Nanoscopic insights into seeding mechanisms and toxicity of α-synuclein species in neurons

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New strategies for visualizing self-assembly processes at the nanoscale give deep insights into the molecular origins of disease. An example is the self-assembly of misfolded proteins into amyloid fibrils, which is related to a range of neurodegenerative disorders, such as Parkinson's and Alzheimer's diseases. Here, we probe the links between the mechanism of α-synuclein (AS) aggregation and its associated toxicity by using optical nanoscopy directly in a neuronal cell culture model of Parkinson's disease. Using superresolution microscopy, we show that protein fibrils are taken up by neuronal cells and act as prion-like seeds for elongation reactions that both consume endogenous AS and suppress its de novo aggregation. When AS is internalized in its monomeric form, however, it nucleates and triggers the aggregation of endogenous AS, leading to apoptosis, although there are no detectable cross-reactions between externally added and endogenous protein species. Monomer-induced apoptosis can be reduced by pretreatment with seed fibrils, suggesting that partial consumption of the externally added or excess soluble AS can be significantly neuroprotective.

optical nanoscopy | seeding | neurodegenerative disease | prion-like behavior | α-synuclein

The proliferation of α-synuclein (AS) aggregates (1–6), including the existence of distinct "prion-like" strains (7, 8) as well as their spatial propagation throughout the brain (9), has been proposed to occur in the brains of patients suffering from Parkinson's disease, but their links to pathology and to neuronal death have remained elusive (10–13). In this study, we use optical nanoscopy (14–18) to observe neurons directly and to assay AS internalization, as well as fibril-induced templating reactions involving endogenous AS at the molecular level. We further correlate this information with toxic phenotypes.

We have previously shown that the presence of AS short fibrils (seed fibrils or seeds) preformed in vitro (*Materials and Methods* and Fig. 1 and Fig. S1) favors elongation reactions over spontaneous nucleation (term used for seed-independent aggregation hereafter) in vitro (18). Furthermore, the seed fibrils were found to display highly inhomogeneous growth kinetics, with a significant fraction showing little or no growth at all (18). Here, we use two-color direct stochastic optical reconstruction microscopy (dSTORM), a superresolution imaging method (14), to investigate how such processes may be modified in the cellular environment. The results show the potential of this technique for studying the mechanisms of aggregation events in vivo and provide evidence for the neuroprotective role of reducing the concentration of free AS in the cellular environment.

Results and Discussion

Externally Added Seed Fibrils of AS Act as Templates for Exogenously Added Monomeric AS and Prevent Its Nucleation. We first incubated neuronal cells with AS seed fibrils [50 nM, 5% covalently labeled with Alexa Fluor 568 (AF568), green] and AS monomers [500 nM, 10% covalently labeled with Alexa Fluor 647 (AF647), red], either each individually or both in sequence. Either seed fibrils and/or monomeric protein were taken up by cells within 1 h (Fig. S2). Two-color dSTORM imaging permitted us to distinguish between seed species and their subsequent elongation by monomer addition (details are provided in *SI Materials and Methods*). When cells were incubated with monomer only, we found that spontaneous aggregate formation by monomeric AS within cells occurs faster than in vitro (Fig. 2 *A*, *C*, and *D*), where aggregation proceeds slowly in the absence of mechanical agitation and/or surfaces that induce primary nucleation (19, 20). This observation suggests that within a cellular environment, catalytically active surfaces, such as lipid bilayers (20) or low pH in endosomes (21), enhance the nucleation rate of AS. In the presence of both monomers and seed fibrils, however (Fig. 2 *B* and *D*), elongation of the latter via monomer addition dominates over spontaneous formation of aggregates. Indeed, dSTORM experiments performed in SH-SY5Y cells show that the majority of added monomeric AS (red) is sequestered by the added AS seeds (green) (Fig. 2 *B* and *D*). In particular, Fig. 2*D* shows a comparison between the lengths of aggregates formed by nucleation of exogenously added monomeric protein when it is added together with seed fibrils (red triangles, indicated by arrowheads in Fig. 2 *B*, *ii* and *iii*) and the extent of seed elongation by exogenously added monomeric protein (dark blue squares, indicated by arrows in Fig. 2 *B*, *ii* and *iii*). To quantify seed fibril elongation by added monomeric AS, we analyzed the length distributions of the species observed in each of the two detection channels (red for monomer and green for seed fibrils) separately. We applied masks

Significance

The self-assembly of normally soluble proteins into fibrillar amyloid structures is associated with a range of neurodegenerative disorders. Here, we monitor the fate of different forms of α-synuclein (AS), a protein implicated in Parkinson's disease, via optical nanoscopy directly in neuronal cells. We show that exogenously added preformed AS fibrils elongate by the addition of endogenous AS, naturally present in neurons. In contrast, exogenously added monomeric AS induces aggregate formation within the cells and leads to apoptosis. The latter is significantly reduced by the addition of preformed fibrils, suggesting a neuroprotective role of fibrillar species. The visualization of these effects at the nanoscale shown here opens up new avenues for understanding the links between AS aggregation and neuronal toxicity.

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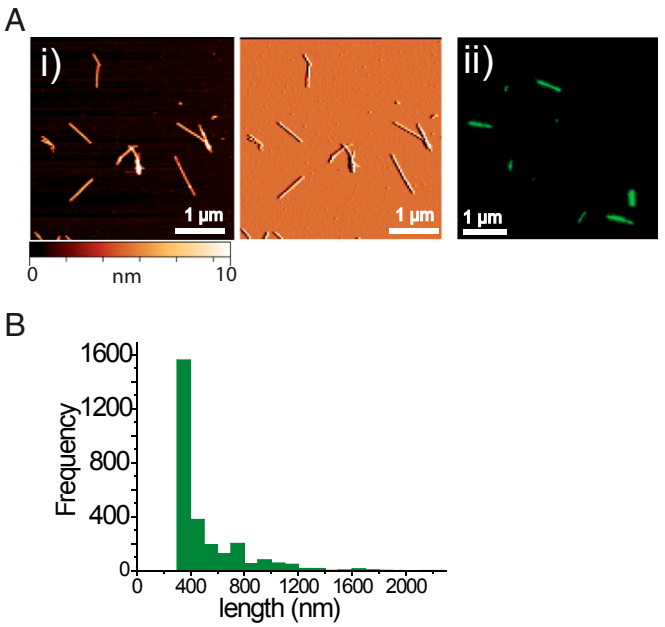

Fig. 1. (*A*, *i*) Atomic force microscopy (height and topographic profiles in *Left* and *Middle* panel, respectively) and (*A*, *ii*) dSTORM images of AS seed fibrils labeled with AF568, formed and imaged in vitro before addition to neuronal cell cultures. (*B*) Histogram depicting the length distribution of such seed fibrils, determined by dSTORM imaging.

to imaged areas in which green and red signals colocalized and subsequently quantified the length of the red aggregates, which had elongated the seed fibrils. Similarly, to quantify the nucleation of added monomeric protein, we measured the length of the aggregates of the red channel, which did not colocalize with any green seed fibrils (details are provided in *Materials and Methods*). Due to the high spatial resolution of dSTORM imaging, we were able to distinguish between these two types of aggregation processes.

Seed Fibril Elongation Dominates over Nucleation of Endogenous AS. In a next step, we investigated whether or not exogenously added AS seed fibrils can be elongated by the endogenous AS present in dopaminergic neurons. We incubated both ventral-mesencephalic (VM) and SH-SY5Y cells with labeled AS seeds (50 nM, 5% covalently labeled with AF568, green) for 1 h before washing and incubating the cells in AS-free medium for 24 h. The neurons were then fixed and stained with primary antibodies (Abs) against endogenous AS for either VM or SH-SY5Y cells, followed by a secondary AF647-labeled Ab. The dSTORM images (Fig. 3) show that the exogenously added seed fibrils (green) are elongated through the addition of endogenous AS (red). We refer to the ensuing fibrillar species as heterofibrils (Fig. 3 *B* and *C*) in both VM and SH-SY5Y cells. Moreover, we have measured seed elongation by comparing the size of seed fibrils in vitro with fibrils that were present in cells after 24 h of incubation in AS-free medium (AFM) and transmission EM and have obtained similar results as described above using super-resolution imaging (details are provided in *SI Materials and Methods*, Fig. S3).

A comparison of the lengths of endogenous AS aggregates, which do not colocalize with seeds, and must therefore have formed by spontaneous nucleation (Nucleation in Fig. 3*D*), with those from AS aggregates that form the elongated segment of the added seed fibrils, giving rise to heterofibrils (Seed elongation in Fig. 3*D*), demonstrates that endogenous AS is preferentially recruited to elongate exogenous seeds rather than undergoing nucleation. The analysis of the length distributions for seed elongation and monomer nucleation was performed in a similar fashion as described earlier for seeded elongation by exogenously added monomer (*SI Materials and Methods*). In order to examine the likelihood of random colocalization between objects in the red and green channels, we performed a quantitative coclustering analysis using Ripley's *K* function (*SI Materials and*

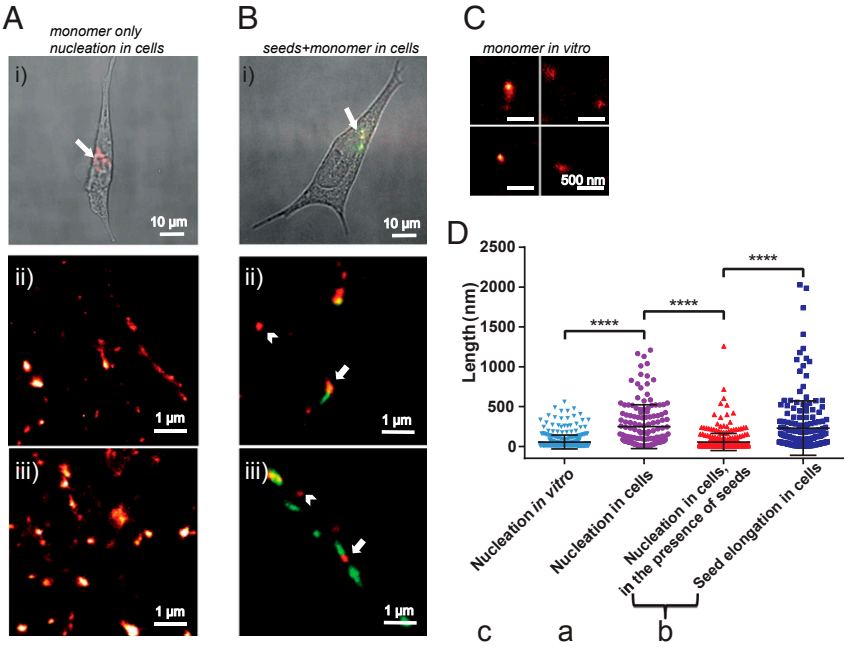

Fig. 2. (*A*, *i*) Overlaid differential interference contrast and conventional fluorescence image of an SH-SY5Y cell treated for 1 h with AF647-labeled (red) AS monomer followed by 24 h of incubation in AS-free medium. (*A*, *ii* and *iii*) Zoomed-in dSTORM images showing the nucleation of monomeric AS inside neuronal cells, after incubation for 1 h followed by incubation for 24 h in AS-free medium. The image in *A*, *ii* corresponds to the aggregates in the area indicated by the white arrow in *A*, *i*. (*B*, *i*) Overlaid DIC and conventional fluorescence image of an SH-SY5Y cell treated for 1 h with AF568-labeled (green) AS seeds and then for 1 h with AF647-labeled (red) AS monomers followed by 24 h of incubation in AS-free medium. (*B*, *ii* and *iii*) Zoomed-in dSTORM images showing the seeds elongated by exogenously added monomeric AS, after 24 h of incubation in AS-free medium (red, indicated by arrows). The image in *B*, *ii* corresponds to fibrils in the area indicated by the white arrow in *B*, *i*. (*C*) dSTORM images of monomeric AS after 24 h of incubation in vitro: No aggregation is observed. (*D*) Quantification of the lengths of different AS species observed: monomeric AS after 24 h of incubation in vitro (light blue inverse triangles), aggregates formed of added monomeric AS after 24 h of incubation in cells that had been treated with monomeric AS only (purple circles), aggregates of added monomeric protein (AF647-labeled) in cells that do not colocalize with seeds after 24 h and indicated by an arrowhead in *B*, *ii* and *iii* (red triangles), and the extent of seed elongation by addition of monomeric protein (AF647-labeled) in cells treated consecutively with seeds and monomeric AS after 24 h and indicated by an arrow in *B*, *ii* and *iii* (dark blue squares). The statistical analysis was performed using one-way ANOVA: $F(2,713) = 48.31$ followed by a Tukey's multiple comparison test (****$P < 0.0001$).

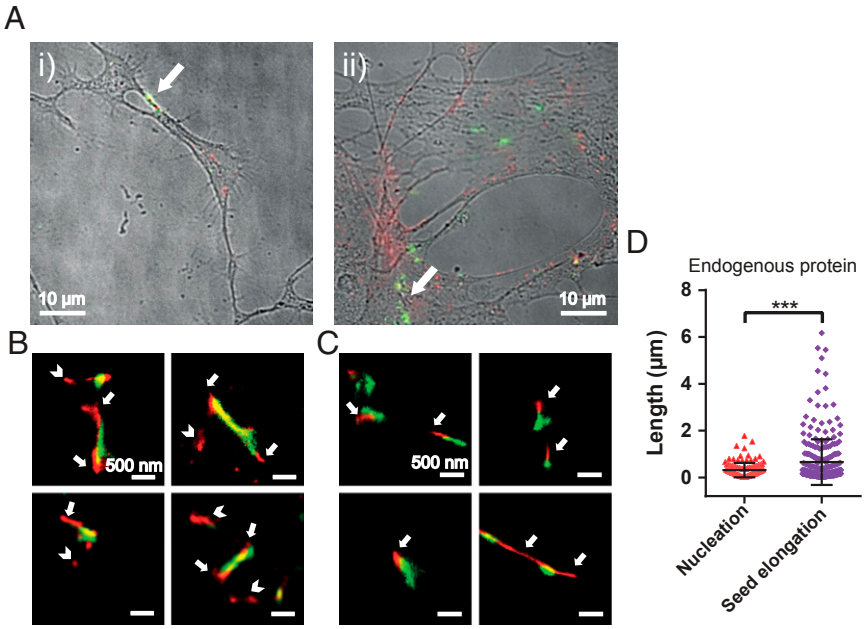

Fig. 3. (*A*, *i* and *ii*) Overlaid differential interference contrast and wide-field fluorescence images of VM cells treated for 1 h with AF568-labeled AS seed fibrils (green), incubated for 24 h in AS-free medium, and immunostained for endogenous AS with a secondary Ab tagged with AF647 (red). (*B*) Zoomed-in dSTORM images of heterofibrils formed of exogenous seeds (green) elongated by endogenous AS (red, indicated by arrows) in VM cells. The top two images correspond to fibrils located in the areas indicated by the white arrows in *A*. (Scale bars: 500 nm.) (*C*) Zoomed-in dSTORM images of heterofibrils formed of exogenous seeds (green) elongated by endogenous AS (red, indicated by arrows) in SH-SY5Y cells. (*D*) Quantification of the extent of seed elongation by endogenous AS, as indicated by arrows in *B* and *C* (Seed elongation), and of the size of aggregates consisting of endogenous AS only, as indicated by arrowheads in *B* (Nucleation). The statistical analysis was performed using an unpaired *t* test (***$P < 0.001$). The experiment was repeated eight times in SH-SY5Y cells and seven times in primary VM cell cultures, and for each experiment, at least eight randomly chosen areas on the glass coverslip were imaged.

Methods). The results in Fig. S4 show that there is no random colocalization between seed fibrils and monomeric protein. On the contrary, there is a clear positive correlation between seeds and addition of monomer, suggesting that seed fibrils grow by elongation reactions.

Furthermore, we found that neither of the primary Abs used displayed significant cross-reactivity with the labeled AS added exogenously. We compared the length of heterofibrils formed in cells with the length of the initial AF568-labeled seed fibrils measured in vitro by staining the latter with the same primary and secondary Abs as used in cells (Fig. S5). The average length of the heterofibrils in cells was significantly greater than the average length of the initial seed fibrils. Overall, these data suggest that, in neurons, the rate of monomer addition to a preformed seed fibril is significantly faster than the rate of spontaneous nucleation, for both exogenously added and endogenous monomeric protein.

Monomeric, but Not Fibrillar AS, Added Exogenously to Neurons Induces Apoptosis After 72 H. Many studies have recently shown that smaller, oligomeric species of AS, rather than mature fibrils, induce toxicity (12, 13, 22–24). Here, we addressed directly whether or not seed fibrils that are capable of seeding endogenous AS can induce toxicity in neuronal cells, as some reports have suggested (8, 25, 26). Using an apoptosis detection assay (Fig. 4*D* and Figs. S6 and S7) we show that adding unlabeled seed fibrils (either 50 nM or 500 nM) to neurons does not lead to significantly increased cell death within 72 h of incubation in AS-free medium in comparison to untreated control neurons. In contrast, we find that the addition of unlabeled monomeric AS (500 nM) leads to significantly increased levels of apoptosis in VM cells under similar experimental conditions (Fig. 4*D* and Figs. S6 and S7), confirming reports that correlate increased levels of AS with disease pathology (27, 28).

Exogenously Added Monomeric AS Triggers the Nucleation of Endogenous AS. To test whether or not exogenous monomeric AS induces toxicity via coaggregation with endogenous AS, we added monomeric AF647-labeled AS (500 nM, 10% covalently labeled with AF647, red) to VM cells in the absence of seed fibrils. Using the same protocol as described above for the detection of heterofibrils in VM and SH-SY5Y cells, we observed that aggregates of endogenous AS were formed throughout the cell, even in areas that were not in close proximity to incorporated exogenous protein. Moreover, dSTORM imaging revealed that the mean area of endogenous AS particles (stained with a primary Ab and a secondary Ab conjugated with AF568, green) formed in the presence of exogenously added monomer was significantly higher than the mean area of endogenous AS species present in control cells that had not been treated with exogenous AS monomers (Fig. 4*C*). It thus appears that the endocytosed exogenous monomer triggers the aggregation of endogenous AS (Fig. 4 *A*, *iii*) without the two moieties necessarily coming into direct contact. Similar results were obtained for SH-SY5Y cells (Fig. S8). However, as we have previously shown in Fig. 2, exogenously added monomeric AS self-nucleates and forms small aggregates inside the cells. It therefore remains to be determined whether or not the exogenously added monomeric protein, upon formation of small aggregates, can indirectly trigger endogenous AS nucleation via other mechanisms, such as cell stress or the production of oxidative species, or through a general loss of protein homeostasis. Overall, these findings therefore link the aggregation of endogenous AS induced indirectly by exogenous monomer with an increased toxicity.

Endocytosed Monomeric AS Has a Reduced Propensity to Seed Endogenous Compared with Preformed AS Fibrils. Having established that seed fibrils can elongate via addition of monomeric AS, both externally added and endogenous, we investigated the

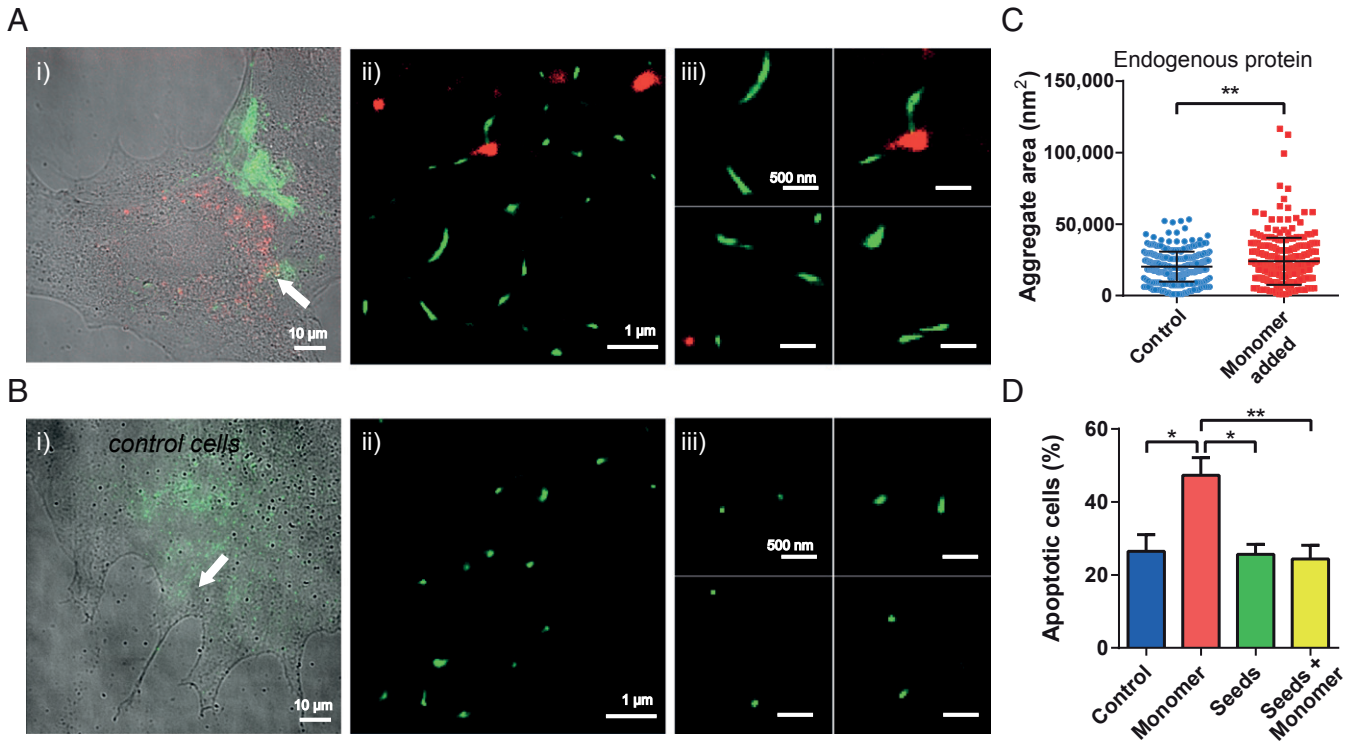

Fig. 4. (*A*, *i* and *B*, *i*) Overlaid differential interference contrast and wide-field fluorescence images of VM cells immunostained for endogenous AS using a secondary Ab tagged with AF568 (green), either treated for 1 h with monomeric AS labeled with AF647 (red), followed by a 24-h incubation in AS-free medium (*A*), or untreated (*B*). (*A*, *ii* and *B*, *ii*) Zoomed-in dSTORM images in the areas indicated by white arrows. (*A*, *iii* and *B*, *iii*) Zoomed-in dSTORM images of aggregates of the endogenous AS species (green) in both treated (*A*) and control (*B*) cells. (Scale bars: 500 nm.) (*C*) Size distribution of endogenous AS species formed in control cells compared with cells treated with monomeric AS. The statistical analysis was performed using an unpaired *t* test (**$P < 0.01$). The experiment was repeated seven times, and 10 randomly chosen areas were imaged each time. (*D*) Percentage of apoptotic cells in control cells (blue), cells treated with monomer only (red), cells treated with seeds only (green), and cells treated consecutively with seeds and monomer (yellow). The statistical analysis was performed using repeated measures ANOVA: $F(3,12) = 7.198$ followed by a Tukey's multiple comparison test (*$P < 0.05$; **$P < 0.01$). The experiment was repeated four times, and two samples per condition were analyzed each time.

growth propensity of aggregates formed by endocytosed monomeric protein. We find that these aggregates have a reduced propensity to seed endogenous AS relative to preformed AS seed fibrils. Indeed, in previous experiments performed in vitro (18), we observed a high level of heterogeneity in the elongation rates for individual AS fibrils within a given population. We thus hypothesized that aggregates formed of endogenous AS upon addition of exogenous monomer might correspond to nonfibrillar structures or fibrillar populations with low seeding propensity. To test this idea, we treated VM cells for 1 h with AF647-labeled monomeric AS (red), incubated them in AS-free medium for either 3 or 7 days, and then incubated them for 1 h in medium containing monomeric AF568-labeled AS (green). This procedure was followed by a 24-h incubation period in AS-free medium (details are provided in *SI Materials and Methods*). Subsequent dSTORM imaging (Fig. S9 *A* and *B*) reveals little growth of AF647-labeled AS aggregates via addition of AF568-labeled monomer, despite the two being clearly colocalized. Most of the aggregates appear globular, with only a few featuring elongated, fibrillar shapes. Taken together with the in vitro data reported earlier, these findings are consistent with the concept of amyloid fibril structural polymorphism (5, 29) (i.e., that aggregates of the same peptide can exhibit a variety of conformational structures). This observation is interesting in light of recent reports demonstrating that fibrillar mouse explants do not induce seeding in all cases in nontransgenic mice (30) and in other animal models of disease (31–33). Furthermore, our results indicate that in addition to fibrillar AS species, soluble AS can readily aggregate following uptake by cells, a conclusion similar to the conclusion drawn from experiments with Tau in a cellular model of Alzheimer's disease (21).

Apoptosis Can Be Counteracted by the Addition of Seed Fibrils Before Exposure to Monomeric AS. In a final set of experiments, we found that upon preincubation of neurons with seed fibrils for 1 h before the addition of monomeric AS, apoptosis was reduced to the levels observed in control cells (Fig. 4*D*). These results indicate a direct correlation between the nucleation of endogenous AS and apoptosis when exogenous monomeric AS is added to neurons alone, but not when seed fibrils are also present. It appears likely that free monomeric AS is rapidly sequestered by the added seed fibrils, thus reducing the levels of soluble protein and decreasing the propensity for de novo formation of aggregates. The process of transmission of toxicity-inducing species from cell to cell thus appears to be potentially more complex than the simple transmission of fibrillar aggregates.

In conclusion, we have established a nanoscopic assay to track aggregation processes directly in neuronal cells, which provides for a powerful tool to probe the links between specific mechanisms of AS amyloid fibril self-assembly and toxicity. In particular, we have shown that exogenously added fibrils can seed endogenous AS and that subsequent elongation of seed fibrils dominates over nucleation of endogenous AS. Moreover, exogenously added monomeric AS triggers aggregation of endogenous AS, and monomeric, but not fibrillar, AS added exogenously to neurons induces apoptosis. The latter effect, however, can be counteracted by the addition of seed fibrils before exposure to monomeric AS, which may prevent the formation of small toxic species by reducing the

excess monomeric protein pool. Taken together, our data suggest that the level of soluble AS is crucial to the development of AS pathology and that the relative concentrations of the different forms of AS are likely to play a key role in the spreading of disease.

Materials and Methods

WT human AS was recombinantly expressed and purified as described previously (19). Superresolution imaging in vitro and in cells was performed using a dSTORM microscopy setup based on a Nikon Eclipse TE 300 inverted wide-field microscope and a 100×, 1.49-N.A. total internal reflection fluorescence objective lens (Nikon, UK Ltd) as described by Pinotsi et al. (18). The experiments were performed on both neuroblastoma cell cultures and on VM neurons dissected from rat embryos. Details on all of the experimental protocols, methods, and data analysis can be found in *SI Materials and Methods*.

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