Review Article
Therapeutic Potential of α-Synuclein Evolvability for Autosomal Recessive Parkinson’s Disease

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The majority of Parkinson’s disease (PD) is sporadic in elderly and is characterized by α-synuclein (αS) aggregation and other alterations involving mitochondria, ubiquitin-proteasome, and autophagy. The remaining are familial PD associated with gene mutations of either autosomal dominant or recessive inheritances. However, the former ones are similar to sporadic PD, and the latter ones are accompanied by impaired mitophagy during the reproductive stage. Since no radical therapies are available for PD, the objective of this paper is to discuss a mechanistic role for amyloidogenic evolvability, a putative physiological function of αS, among PD subtypes, and the potential relevance to therapy. Presumably, αS evolvability might benefit familial PD due to autosomal dominant genes and also sporadic PD during reproduction, which may manifest as neurodegenerative diseases through antagonistic pleiotropy mechanism in aging. Indeed, there are some reports describing that αS prevents apoptosis and mitochondrial alteration under the oxidative stress conditions, notwithstanding myriads of papers on the neuropathology of αS.

Importantly, β-synuclein (βS), the nonamyloidogenic homologue of αS, might buffer against evolvability of αS protofibrils associated with neurotoxicity. Finally, it is intriguing to predict that increased αS evolvability through suppression of βS expression might protect against autosomal recessive PD. Collectively, further studies are warranted to better understand αS evolvability in PD pathogenesis, leading to rational therapy development.

1. Introduction
Parkinson’s disease (PD) represents a set of clinically and pathologically heterogeneous subtypes. The majority (~85%) of PD is sporadic (sPD) during aging, pathologically characterized by α-synuclein (αS) aggregation and other cellular dysfunction, involving mitochondria, ubiquitin-proteasome system, and autophagy (Figure 1(a)) [1]. Although the mechanism of sPD remains unclear, it is believed that sPD may be caused by interplay among susceptible genes and environmental factors [2]. In contrast, familial PD is associated with mutations of either autosomal dominant (AD) or autosomal recessive (AR) genes (Figure 1(b)) [3]. However, the neuropathological features of AD-PD are similar to those of sPD, and AR-PD forms are accompanied by impaired mitophagy during reproductive time of life associated with lesser αS aggregation [4]. All PD types ultimately lead to the degeneration of dopaminergic neurons in the substantia nigra pars compacta.

Currently, no disease-modifying therapy is available for both familial and sPD, and currently, only symptomatic exists, including oral levodopa [6] and deep brain stimulation [7]. Although transplantation therapy in PD has been extensively investigated using various materials, including human fetal mesencephalic tissue [8] and induced pluripotent stem cells [9], the propagation of αS protofibrils might occur from host-to-graft tissues [8]. Furthermore, although αS immunotherapy trials in PD are ongoing [10], therapy directed against αS aggregation might not be promising given poor and unclear outcomes for amyloid β (Aβ)
immunotherapy in Alzheimer’s disease (AD) [11]. Therefore, it is critical to devise other novel therapeutic strategies.

Despite extensive investigation, a physiological function of amyloidogenic proteins (APs) relevant to neurodegenerative diseases, such as $\alpha$-$\beta$ and $\gamma$-$\Delta$, is unclear. Better understanding of this issue might provide a clue into a new therapy. Based on the similarity with yeast prion, we proposed that evolvability against multiple stressors in the human brain might be related [12,13]. Because AD-PD is similar to sporadic PD in terms of $\alpha$-$\beta$ pathology, while AR-PD is not, the main objective is to discuss that $\alpha$-$\beta$ evolvability might be differentially involved in these subtypes of PD. We speculate that $\alpha$-$\beta$ evolvability might benefit both AD-PD and sPD during development and reproduction, but become detrimental during aging. Furthermore, $\alpha$-$\beta$ evolvability may be regulated by the buffering action of $\beta$-$\gamma$-$\Delta$ homologue of $\alpha$-$\beta$ [14]. Supposing that increased $\alpha$-$\beta$ evolvability through upregulation of $\beta$-$\gamma$-$\Delta$ aggregation during the reproductive portion of the lifespan might be beneficial for AR-PD, suppressing $\beta$-$\gamma$-$\Delta$ expression might effectively promote $\alpha$-$\beta$ aggregation/evolvability, being therapeutic in AR-PD.

Figure 1: Description of $\alpha$-$\beta$ and other PD risk factors. (a) Diagram of the synuclein family of peptides. $\alpha$-$\beta$ has two related proteins, namely, $\beta$- and $\gamma$-$\Delta$. While the N-terminal domains are highly homologous, the C-terminal regions are more divergent. The middle domain of $\alpha$-$\beta$, referred to as NAC, is highly amyloidogenic, [5], whereas that of $\gamma$-$\Delta$ is somewhat less amyloidogenic. In contrast, the NAC corresponding domain is naturally absent from $\beta$-$\gamma$-$\Delta$. So far, six and two missense mutations have been characterized for $\alpha$-$\beta$ and $\beta$-$\gamma$-$\Delta$, respectively [5]. Since evolvability is supposed to depend on the protofibrillar form of APs, $\alpha$-$\beta$ might exhibit greater evolvability associated with increased aggregation property compared to $\gamma$-$\Delta$, while $\beta$-$\gamma$-$\Delta$ instead may negatively regulate $\alpha$-$\beta$ evolvability through its buffering capacity. (b) Classification of familial PD. Currently, more than twenty familial PD (PARK 1–21) have been identified, most of which are associated with mutations of either AD- (PARK 1 and 4: SNCA; PARK8: LRRK2; PARK17: VPS35; and PARK 21: DNAJC13) or AR genes (PARK2: Parkin; PARK6: DJ-1; PARK7: PINK1; PARK9: ATP13A2; PARK14: PLAG6; PARK15: FOXO7; PARK19: DNAJC6; and PARK20: SYNJ1). The former ones are usually late-onset (30–70 years old), frequently during postsenescent aging, whereas the latter ones are early-onset (teens) during the reproductive stage. The functions of the former gene products are related to cellular activity, such as vesicle fusion, mitochondria, autophagy/lysosomes, and endosomes, whereas the latter ones are involved in selective degradation of mitochondria, so called mitophagy. Neuropathologically, the former ones are associated with aggregation of $\alpha$-$\beta$ and formation of Lewy bodies, whereas the $\alpha$-$\beta$ pathologies in the latter are less clear, partially reprinted with modification from Singleton and Hardy (2019) [3] with permission.
2. Beneficial Aspects of αS

αS, a member of the synuclein family of peptides that includes two other related proteins—β- and γ-synuclein (β- and γ-S), was primarily identified as a precursor of the non-Aβ component of AD amyloid (NAC) (Figure 1(a)) [5]. Mounting study revealed that αS was neurotoxic. However, if αS is simply neurotoxic, why then have such detrimental molecules survived across evolution? Indeed, there are a few studies suggesting that αS might also be beneficial.

2.1. Physiological Actions of αS. Song learning of oscine songbirds in the critical period is one major experimental model of research for learning and memory [15]. In 1992, around the same time when αS was isolated as a NAC peptide [5], Clayton and associates identified synelfin through differential hybridization as a gene which is downregulated in the critical period of songbird. Intriguingly, synelfin was the avian homologue of αS, which might be essential for bird song memory formation during a critical period in development [16]. Based on this analogy, it is possible that αS might play a crucial role for learning and memory during mammalian neurodevelopment [17]. Consistent with this, accumulating evidence suggests that αS might be involved in the regulation of synaptic vesicles in a developmentally-regulated manner [18,19]. Furthermore, one may speculate that dementia stimulated by αS in aging might be an antagonistic pleiotropy phenomenon of αS regulation of memory during development. Antagonistic pleiotropy is a theory of aging in evolutional biology, in which genes that enhance fitness in reproduction but diminish it in aging can be favored by natural selection because selection is stronger early in life compared to later in life [20].

2.2. Protective Actions of αS. Consistent with this notion, αS is shown to cooperate with cysteine string protein (a CSPα) in synaptic protection and prevent neurodegeneration [21]. Given that the cochaperone function of CSPα is essential for neuronal survival, mice with CSPα gene deletion exhibit progressive neurodegeneration. Interestingly, the neurodegenerative phenotype of the CSPα mice was ameliorated by cross-breeding with αS transgenic mice but was exacerbated by cross-breeding with αS mice, suggesting that αS may be involved in protection of nerve terminals against injury [21].

In support of this, a limited number of studies previously showed that αS might be involved in the oxidative stress. αS was protective against oxidative stress by suppression of the c-Jun N-terminal kinase stress-signaling pathway in GT1-7 mouser neuronal cells (Figure 2(a)) [22]. Similarly, αS protected primary cultures of mice cortical neurons from apoptosis by alteration of the MAPK signaling pathway [23]. In addition, it was later shown that αS prevented the formation of oxidative stress-induced formation of spherically shaped and hyperpolarized mitochondria, termed “mitospheres,” leading to suppression of apoptosis under the oxidative stress conditions (Figure 2(b)) [24].

3. Evolvability of αS

As discussed, αS may be involved in protection against brain stressors, which is reminiscent of yeast prion. For instance, the [URE3] prion is a nonchromosomal genetic element that produces failure of nitrogen catabolite repression by the self-propagating inactive amyloid form of Ure2p under the nitrogen-deficient condition [25]. Considering that the evolvability of yeast prion is the only physiological phenomenon of APs which is generalizable, where the alteration of aggregation states of APs behave like a genetic switch in response to diverse environmental conditions [13], the concept of yeast prion was applied to APs relevant to neurodegenerative disorders, such as Aβ in AD and αS in PD [12].

3.1. αS Evolvability and sPD. Evolvability is defined as the capacity of a system for adaptive evolution [26]. More specifically, evolvability is composed of two steps: to generate a genetic diversity against environmental conditions including stressors; to deliver their information to offspring [26]. Given that APs including αS are intrinsically disordered proteins which might exhibit various forms [27,28], it is assumed that morphologically diverse αS protofibrils are formed in a stress-specific manner in response to multiple stressors, such as oxidative stress, kindling, physical stress, and neurotoxicity, and might confer resistance against stressors in parental brain [12]. Among multiple heterogeneous species of αS protofibrils, it is predicted that some are toxic, and others are rather beneficial [29]. In support of this notion, it was shown that disordered oligomers were benign to cells, while oligomers with partially formed β-sheet cores and highly hydrophobic surfaces were the most inherently toxic species [30]. Furthermore, it was previously characterized that Aβ conferred oxidative stress resistance [31]. Apparently, similar might be the case for αS and other APs. Given that some species of APs are protective, it is predicted that the stress resistance of APs might show structure-dependence.

In a prion-like manner, αS itself has the capacity to trigger the structural rearrangement of the ubiquitously present αS substrate in a self-perpetuating cascade [32]. Following the stress-induced structural alteration of APs into protofibrils, APs might be subjected to transgenerational transmission via germ cells [12,33]. Considering that APs including αS are ubiquitously expressed, it is predicted that the prion-like propagation of αS might be convenient [28]. Although the heterogeneity of αS protofibrils might be beneficial for αS evolvability in development/reproduction, α-synucleinopathies such as PD might be manifested in parental brain through the antagonistic pleiotropy mechanism in aging [33].

Notably, recent genetic studies, such as genome wide association study, have revealed that the chromosomal genes encoding some molecules relevant to AD-PD, including leucine-rich-repeating kinase 2 (LRRK2), vacuolar protein sorting-associated protein 35 (VPS35) [34], and glucocerebrosidase (GBA), might be linked to susceptibility to sporadic PD [3], suggesting that increased αS evolvability
might be associated with these AD-PD molecules. In particular, the linkage of Gaucher disease to sporadic PD [35] may imply that accumulation of glucocerebrosidase due to loss of function of GBA may promote αS aggregation [36], leading to increased αS evolvability. In addition, many environmental causes, including traumatic injury, pesticides, and hypoxia, are recognized in the development of sporadic PD with αS aggregation [37–39]. Within our theoretical framework, transmission of such environmental stress information might be beneficial for offspring. Thus, with multiple mechanisms of αS aggregation identified, they might all converge at the point of increasing αS evolvability.

3.2. Increase of αS Evolvability in Dominant PD. Since the discovery of A53T αS [40], five missense mutations have been identified in SNCA (Figure 1(a)) [41]. In addition, more than 20 genetic loci have been linked to familial PD with mutations of either AD or AR genes (Figure 1(b)) [3]. It has been shown that heterozygous mutations of the AD genes, including SNCA (PARK1and4), LRRK2 (PARK8), VPS35 (PARK17), and CHCHD2 (PARK21), result in various cellular impairments, involving dysfunction of mitochondria, ubiquitin-proteasome system, and autophagy in aging, leading to late-onset PD (Figure 1(b)). Based on the current concept, the increased aggregative properties of αS due to AD-PD gene mutations might result in increased αS protofibrils transgenerationally transmitted from parent to offspring. Thus, AD-PD molecules may stimulate αS evolvability, which might be evolutionarily advantageous. It is also noteworthy that familial dementia with Lewy bodies (DLB) caused by P123H and V70 M mutations of βS were characterized paradoxically by αS aggregation without aggregation of mutant βS (Figure 1(a)) [42]. Presumably, it is possible that structural alterations of βS due to missense mutations might promote the formation of αS protofibrils, leading to increased αS evolvability.

3.3. Decrease of αS Evolvability in Recessive PD. On the other hand, the significance of αS pathology in AR-PD is obscure. In AR-PD, homozygous mutations of recessive genes, such as Parkin (PARK2), DJ-1 (PARK6), PINK1 (PARK7), ATP13A2 (PARK9), PLA2G6 (PARK14), FOXO7 (PARK15), and DNAJC16 (PARK19), result in loss of function of mitophagy, the selective degradation of mitochondria by autophagy, leading to early-onset PD during reproductive life (Figure 1(b)) [3,43,44]. Although it had
been believed that AR-PD was not associated with αS aggregation [43,45], evidence is accumulating to suggest that αS pathologies, including formation of Lewy bodies, are indeed observed in a AR-PD (Figure 1(b)) [46–49]. The precise mechanism of upregulation of αS pathology in AR-PD remains elusive. Since homozygous mutation of AR-PD genes results in impairment of mitophagy, a critical cellular function [50, 51], it is possible that αS evolvability might be increased by the compensatory mechanism. Therefore, it is predicted that αS evolvability may be beneficial for function of mitophagy.

Because of their autosomal recessive nature, carriers are asymptomatic. Consequently, these familial mutations may be not targeted for removal by natural selection. Thus, it is likely that two forms of familial PD may have survived against the pressure of natural selection through distinct mechanisms.

4. αS Buffering Action on αS Evolvability

Our view of evolvability relevant to APs in neurodegenerative disorders was initially proposed based on the analogy with evolvability of yeast prion [12]. Accumulating evidence, however, suggests that evolvability of yeast prion might be not beneficial due to its toxicity [52–54], raising a concern that evolvability of APs in human brain might also be the case. In this regard, one possible resolution of this might be by virtue of the buffering role of βS on αS evolvability (Figure 3).

4.1. Is Amyloidogenic Evolvability Beneficial? The concept of evolvability of yeast prion was created on the notion that the diverse phenotypes conferred by yeast prion, such as [PSI+] and [URE3] in response to environmental stressors, which is hereditary to offspring according to cell division, may be a beneficial strategy for yeast thriving in the harsh stressful environment [13]. Several lines of evidence, however, make it clear that the prions might be detrimental to yeast, often lethal [52]. In support of this, even the most mild of the variants of [PSI+] and [URE3] prions were detrimental to the host [53,54]. One may assume that the toxicity of amyloidogenic yeast prion might be comparable to the neurotoxicity APs protofibrils in human brain. Similar to yeast prion, APs evolvability in human brain also might not be beneficial.

4.2. Regulation of αS Evolvability by βS. It should be considered, however, that the mode of evolvability might differ significantly between yeast and human brain. The obvious difference is that while yeast proliferates, postmitotic neurons in human brain do not. In yeast, even if yeast prion toxicity is lethal to the majority of the population [53,54], it is predicted that the remaining population could proliferate to compensate. Furthermore, transmission of yeast prion protofibrils to offspring may occur in concert with cell division, a simpler and more efficient means compared to APs in humans that rely on complicated reproductive mechanisms based on germ cells [26]. Thus, even in the presence of cytotoxicity, the evolvability of yeast prion should be more effective compared to APs in human brain.

Also possible, some systems might have evolved to mitigate the toxicity associated with APs evolvability in human. In this regard, it has been described that heat shock protein (HSP) 90 might play a buffering role for evolvability in various biological systems, including plants and drosophila [55,56]. HSPs, however, are commonly expressed between yeast and human biology. Therefore, we presume a possible role for nonamyloidogenic homologues as human-specific modulators of APs evolvability. For instance, βS, a member of the synuclein family of peptides, is non-amyloidogenic due to the absence of the amyloidogenic NAC domain (Figure 1(a)) [5]. Given that βS not only associates with αS but also inhibits αS aggregation, leading to suppression of αS neurotoxicity [14], it is likely that βS might act as a buffer against αS evolvability (Figure 3(a)). Consistently, both α- and βS are abundantly expressed in the central nervous system [57], whereas γS expression is mostly in the peripheral nervous system [58]. Thus, it is possible that the interaction of αS with βS might be important for evolvability against stressors in the central nervous system, while γS may mainly be involved in evolvability in the peripheral nervous system. Collectively, βS could be regarded as “evolution of evolvability,” which is a concept in evolutionary biology that evolution by itself may evolve [59]. The inhibitory effect of βS on the aggregation of αS has been well studied in transgenic (tg) mice [14,60]. Although it was previously shown that α-versus βS was upregulated in autopsy brain of DLB [61], the relationship between α- and βS were never investigated in experimental models. Thus, we focus only on the βS actions at the protein level in this paper.

4.3. Disease Manifestation due to Disequilibrium of βS versus αS. Provided that αS evolvability is critical for the development of offspring’s brain, the expression of βS must be strictly regulated. With marked elevated βS expression, αS aggregation is inhibited [14], thus reducing αS evolvability. Consequently, offspring’s brain cannot obtain sufficient stress information to avoid risk of developmental disorders, and instead, manifestation of neurodegenerative conditions may occur less frequently in aging (Figure 3(b)). In this context, the increased expression of βS in dopaminergic neurons might be related to developmental disorders such as autism spectrum disorders (ASD) (Figure 3(b)). Supporting this, it was shown that plasma αS levels are significantly lower, while plasma βS levels are significantly higher in ASD children than in control individuals [62]. Furthermore, recent study suggests that increased βS expression might be relevant to early degenerative diseases such as multiple sclerosis [63]. Thus, it is possible that upregulation of αS evolvability by downregulating βS might be therapeutically beneficial for early degenerative disorders (Figure 4).

Conversely, markedly diminished βS expression promotes αS aggregation, increasing αS evolvability (Figure 3(c)). This would lead to suppression of neurodevelopmental disorders, whereas neurodegenerative conditions might be increased through the antagonistic
pleiotropy mechanism in aging (Figure 3(c)). The mechanism of the decrease of βS expression, however, is unclear. As described above, some familial DLB are associated with P123H and V70M mutations of βS without aggregation of mutant βS (Figure 1(a)) [42]. Presumably, structural alterations of βS due to missense mutations might result in a loss of function of the inhibitory effect of βS on αS aggregation/proteins formation, leading to increased αS evolvability [64]. Furthermore, it is also possible that morphological alteration of wild type βS may also occur in aging [64]. Notably, it was shown that CSF βS concentrations tend to be higher in PD dementia and DLB patients in comparison with PD and controls [65], suggesting that βS might be linked to dementia symptoms rather than motor impairment.

Taken together, βS may be an important buffer to protect against αS neurotoxicity and negatively regulate αS evolvability. Considering that βS is beneficial for evolution, creation of βS may be interpreted as an evolution of amyloid-related evolvability [59]. Yet, the degree of disequilibrium between βS and αS might underlie both early and late (aging-related) degenerative diseases.

5. Therapeutic Strategy Based on Amyloidogenic Evolvability

At present, no effective medical or surgical disease-modifying therapies for PD exist. An exciting prospect, therefore, is that our concept of αS evolvability might provide insight into novel therapeutic strategies against PD. Supposing that increase of αS evolvability might be beneficial for mitophagy, suppressing expression of βS should be therapeutic for recessive PD.

5.1. A Therapeutic Strategy against Recessive PD. Given that neurodegeneration in aging might be attributed to
Figure 4: Illustration of the evolvability-based therapeutic strategy against autosomal recessive PD. The majority of PD is late-onset sPD associated with aggregation of a wild type αS. sPD might be caused by interaction of various genes, including SNCA, LRRK2, MAPT, and GBA, with environmental factors, such as trauma, pesticide, and hypoxia. In the reproductive stage, αS evolvability is beneficial for various cellular functions, such as mitochondria, lysosome-autophagy, and ubiquitin-proteasome system. However, these functions are later impaired through antagonistic pleiotropy, and the late-onset PD is manifested in aging. AD-PD is caused by missense mutations of the AD-PD genes, including SNCA (PARK 1 and 4), LRRK2 (PARK 8), VPS35 (PARK 17), and CHCHD2 (PARK 21) in addition to SNCB (V70M and P123H). The neuropathology in AD-PD is similar to that of sPD and is characterized by aggregation of αS. On the other hand, AR-PD caused by missense mutations of the AD-PD genes, including Parkin (PARK 2), DJ-1 (PARK 6), PINK1 (PARK 7), ATP13A2 (PARK 9), PLA2G6 (PARK 14), FOXO7 (PARK 15), and DNAJC16 (PARK 19), and is associated with impairment of ubiquitin-proteasome, mitochondria, and autophagy, namely, mitophagy in the early-onset PD. Given the buffering effect of βS on αS evolvability, increase in αS evolvability through βS downregulation might be therapeutically beneficial in autosomal recessive PD. To achieve this, βS expression could be reduced by various methods, including ASO targeting βS mRNA and passive βS immunization therapy (Tx).

amyloidogenic evolvability during reproductive stages through antagonistic pleiotropy [33], the pathological features of α-synucleinopathies in aging, involving mitochondria, ubiquitin-proteasome, and autophagy might be attributed to beneficial effects of αS on these cellular functions in the developmental/reproductive stage. As described above, αS may confer resistance against oxidative stress-induced mitochondrial dysfunction. Yet, the beneficial effect of αS on mitochondria in development/reproduction might become detrimental in aging through the antagonistic pleiotropy. A similar mechanism might apply to the effect of αS on autophagy. Yet, a number of reports show that αS is detrimental to protein degradation systems, such as ubiquitin-proteasome and autophagy, under neurodegenerative conditions in aging [66,67], but there are few studies assessing the effect of αS on protein degradation systems during development/reproduction.

It is naturally predicted that upregulating αS evolvability might improve or reverse impaired mitophagy in autosomal recessive familial PD. With this in mind, exogenous αS might be therapeutically administered to patients, but adverse effects would limit its use. Alternatively, given that βS inhibits αS aggregation [14], suppressing βS expression, such as with antisense oligonucleotides against βS mRNA [68] or anti-βS immunotherapy [69], might effectively increase αS expression, leading to increased evolvability (Figure 4). However, considering that αS promotes neurodegeneration in aging, therapeutic dose reduction of βS, to be safe and effective, should be applied only during reproductive time of life. Furthermore, caution must be needed to the possibility that increased αS expression during reproductive life might underlie neurodegeneration in aging.

Our view of evolvability may explain unresolved issues in the field of PD research. Among numerous familial PD studies in animal models, it is puzzling why there is a lack of apparent neurodegeneration of DA neurons in mouse models of PD [70], including tg mice expressing αS in dopaminergic cells [71] and mice with triple knockout of Parkin, PINK1, and DJ-1 [72]. We hypothesize that αS evolvability might confer resistance against stressors in dopaminergic cells in mice. Indeed, mouse αS aggregates faster than does human αS [73], suggesting that the activity of evolvability by αS protofibrils in mice may be more potent than that in humans.

5.2. Therapeutic Strategy against Dominant PD. In contrast, αS aggregation associates with late-onset familial PD with an autosomal dominant inheritance in aging similarly to sPD [74]. Thus, it is generally believed that βS may protect against neurodegeneration induced by αS protofibrils. Supporting this, neurodegenerative features associated with αS
transgenic mice were ameliorated in bigenic mice of α- and βS [14]. Furthermore, the balance of mRNA expression level of β- versus αS was reduced in autopsy brains of α-synucleinopathies [61]. Hence, a differential therapy strategy may be required, i.e., reduce βS expression for AR-PD during reproductive time of life, while increasing βS expression in AD-PD and sPD in the postreproductive life.

5.3. Analogy with Lysosomal Storage Diseases (LSDs). Notably, the relationship between AD-PD and AR-PD is reminiscent of that between nonneuropathic and neuropathic LSDs such as Gaucher disease (GD). In type 1 GD, neuropathy might be absent by virtue of increase of αS evolvability, while PD might be manifested through the antagonistic pleiotropy mechanism in aging. In contrast, neuropathy is severe in early life stage of type 2 and 3 GD due to the decreased αS evolvability [75]. It was predicted that increase of αS evolvability by suppressing βS expression might be potentially therapeutic for type 2 and 3 GD [75]. Thus, the mechanism by which αS evolvability differentially involved in either AD or AR PD might be similar to that in GD subtypes.

Besides LSDs, similar differential mechanism might be applicable to the pairs of early and late degenerative diseases. For instance, schizophrenia is an early degenerative disease in development/reproduction stages which might be transgenerationally linked to AD through amyloid evolvability [76]. We assume that increase of αS evolvability might be beneficial for schizophrenia, while detrimental to AD. Given the interaction of Aβ with βS [77], decreased expression of βS might be beneficial for schizophrenia. Furthermore, it is possible that αS evolvability might be decreased due to the increased expression of βS in ASD in development [62]. Thus, it is tempting to speculate that suppression of βS expression might be therapeutic also for ASD.

6. Concluding Remarks

In conclusion, αS evolvability might be differentially involved between AD-PD and AR-PD. In the former, αS evolvability might be beneficial during development and reproduction, but neurodegeneration might be manifested during aging through the antagonistic pleiotropy mechanism. In the latter, the intensity of disease might be severe due to the absence of αS evolvability. Since αS evolvability is associated with neurotoxicity of amyloid protofibrils in human brain, it is possible that βS might act as an important buffer against αS evolvability and neurotoxicity. Therefore, α- and βS, the paired amyloidogenic and nonamyloidogenic homologue, might be have been created through the evolution of evolvability. Such an evolution, however, might have resulted in new disorders, leading to increased risk of developmental disorders, while conversely, reduced βS might upregulate αS evolvability, leading to aging-associated neurodegenerative disease.

Admittedly, our scenario linking yeast prion to human brain, germ line, and offspring are not based on solid evidence. However, considering that current medical and surgical therapies for PD, especially AR-PD, are symptomatic and lack significant disease-modifying effects [78], it is intriguing to speculate that increased αS evolvability in reproduction might be therapeutic against autosomal recessive familial PD. Given that βS inhibits αS aggregation, suppression of βS expression by various methods, such as ASO and immunotherapy, might effectively increase αS expression, producing greater αS aggregation and evolvability and leading to amelioration of AR-PD. Notably, the same therapy was applied to LSDs, suggesting that increasing amyloid evolvability might be a common strategy for the treatment of early degenerative diseases. Collectively, further investigation of αS evolvability may shed light on new avenues for mechanism-based therapy development in PD.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

MH conceived the concept and MH, JW, and GH wrote the paper. All authors have read, discussed, and approved the manuscript.

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