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Is there a link between genetic defects in the complement cascade and Porphyromonas gingivalis in Alzheimer’s disease?

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ABSTRACT

Defects, as determined by Genome-Wide Association Studies (GWAS), in the complement cascade of innate immunity have been suggested to play a key role in Alzheimer’s disease (AD). These defective genes encode components (C1s), complement receptor 1, complement component 9, and clusterin, a fluid-phase regulatory protein. A dysregulated complement cascade has been shown to relate to poor cell activation, defective complement-mediated clearance, and possible cognitive decline in AD patients. Porphyromonas gingivalis, a putative keystone pathogen of periodontal disease, has been reported to be associated with human AD brains of humans. The inflammatory burden following an experimental oral infection in mice and putative entry of this bacterium into the brain appears to drive the formation of amyloid-beta plaques and neurofibrillary tangles, followed by loss of cognition. P. gingivalis is a master of immune subversion in this inflammatory cascade and may establish microbial dysbiosis where it is located. Here we discuss if P. gingivalis may enhance the detrimental effects of the defective GWAS complement cascade protein genes thereby contributing to formation of hallmark lesions of AD and excessive chronic inflammation and hallmark pathology in AD. It appears that P. gingivalis may rather emulate regulate genes involved in epigenetic mechanisms of AD by its LPS with little effect on and not defective genes in the complement system.

KEYWORDS

GWAS, periodontitis, P. gingivalis, immune subversion, complement, dysbiosis
Alzheimer’s disease (AD) is a neurodegenerative disease and the most common form of dementia. It differs from other forms of dementia by the presence of two hallmark proteins, amyloid-beta (Aβ) plaques and hyperphosphorylated tau bound to neurofibrillary tangles (NFTs). The cause of AD remains largely undefined. It is widely accepted that this complex neurological condition can co-exist with other complex diseases such as atherosclerosis and cerebrovascular/ischemic stroke [1-5]. The link with complex diseases is the apolipoprotein E gene allele 4 (APOE ε4) inheritance [6-8]. The consequence of the APOE ε4 inheritance is inappropriate defective complement activity [9, 10] because this isoform resists the innate immune cascade checkpoint control at C1r [11], which is a subcomponent of the complement C1 complex [8]. Sustained complement activation is a potent driver of inflammation in the body including the brain [11-15]. Moreover, the abundant hallmark pathological lesions (Aβ plaques and NFTs), microbial pathogens, and physical injury can activate this innate immune cascade extracellularly as depicted by Aβ and/or intracellularly as per NFT bearing neurons [11-15]. Thus effectively makes it impossible to it is not possible to disregard an inappropriate unresolved defective complement pathway activity in AD.

Over the years several pathogens of bacterial, viral and fungal origin have been shown to be associated with AD brains [16]. The variability of these microbes has significantly hampered the focus elucidation of their. However, the etiologic role of these microbes in AD pathogenesis is still in question. have raised the raising questions as to whether each of them species must should be considered a cause or result of inflammation in the AD brain. In vitro agent or if the ensuing brain inflammation they may cause unifies their role. Recent studies have proposed that the putative keystone periodontal pathogen Porphyromonas gingivalis can be a risk factor that contributes to AD development in some individuals [17]. Periodontitis is a chronic inflammatory disease affecting the tooth supporting tissues, caused by polymicrobial dysbiosis [18, 19]. It has been proposed that imbalance in complement activity may influence dysbiosis of host microbiomes [20]. Pathogens adopt and adapt to survival and utilization of longstanding inflammatory environments as demonstrated by the presence of P. gingivalis in the subgingival crevice (as commensal and pathogen) and at distant sites (heart, placenta, and perhaps brain) with inflammatory components for the development of systemic diseases [21].

Aβ plaques and NFTs have been detected in brains of mice with the sporadic form of AD after infection with P. gingivalis [22]. Dominy et al. [17] showed that the enzymes gingipains produced by P. gingivalis can degrade the Tau protein, which is involved in NFT
formation in AD. In mouse brains, these lesions, purported entry of *P. gingivalis*,
complement activation and APOE gene knock-out, all of which can accompany intracerebral
inflammation [22, 23]. The recognized innate immune subversion caused by *P. gingivalis*, the
antimicrobial protection hypothesis for lesions [24], and genetic polymorphisms in some
complement genes [25-28] have relevance towards a basis for unresolved complement
imbalance in AD. Lamont et al. [29] proposed that longstanding inflammatory conditions of
the brain, typically AD, are related to growing old. During the lifespan of man there are
changes both in the architecture such as an increased permeability in the blood-brain barrier
(BBB) of the hippocampus [30], and functioning of the immune system (immunosenescence)
[31]. The term immunosenescence refers to decline in fidelity and efficiency with age,
resulting in an increased susceptibility to infectious diseases and pathological conditions
relating to inflammation (e.g. cardiovascular disease and AD) or autoreactivity (e.g.
rheumatoid arthritis) as described by Caruso et al. [32]. As an analogy to dysbiosis leading to
to periodontitis, this could perhaps promote the inflammophilic character of *P. gingivalis in
the old brain* [31]. Therefore, *P. gingivalis* may becomes inflammophilic during advancing
age.

The complement system

The complement system is comprised of more than 50 proteins, including the component
proteins C1-C9, which are part of the innate immune system. There are regulatory proteins
that serve to inhibit the complement cascade at various points [29]. The effector molecules
(opsonins) illicit ongoing damage and initiate signaling cross-talk. Examples of membrane
bound regulatory proteins include membrane cofactor protein (MCP or CD46), decay-
accelerating factor (DAF or CD55), complement receptor 1 (CR1 or CD35), and CD59. The
soluble or fluid phase regulators, which form the focus of this review, are C4 binding protein
(C4bp) and clusterin. Complement can be activated through the classical, alternative or lectin
pathways [33]. An antibody bound to antigen or a solid surface can activate the classical
pathway. Spontaneous hydrolysis of the complement protein C3 or binding of C3b to
microbes activates the alternative pathway through the feedback loop, while mannose
moieties on bacteria activate the lectin pathway [33-35]. All these pathways merge at the C3
convertase (C4b2a) stage, which causes hydrolysis of C3 into C3a and C3b fragments [33],
see Figure 1 and 2. While C3a is a potent anaphylatoxin that regulates immune responses
such as inflammation in the fluid phase, C3b opsonizes target cells and promotes activation

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of the terminal complement pathway, which ends with the assembly of the membrane attack complex (MAC) on target cells destined for killing [36]. All nucleated human cells can limit the lytic effect of the activated complement by expressing complement regulatory proteins [37]. However, gene polymorphisms may have major effects on the function of specific gene defects. Hence with polymorphic complement cascade genes identified in AD, we know little about their contribution to the overall effect on disease pathogenesis.

Genome-Wide Association Studies link defects in the complement cascade with Alzheimer’s disease

Genome-Wide Association Studies (GWAS) [25-28] reported the four defective genes that potentially link to AD progression: 1) complement sub-component 1s (C1s); 2) complement receptor 1; 3) complement component 9; and 4) clusterin, a fluid-phase regulatory protein. This is of concern because the brain, unlike other organs, is devoid of a traditional lymphatic vasculature system, meaning that an efficient complement cascade is critical for clearance of damaged cerebral tissue debris. Consequently, defective complement genes scattered within the early, middle and late stages of this cascade may be responsible for disabling the phagocytic activity of local microglia, resulting in inefficient removal of waste proteins such as Aβ and possibly “ghost” NFTs (tangles without cell surface membrane of the neuron) as typically seen in AD brains. An added complication of the AD brain is its association with microbes.

Hence, the overall aim of this review is to discuss if the activated complement cascade in the presence of mutated complement components, together with P. gingivalis immune subversive properties, could possibly contribute to the severity, pathology, and progression of this neurodegenerative disease and result in common complement mediated chronic inflammatory activity.

Complement proteins of polymorphic genes relevant to AD

1) C1s

C1s complexes with two molecules, C1r and C1q, and form C1 as the first component of the classical complement activation. C1 is a serine esterase that activates C4 and C2 thereby driving the classical pathway of complement activation [38]. C1 is not stable as it dissociates rapidly by the activity of the fluid phase regulator C1 inhibitor [39]. Interestingly, the
virulence associated gene 8 (Vag8) in *Bordetella pertussis* is a complement evasion molecule that mediates its effects by binding to the complement regulator C1 inhibitor (C1-INH), which is a fluid phase serine protease [40]. The absence of functional C1s (defected gene) suggests that C1 cannot be activated in the context of its ability to initiate the classical complement cascade [41]. In this scenario, the resident microglial cells that express the phagocytic C1qR receptor [42] would fail in their function. However, if the C1s subcomponent is seen as an inactive protein, this could represent a pool of "inactivated" C1. "Inactivated" C1 can complex with C1r and C1q and activate the classical complement pathway initiate defective complement activation [41]. Literature supports inappropriate incomplete complement activation in AD brains [11-15]. This suggests that "inactivated" C1 eventually binds to other "activators" (Aβ, NFTs, microbial pathogens, physical injury) which propagate the inappropriate incomplete complement pathway activity by cleaving the next component in the cascade in demented brains.

2) CR1

The GWAS support a CR1 gene defect in AD. This finding appears reasonable as AD patients have reduced resistance to infection by bacteria and viruses and yeasts that may promote development of AD [16]. In the context of bacterial infections for the pathogenesis of AD, prominence is being given to *P. gingivalis* [17, 23] that reaches the brain via the haematogenous route and *Chlamydia*-associated infections that are able to reach the brain via infected monocytes following increased BBB permeability [43]. The herpes simplex virus (HSV) type 1 [44] infections are endemic in the host and they become re-activated in some individuals leading to AD. All the above listed infections associate with the Aβ hallmark lesion of AD [22, 45, 46], and both *P. gingivalis* infection and the HSV type I infection lead to cognitive deficit in mice [22, 46].

and their neurons become severely compromised in both structure and function, as depicted by the Tau neurofibrillary tangle bearing cells typical of AD–CR1, also known as the C3b/C4b receptor, is a transmembrane glycoprotein that functions to inhibit activation of the C3/C5 convertase stage of the three converging activation pathways. Hence the location of CR1 in the complement cascade is pivotal to all subsequent effector pathways. CR1 helps to regulate activation of the complement cascade and promotes phagocytosis of cellular debris, as well as Aβ plaques, and adherence of immune complexes to erythrocytes. It has been demonstrated that the AD brain is generally deficient in CR1 [37]. Notably, it has been

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reported that *P. gingivalis* infection mediates immune subversion in relation to CR1 [47]. Such observations reinforce regions of genetic weaknesses (as per CR1 gene defect, see [26]) that are also exploited in this case by *P. gingivalis*, albeit in a fully functional complement system, the overall immune-mediated clearance of pathological and aggregated protein.

3) C9

Complement component protein C9 is part of MAC, and its insertion into cell surface membranes induces pores to lyse target cells. Other than the GWAS, little is known about the deleterious effects of the defective C9 gene in relation to AD pathogenesis, or indeed in other complement deficiency related conditions. The earliest reports linking complement to Aβ plaques suggest that the activated complement cascade does not proceed to C9/MAC formation [48, 49]. Whether or not such an observation points to an underlying genetic defect in the C9 gene or incomplete activation of the complement cascade in presence of active genes remains to be clarified. However, if the defective C9 gene has lost its function, this may be one factor that can influence dysbiosis of the host’s oral/gut microbiomes as reported for AD [50]. One possibility is that the functional loss of complement activity (unable to kill the pathogen) would support the spread of microbes such as *P. gingivalis* in the body via increased permeability of the BBB in the elderly and the AD brains to circulating pathogens. In the context of a deregulated complement genes [14 because of incomplete activation of the complement cascade], Having established *P. gingivalis* colonization, the bacteria would dampen the proinflammatory activity of C5a by citrullination (discussed below). Thus, there remains a potential for a microbial component of AD brains that could promote rampant complement activation (due to gene deregulation) and the resulting excessive inflammation.

4) Clusterin

The polymorphism in the clusterin gene has a more convincing role in the pathogenesis of AD, relating to subtype (mild cognitive impairment and dementia), and the rate of progression [51-53]. It is one of the complement cascade regulatory plasma proteins that significantly increases during AD as compared with non-AD controls [54]. Clusterin also stimulates expression and secretion of various chemotactic cytokines, including tumor necrosis factor-alpha (TNF-α), which plays a critical role in promoting macrophage chemotaxis via the phosphoinositide 3-kinase/protein kinase B1 (Pi3K/Akt), mitogen-
activated protein kinase/extracellular signal-regulated kinase (ERK) and c-Jun N-terminal kinase (JNK) pathways [55]. Pathogen-driven signaling pathways with kinases that phosphorylate proteins may also be involved in abnormal phosphorylation of Tau proteins, which are the major constituents of NFTs in AD. This possibility was illustrated by Ilievski et al. [22] who demonstrated ser396 phosphorylation following P. gingivalis oral infection in mice. Alternatively, gingipains can digest the normal Tau protein into fragments that may be toxic to neurons [17]. Further research should clarify the concomitant role of P. gingivalis and polymorphic complement genes in AD pathogenesis.

The role of Aβ plaques and NFTs in the classical complement pathway activation in AD

The inflammatory component of AD was recognized through the classical complement pathway activation and receptors for specific (C3a, C5a) opsonins [11, 12, 56, 57]. Based on these early data, the fibrillary insoluble Aβ plaques were suggested to act as extracellular triggers of complement activation [58-61]. NFTs are intracellular triggers of complement activation via the classical pathway [62]. Building on the Dominy et al. [17] observation that gingipains degrade Tau protein could reveal new triggers of intracellular complement activity in AD brains. We now know that APOE e4 gene inheritance is less efficient in inhibiting complement activation at the C1q checkpoint and that it adds to further risk for complement mediated inflammation independent of Aβ [8]. Taken together with the GWAS identified complement gene defects, this strengthens the inflammatory hypothesis of AD via inappropriate, inadequate complement activity [11-15].

Apolipoprotein E-C1q complexes as inhibitors of the activated classical complement pathway

It is becoming clear that the APOE e4 susceptibility gene may be linked to deregulating C1q to keep the classical complement pathway activated [8]. This causes a dysregulated innate immune inflammatory response via cytokine liberation by activated monocytes/macrophages/microglia [63]. In the brain, the oxidized lipids also accumulate at the periphery of Aβ plaques [8], which leads to yet more inappropriate, inadequate activation of complement activity. The APOE e4 susceptibility gene is also linked with environmental
risk factors, including the host's dysbiotic oral microbiome [64]. The sustained inflamed environment of the brain could act as an intrinsic environmental factor that supports dysbiosis.

**Synaptic loss: A potential consequence of activated complement cascade**

The phagocytic role in the brain is well-recognized as an arm of the complement cascade and generally regarded as being beneficial to the host. However, in AD brains activated complement CR1 helps to regulate and promote phagocytosis, in microglia, of the cellular debris. With the CR1 activity being suppressed (via the deregulated CR1 gene and immune evasion strategies of P. gingivalis) this would suggest accumulation of abnormal proteins. Although this is the case in AD, but an additional outcome appears to be the excessive loss of synapses. This is supported by an interpretation from in vivo studies, whereby the classical complement pathway was activated via (oligomeric) Aβ and leading to excessive pruning of synapses by microglia [65]. Similarly, there remains a possibility for viral and P. gingivalis infections to contribute to synaptic loss via complement activation independently of Aβ [23, 59, 60, 61].

**Concept of cognitive deterioration in AD**

Cognitive deterioration (difficulties in decision making and deteriorating mental function with changes in mood and behaviors) is an essential component of the clinical picture of AD. Exactly what causes functional loss in AD remains unknown. However, the original synaptic loss theory [66, 67] is still considered valid, as it continues to correlate with deteriorating memory. A question arises as if the mechanism of overt synaptic loss relates to an overactive complement cascade [65, 68]. Observational studies demonstrate that some very elderly subjects bypass AD, whilst harboring equivalent numbers of Aβ plaques and NFTs in their brains. This suggests that these lesions, per se, do not necessarily cause functional deficits. Such individuals have been termed as having a “cognitive reserve” [69, 70]. Another group of elderly patients’ brains have shown extensive numbers of Aβ plaques and NFTs without the individual receiving a diagnosis of clinical AD. These individuals have been referred to as having “resilient” brains [71]. The difference between those with cognitive reserve and resilient brains, over individuals with AD, is the absence of intracerebral inflammation [71].
This observation emphasizes the role of chronic inflammation, in some individuals, for the functional loss.

**Microbial component in AD pathophysiology**

The studies carried out by Vasek et al. [68] supporting the role of complement activity via an initial infection causing overt **pruning** of synapses and giving rise to clinical symptoms, can be explained through classical plaques. Research has linked Aβ to a broad-spectrum antimicrobial peptide (AMP) [72-74]. If Aβ deposition represents the host’s response to a previous infection, then its role as an AMP is consistent with triggering complement activation [24, 23]. This forms a common link with the antimicrobial protection hypothesis [23], whereby the modality of Aβ’s pathophysiology is shifted towards a dysregulated innate immune response, and indirectly, with the microbial infection hypothesis and the amyloid cascade hypothesis [25]. The only difference is that that the amyloid hypothesis maintains that Aβ is toxic, whilst the antimicrobial protection hypothesis suggests AD pathology develops from a pattern of innate immune responses mounted by an immune challenge.

*P. gingivalis* is an oral pathogen that has been used to develop models for periodontal infection and AD in mice [22, 23]. Most interestingly, the periodontal infection model of Ilievski et al. [22] has demonstrated detection of Aβ and NFTs in mouse brains. Therefore, by example of *in vivo* bacterial infections, *P. gingivalis* gives rise to Aβ in the brain produced by the host with implication for pathogen *entrapment* and *killing*. This confirms that *P. gingivalis* can initiate Aβ and NFT formation and that this, over time, will contribute to the overall burden of hallmark AD lesions proteins (Figure 2). In addition, *P. gingivalis* activates complement in the absence of Aβ in the brain [23]. Complement activation following bacterial entry into the brain is to be expected, but this observation may also explain memory impairment possibly through intercommunication with toll-like receptor (TLR) activation, lipopolysaccharide (LPS) (a TLR4 agonist) and complement activation [49, 76-78].

Collectively, they may also cause **pruning** of synapses [60, 65, 66] if CR1 functionality is suppressed by its polymorphism or via immune evasion strategies of bacteria like *P. gingivalis*.

*P. gingivalis* and its complement subversion

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**Commented [PB46]:** Please clarify. If Pg initiates AB-AMP, then it is killing itself. This is the host’s defense.

**Commented [SKS<oD47R46]:** In reply to “If Pg initiates AB-AMP, then it is killing itself. This is the host’s defense.” Pg certainly initiating AB-AMP as Ilievski have demonstrated. However, if Pg is killed by the AB-AMP is still unknown. We are planning to test this hypothesis in our laboratory soon.

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P. gingivalis has been shown to be a major manipulator of the immune system \([79-84]\) and is considered a keystone pathogen in “chronic” periodontitis \([85]\). Furthermore, periodontitis has a clear relationship with late onset AD, which is the most common form of AD \([86-90]\).

Gingipains as players in immune subversion

Gingipains are virulence factors of key importance to the immune subversion activity of P. gingivalis. There are which has two main types of cysteine proteases \([92]\) encoded by three different genes (rgpA, rgpB and kgp). Of these, the lysine specific gingipains is the product of kgp and the arginine specific gingipains rgpA and rgpB. These proteases can cleave the complement components C1-C5, prevent deposition of C3b on the bacterial surface and capture the C4b binding protein \([93-97]\). By hijacking binding to the complement regulator C4bp on the bacterial surface, P. gingivalis prevents assembly of the membrane attack complex and acquires the ability to regulate C3 convertase \([95]\). Thus, gingipains do not only destroy complement through proteolytic degradation, they also inhibit complement activation by binding to the complement inhibitor C4bp \([95]\).

If gingipains are involved in AD, they would likely enhance the effect of polymorphic complement gene defects, allowing for a local infection. Recruitment of additional bacteria that are resistant to the bactericidal activity of complement is also feasible \([88,94]\). Besides, it is possible that gingipains, together with defective complement component genes, aggravate and sustain AD through ineffective clearance of cellular debris, which in turn, aids the accumulation of Aβ and NFTs. Tau protein that is associated with NFTs in AD brains is reported to be a substrate for gingipains \([17]\). Whether this is a strategy of P. gingivalis to keep complement activated or is independent of complement requires further research.

P. gingivalis and citrullination in AD

P. gingivalis can also reduce the antibacterial and proinflammatory activity of C5a by deiminating its C-terminal arginine \([98]\). Post-translational enzymatic modification of arginine residues in proteins formed as part of the complement cascade are some of the subservive physiological processes demonstrated by P. gingivalis. This offers a plausible and exclusive link to disabling complement C5a enzymatic conversion of arginine to citrulline. Protein citrullination causes deregulation of the host’s inflammatory signaling network by...
altering the spatial arrangement of the original 3D-structure and function of immune proteins [99]. It is likely that degradation of complement proteins allows colonization and proliferation of bacteria possessing higher sensitivity towards complement mediated killing than found in P. gingivalis itself [82]. Accordingly, P. gingivalis may support survival of an inflammospheric biofilm community by helping bystander bacteria in the brain to evade complement-mediated killing. The concept of the brain possessing its own microbiome has not been fully explored and future studies will undoubtedly reveal whether alternative mechanisms exist for complement activation not proceeding to C9/MAC formation in AD [48, 49].

The presence of CR1 on peripheral blood cells, especially erythrocytes and macrophages, is abundant and suggestive of an important and significant role of CR1 in AD. For example, as a receptor for the components C3b and C4b, CR1 helps to regulate activation of the complement cascade and promotes phagocytosis of cellular debris, as well as Aβ and adherence of immune complexes to erythrocytes.

Clusterin is a plasma protein that may play an important role in regulating C5b7-8 stages of the terminal complement complex pathway, and in the subsequent pathogenesis of AD. The blood plasma analysis of APP/PS1 AD transgenic mice demonstrated greater concentration of clusterin, and an age-dependent upregulation in the brain, and its co-localization with Aβ plaques [48, 51, 52]. Clusterin also stimulates expression and secretion of various chemotactic cytokines, including TNF-α, which plays a critical role in promoting macrophage chemotaxis, via the PI3K/Akt, ERK and JNK pathways [55].

Data from GWAS suggest an involvement of CR1 and clusterin gene defects in AD [25-28]. Since P. gingivalis has the capacity to affect CR1 and clusterin, this strengthens the possible pathogenic role of this bacterium in AD, at least through increased immune subversive activity. For example, outside the brain, P. gingivalis was found to fix C3 and readily adhere to erythrocytes via CR1, and this led to a rapid degradation of C3 into iC3b, and presumably, C3dg on the erythrocyte cell surface [100].

P. gingivalis and its possible subversion of C9
C9 is the ninth complement component protein, which is also a part of MAC. Its insertion into cell surface membranes induces pores, causing lysis. \textit{P. gingivalis} gingipains (RepA, and RepB) degrade the central complement component C3. This prevents deposition of both C3b opsonin and MAC on \textit{P. gingivalis} cells, by which the bacterium protects itself against complement [101]. It is known that the complement cascade does proceed to MAC formation in periodontitis, and this is due to the membrane bound regulator CD59 being partially effective. This allows for degradation of collagens and heme, which form essential nutrients for the bacterium. It tells us that the complement cascade is highly adaptable for exploitation by pathogens. Generalized gene defects are conducive to this exploitation, as reported by Kapferer-Seebacher et al. [96,102] for the effects of C1S gene mutation in periodontitis in patients with Ehlers-Danlos syndrome. Such findings support sustained inflammation in periodontitis and AD brains, and the GWAS finding of the defective C9 gene causing deficiency in overall C9 protein synthesis, might primarily affect the brain.

To date, there is only one report that tested complement activation in mouse brains. It confirmed entry of \textit{P. gingivalis} [23] and demonstrated MAC on some neurons. Although the difference from sham treated animals was not statistically significant, the data suggested that \textit{P. gingivalis} may have the capacity to suppress the activity of C9 and impair MAC assembly via immune subversion.

\textit{P. gingivalis} and epigenetic modifications

In the stimulation and maintenance of inflammation epigenetic pathways have received special attention because of their upstream regulations. Epigenetic modifications lead to chemical changes in DNA and associated proteins which cause remodeling of the chromatin and activation or inactivation of gene transcription. These changes can contribute to development and maintenance of cancer, autoimmune and inflammatory diseases, including periodontitis [103, 104]. Interestingly, knowledge of the modification of epigenetic mechanisms may provide insight into key regulatory pathways of genes involved in the maintenance of chronic inflammation. Thus, the role of DNA and histone modifications, which are major epigenetic regulations, have been described in periodontitis where gene expression can be affected by DNA methylation [105]. It has also been demonstrated that chronic inflammation in periodontitis may be linked with aberrant DNA methylation in the gingival tissues [106, 107]. In AD epigenetic mechanisms have been found to be dysregulated during disease progression, already in its early stages [108]. Furthermore, recent
methylome-wide association studies (MWAS) in humans have supported the concept that aberrant DNA methylation is associated with AD [109]. Whilst increased methylation in the gene promoter region is related to reduction in gene expression, hypomethylation is closely associated with transcriptional activation [110]. Recently, Diome et al. [103] investigated if epigenetic modulations is involved in periodontitis by using human periodontal ligament stem cells (hPDLSCs) as an *in vitro* model. They found that *P. gingivalis* LPS significantly reduced DNA methylase DNMT1, while it markedly upregulated the level of histone acetyltransferase p300 and NF-kB in hPDLSCs. This demonstrated that *P. gingivalis* LPS markedly regulates genes involved in epigenetic mechanism, which may result in induction of inflammation locally and systemically.

Molecular inhibitors as possible therapy in AD

The emergence of complement as an important player in normal brain development and pathological remodeling has come as a major surprise to most neuroscientists and almost all of those working in the field of complement biology [23]. The role of inflammation in AD is well established. Interestingly, resolvin E1 and lipoxin A4 resolved the inflammation in a murine model of AD [111]. This leads to the question whether complement mediated therapy should also be considered to reduce the inflammatory load in AD and if so, when and how? Indeed, AD and periodontitis have complement-TLR intercommunication mediated inflammation in common. The contribution from peripheral sources to inflammatory mediators has an early impact on priming of intracerebral glial cells. An ideal window to control the impact of peripheral inflammation from periodontitis on AD would therefore appear to be from the time of diagnosis of the oral disease. The clinical value of inhibiting all three main pathways of complement activation was recently suggested in periodontitis [112]. This can be achieved by targeting the central component C3, which directly inhibits inflammation and indirectly counteracts dysbiosis. By using a locally administered peptidic compound (Cp40/AMY-101), non-human primates were protected from induced and naturally occurring periodontitis (reference). This could pave the way for clinical trials for the treatment of human periodontitis and even for prevention of periodontitis in high-risk patients, but this has not yet been tested in AD.

As for *P. gingivalis*, Dominy et al. [17] proposed that potent and selective gingipain inhibitors (Kgp) could be valuable for treating *P. gingivalis* colonization of the AD brain. Using effective molecular inhibitors of gingipains at later stages of this neurodegenerative disease could be beneficial.
disease may be tried, but there are many causes of AD and multiple bacterial phylotypes discovered in demented brains.

**Concluding remarks**

There is no generally accepted view on the pathogenesis of AD, which is considered a multifactorial disease. Recent research has shown that an imbalanced complement system plays an important role in the AD brain. Whether nature provided this early immune system to be protective, as suggested by the Aβ-AMP concept, or other forms of toxicity in old age is a subject open to debate. By affecting some of the gene defective proteins, *P. gingivalis* may amplify complement mediated inflammatory dysbiosis, but this has to be proven.

Now that the GWAS has demonstrated the role of defective complement activation in AD development, this supports our working hypothesis that AD in some patients is mediated by the host’s inflammatory responses and justifies the rationale for novel interventions to improve lifestyle, behavior and regular dental care. However, there is no definite proof yet of a link in AD between defects in the complement cascade of innate immunity and *P. gingivalis*. This bacterium could rather emulate genes involved in epigenetic mechanisms by its LPS, which may result in induction of inflammation locally and systemically. Future research should try to establish a better foundation for the notion that there could be a genetic basis for *P. gingivalis* infection in AD.

**Acknowledgments**

SKS acknowledges the receipt of a PreViser award from the Oral and Dental Research Trust, 2018, and additional financial support from the School of Dentistry, University of Central Lancashire, UK.

**Disclosure statement**

The authors declare no conflict of interest.

**Funding**
SKS has received a PreViser award from the Oral and Dental Research Trust, 2018 and 2019.

References


[3941] Ziccardi RJ, Tschopp J. The dissociation properties of native C1.


Figure 1. Illustration showing the effects of *P. gingivalis* oral infection and its local subversive effect on degradation of opsonins with IgG, C1q, iC3b and MAC to evade complement mediated death and at the same time amplify inflammation. In the brain, a nerve cell infected by *P. gingivalis* itself or internalization of outer membrane vesicles (microbullets) initiate microglial surveillance. This results in an inflammatory activity when the host cell encounters Aβ (in its capacity as an AMP) opsonized by IgG, C3b and iC3b opsonins in the paths of the neuronal processes. Due to polymorphic defects in the complement regulating proteins, and the inability of microglia to clear Aβ, inflammation is thought to be amplified and sustained.
Figure 2. A “frustrated innate immune system” in the inflamed Alzheimer’s disease brain. This contribution is from multiple sources including the polymorphic complement component genes \([26, 27, 28]\), APOE variant \([8]\), blood-brain barrier defects \([30]\), pathogen entry, and Aβ as a defence peptide released in response to infections \([24]\). All these contribute to complement activity, reduced cell activation, defective phagocytosis and chronic inflammation \([15]\). There would be clinical value in inhibiting all three main pathways of complement at the C3 stage. Hope lies in the peptidic compound \((\text{Cp40/AMY-10})\) \([105]\), gingipains inhibitors \((\text{COR388})\) \([16]\) and better oral hygiene \([106]\).