypothesize that smoking during middle-age, via chronic OxS, may shorten the length of the preclinical period by shifting the inception of AD-related pathological A $\beta$  processing, tau protein hyperphosphorylation, and, potentially, mild cerebrovascular dysfunction (via subclinical cerebrovascular disease and/or cerebral amyloid angiopathy) to a significantly younger age. We predict that the greatest AD pathological findings will be most apparent in actively smoking APOE  $\epsilon$ 4 carriers.
- CVD, stroke, diabetes, hypertension, and hypercholesterolemia have been individually proposed as potential modifiable risk factors for AD,<sup>25, 68, 252</sup> and these conditions are also associated with increased risk for vascular dementia.<sup>253, 254</sup> Since smoking is moderately-to-strongly associated with increased risk for the development of the aforementioned medical conditions,<sup>13, 68, 207, 255</sup> a global decrease in the prevalence of smoking would also likely promote a further reduction in the number of people who develop and suffer from AD<sup>68, 207</sup> as well as vascular dementia.
- The significantly increased risk for smoking-related CVD, COPD, and cancer have been recognized by most health care providers and the general public for decades, but, unfortunately, tobacco use is treated at a much lower frequency than other chronic conditions (e.g., diabetes, hypertension).<sup>256</sup> Additionally, it has been argued that if healthcare providers have the perception that smoking does not increase risk for, or is somehow protective of, AD, this may serve as an additional barrier to encourage engagement in smoking cessation interventions, particularly in elders.<sup>207</sup> The aforementioned may act in concert to contribute to the general undertreatment of tobacco use in the US, which may have even greater adverse ramifications for active-duty military personnel, given their higher prevalence of smoking. We fully recognize the challenges associated with maintenance of sustained smoking cessation with currently available behavioral and pharmacological interventions;<sup>7, 257</sup> however, more aggressive global efforts aimed at smoking prevention in youth, and facilitation of sustained smoking cessation in adults, may ultimately promote a significant decrease in the prevalence of future AD cases worldwide.
- Considering multiple studies observed former smoking (i.e., individuals that quit) during lifetime was associated with AD-related neuropathology and increased risk for AD, we strongly support that the FDA Family Smoking Prevention and Tobacco Control Act to impose even greater restrictions on tobacco product advertising and marketing to youth to prevent the onset of smoking, as well as more vigorous efforts by the DoD to incentivize new US Armed Service recruits not to smoke, and active duty personnel to stop smoking.
- Given there are no currently available pharmacological interventions that prevent the onset of AD pathophysiology, or significantly alter its clinical course, it is imperative to better delineate the mechanisms by which potentially “modifiable”

risk factors, such as smoking, confer increased risk for AD during the preclinical stages, to identify those at the highest imminent risk and potentially inform development of more efficacious treatment interventions.<sup>27</sup> Specifically, if we understand how smoking increases risk for AD during the preclinical stages, the associated pathophysiological mechanisms (e.g., OxS)<sup>204</sup> may be mitigated through targeted treatment, or more ideally, the mechanisms halted via smoking cessation. Furthermore, determining if smoking is associated with greater AD-related pathophysiology and neuropathology during the specific preclinical AD stages is highly relevant, as those who are in Stage 1–3 may be at risk for clinically significant cognitive and functional decline over time.<sup>258</sup> Prospective longitudinal research specifically focusing on the neurobiological consequences of smoking (including the potential interactions among smoking status, age, APOE genotype and other emerging AD risk factors), as well as the neurobiological effects of sustained smoking cessation, in adolescents to elders, is clearly warranted and necessary to delineate the potential mechanisms by which smoking places individuals at greater risk for AD. The study of young-to-middle-aged adults has the advantage of minimizing the likelihood of clinically significant smoking-related diseases<sup>259</sup> that may affect brain neurobiology, and survivor bias. Such research must be also be conducted to better inform and change perceptions among health care providers, civilians, veterans and active-duty military about the adverse effects of smoking on the brain and its functions. Additionally, expanded research efforts focusing on the neurobiological and neurocognitive consequences of chronic smoking in conditions where it is highly prevalent (e.g., alcohol use disorders, schizophrenia-spectrum disorders, mood disorders, PTSD) is required to further inform policy on regulation of the manufacture, distribution and marketing of tobacco products in the US and abroad.

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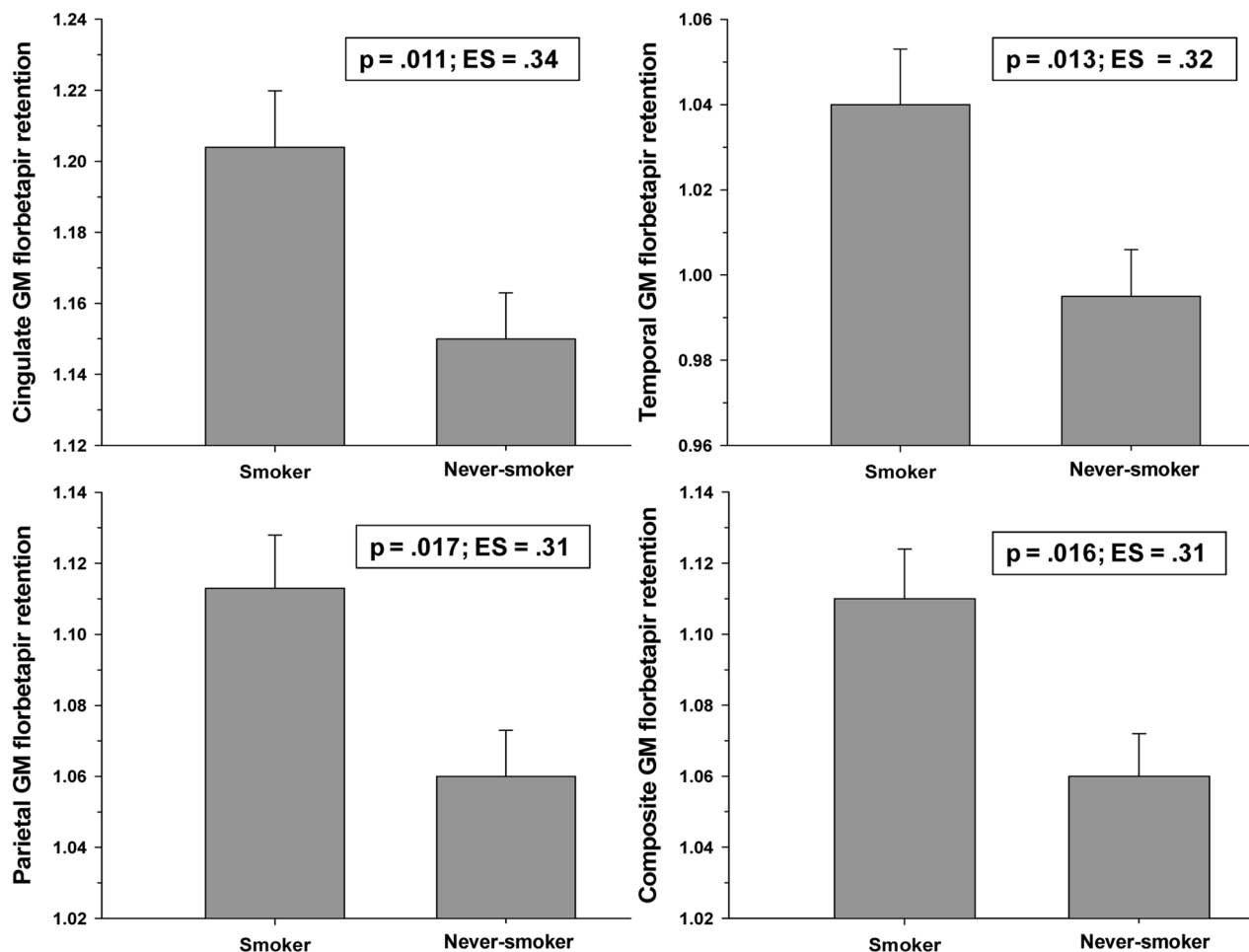


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**Figure 1.** Regional florbetapir retention for smokers and never-smokers. Retention values for each region represent the ratio formed by standardization to whole cerebellar florbetapir retention. Bars represent the group mean and error bars are the standard error of the mean; ES = Cohen's *d* effect size.