Zn\(^{2+}\)-A\(\beta\)40 Complexes Form Metastable Quasi-spherical Oligomers That Are Cytotoxic to Cultured Hippocampal Neurons\(*S\)

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Background: The mechanism by which interaction between A\(\beta\) and Zn\(^{2+}\) induces A\(\beta\) aggregation and cell toxicity is elusive.

Results: Zn\(^{2+}\) and A\(\beta\)40 form metastable neurotoxic oligomers.

Conclusion: A\(\beta\)40 binding to Zn\(^{2+}\) leads to formation of small neurotoxic oligomers that become benign upon further self-assembly.

Significance: We provide a structure-function analysis of Zn\(^{2+}\)-stabilized A\(\beta\)40, a neurotoxic species that may contribute to the pathology in AD.

The predominant proteinaceous component of amyloid \(\beta\)-protein (A\(\beta\)) oligomerization associated with Alzheimer disease are increasingly recognized. However, the detailed structures dictating oligomerization associated with Alzheimer disease are increasingly recognized. Here, we show that small Zn\(^{2+}\)-bound A\(\beta\)1–40 (Zn\(^{2+}\)-A\(\beta\)40) oligomers formed in cell culture medium exhibit quasi-spherical structures similar to native amylospheroids isolated recently from Alzheimer disease patients. These quasi-spherical Zn\(^{2+}\)-A\(\beta\)40 oligomers irreversibly inhibit spontaneous neuronal activity and cause massive cell death in primary hippocampal neurons. Spectroscopic and x-ray diffraction structural analyses indicate that despite their non-fibrillar morphology, the metastable Zn\(^{2+}\)-A\(\beta\)40 oligomers are rich in \(\beta\)-sheet and cross-\(\beta\) structures. Thus, Zn\(^{2+}\) promotes A\(\beta\)40 neurotoxicity by structural organization mechanisms mediated by coordination chemistry.

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This article contains supplemental Figs. S1–S6.

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The abbreviations used are: AD, Alzheimer disease; A\(\beta\), amyloid \(\beta\)-protein; APP, amyloid \(\beta\)-protein precursor; TEM, transmission electron microscopy; AFM, atomic force microscopy; ThT, thioflavin T; MEM, minimal essential medium; HS, horse serum.
and do not convert into fibrils (17). Interaction of Zn\(^{2+}\) with A\(\beta\)40 increases the exposure of hydrophobic surfaces in A\(\beta\)40 (18).

Zn\(^{2+}\)-induced A\(\beta\) aggregates were proposed as neurotoxic agents disrupting synaptic communication (11, 13). However, the molecular determinants driving neurotoxicity remain elusive. We thus set out to perform a detailed structure-toxicity analyses of A\(\beta\)40 in the presence of Zn\(^{2+}\) in serum-free culture media. Here, we report the self-assembly pathways and structure-toxicity interplay of Zn\(^{2+}\)-induced, quasi-spherical metastable A\(\beta\)40 oligomers (Zn\(^{2+}\)-A\(\beta\)40). These oligomers possess conformational characteristics typical of fibrillar structures, yet their morphology is non-fibrillar. They irreversibly affect spontaneous calcium activity and neuron viability.

**EXPERIMENTAL PROCEDURES**

**Reagents**—All reagents were purchased from Sigma-Aldrich (Israel) unless mentioned otherwise. All reagents were of analytical grade. Purified deionized water was prepared using a Milli-Q water-purification system (Millipore, Billerica, MA).

**A\(\beta\)40 Sample Preparation**—A\(\beta\)40 was purchased from rPep-tide and prepared for experiments as described previously (14). Briefly, A\(\beta\)40 was dissolved at 665 \(\mu M\) (defined by UV-Vis spectroscopy with \(\varepsilon_{222} = 2300 \text{ M}^{-1} \text{ cm}^{-1}\)) in 10 mM NaOH, sonicated for 1 min in a Branson 1510 bath sonicator, and centrifuged for 10 min at 12,000 \(\times g\) at 4 °C to precipitate large aggregates. Concentrations of stock solutions prepared this way were occasionally confirmed by amino acid analysis. The differences in the concentrations determined by absorption and amino acid analysis were < 8%. The stock solutions were diluted to 230 \(\mu M\) in 10 mM MOPS (pH 6.9 ± 0.1). These solutions did not scatter near-UV light at 300 nm, suggesting that they did not contain large aggregates or fibrils. Moreover, A\(\beta\)40 preparations were hardly distinguishable from the control (buffer) by transmission electron microscopy (TEM) examination at \(t = 0\) (supplemental Fig. S1a). In such preparations, A\(\beta\)40 monomers coexist with low-molecular-weight oligomers (19). Zn\(^{2+}\)-A\(\beta\)40 oligomers were prepared by adding 0.01 M ZnCl\(_2\) (in 10 mM MOPS) to the A\(\beta\)40 solution. For fibril preparation, 230 \(\mu M\) A\(\beta\)40 was incubated for 7 days at 37 °C without agitation. Fibril formation was examined by TEM (supplemental Fig. S2).

In TEM, atomic force microscopy (AFM), CD, thioflavin T (Th/T) fluorescence, and cell-culture experiments, the final A\(\beta\)40 and Zn\(^{2+}\) concentrations were 10 and 20 \(\mu M\), respectively (A\(\beta\) concentration calculated for the monomeric protein). We estimated the concentration of free Zn\(^{2+}\) in our preparations by using data published by Bush et al. (13), assuming two binding sites for Zn\(^{2+}\) on A\(\beta\):

\[
B = \frac{(R1 \times L_2)/(K_{d1} + L_2) + (R2 \times L_1)/(K_{d2} + L_2)}{2}
\]

where \(B\) is the concentration of Zn\(^{2+}\)-A\(\beta\)40 oligomers, \(L_1\) is the concentration of free Zn\(^{2+}\), \(R1\) and \(R2\) are the concentrations of each Zn\(^{2+}\)-binding site, and \(K_{d1}\) and \(K_{d2}\) are the respective dissociation constants.

Accordingly, the concentration of free Zn\(^{2+}\) in our preparations is estimated at 5.15 \(\mu M\). These calculations suggest that under the conditions we used, each A\(\beta\)40 molecule binds ~ 1.5 Zn\(^{2+}\) ions.

TEM, AFM, CD, and Th/T experiments were performed in serum-free cell-culture medium (129 mM NaCl, 4 mM KCl, 1 mM MgCl\(_2\), 2 mM CaCl\(_2\), 10 mM glucose, and 10 mM HEPES (pH 7.4) with osmolarity adjusted to 320 mOsm) using dilutions identical to those used in cell culture experiments. Fibril suspensions in MOPS were sonicated for 20 s, centrifuged for 20 min at 2000 \(\times g\), washed three times in 10 mM MOPS, and finally added to neuronal cultures. All morphologies were prepared in MOPS and comprised 8.7% of the final volume of culture medium.

**Electron Microscopy**—Images were acquired using a Tecnai 12 transmission electron microscope (FEI, Eindhoven, The Netherlands) operated at 120 kV. Micrographs were taken using a MegaView III charge-coupled device camera (SIS, Münster, Germany). Aliquots of different A\(\beta\)40 preparations were adsorbed for 1 min onto carbon-coated copper grids and negatively stained with 1% (w/v) uranyl acetate for 30 s. TEM images were analyzed using ImageJ.

**Atomic Force Microscopy**—Aliquots (5 \(\mu l\)) of freshly prepared Zn\(^{2+}\)-A\(\beta\)40 were spotted onto freshly cleaved mica (Ted Pella, Inc., Redding, CA), incubated at room temperature for 3 min, rinsed with Milli-Q water, and air-dried. At least five different regions on the mica surface were examined.

Images were collected using a MultiMode AFM with a NanoScope V controller (Veeco Metrology LLC, Santa Barbara, CA) equipped with an E-scanner in tapping mode at 22–24 °C. All images were recorded using silicon microcantilevers (OMCL-AC240TS-W2, Olympus) with a spring constant of ~2 N/m (manufacturer-specified) and at a scan rate of 1–3 Hz. The target amplitude was 300 mV with a set point of ~230 mV for all measurements. Images were acquired in different scan directions and at different scales to verify the consistency of the evaluated structures.

Profiles of Zn\(^{2+}\)-A\(\beta\)40 oligomers were acquired from the AFM images, and the corresponding aggregate heights were calculated, binned, normalized, and plotted using Matlab (MathWorks, Inc., Natick, MA).

**Circular Dichroism Spectroscopy**—Room-temperature CD spectra of 10 \(\mu M\) Zn\(^{2+}\)-free A\(\beta\)40 or Zn\(^{2+}\)-A\(\beta\)40 solutions in serum-free media were measured at \(t = 0\) h and \(t = 2\) h in 2-mm path-length quartz cuvettes (Helma, Jena, Germany) in the spectral range of 200–260 nm. Spectra were recorded using a JASCO 815 spectropolarimeter at a 100-nm/min scan rate with 0.2-nm resolution. For each sample, four spectra were acquired and averaged. The background was subtracted, and the spectra were smoothed using OriginPro 8.0.

**X-ray Powder Diffraction**—MOPS stock solutions containing Zn\(^{2+}\)-A\(\beta\)40 were centrifuged at 12,000 \(\times g\) for 10 min at 4 °C. The pellet was washed gently three times with 1 ml of Milli-Q water containing 1 \(\mu M\) ZnCl\(_2\), placed as a thick film onto a silicon zero-background sample holder, and air-dried for 30 min at room temperature. X-ray diffraction measurements were carried out in reflection mode using a TTRAX III \(\theta\)-\(\theta\) diffractometer (Rigaku, Japan) equipped with a rotating copper anode operating at 50 kV and 200 mA and a scintillation detector.
Parallel-beam optics (angle divergence ~0.05°) formed by a multilayered mirror (Rigaku, Cross Beam Optics, Japan) were used to obtain high-quality data from a dried-drop sample at low diffraction angles. Specular diffraction (θ/2θ scan) was performed under ambient conditions from 2° to 30°. The average measurement time was ~5 h. After 10 h, sample degradation was observed. The cross-section of the x-ray beam was 1 × 5 mm², and the angular divergence of the reflected beam was limited to 0.114° by a parallel slit analyzer (PSA-80).

Peak positions and widths of the Bragg reflections were determined by a self-consistent profile-fitting procedure using Jade 9.1 (Materials Data, Inc., Livermore, CA). The coherent diffraction lengths observed in Zn²⁺-Aβ40 were estimated by the Scherrer formula from the broadening of the corresponding peaks.

ThT Fluorescence—Triplicate 200-μl samples were examined in plastic clear-bottom 96-well plates (Nunc 96F MaxiSorp, Thermo Fisher Scientific, Roskilde, Denmark). The plates were incubated at 25 °C for 72 h without agitation in a Synergy HT multi-mode microplate reader (Bio-Tek Instruments, Winooski, VT) with excitation and emission wavelength/slit widths of 400 nm/30 nm and 485 nm/20 nm, respectively. To prevent evaporation, plates were tightly sealed with Parafilm (Plastic Packaging, Chicago, IL). The ThT fluorescence data were background-subtracted and plotted using OriginPro 8.0.

Hippocampal Neuron Cultures—Animal experiments were performed in accordance with the guidelines of the Institutional Animal Care and Use Committee of the Weizmann Institute and the Israeli national guidelines on animal care. Cell cultures were prepared as described previously (20). Briefly, rat pups were decapitated on the day of birth (P0), and their brains were removed and placed into Petri dishes containing chilled (4 °C), oxygenated Leibovitz L15 medium (Invitrogen) supplemented with 0.6% glucose and gentamicin (20 μg/ml, Sigma). Hippocampi were isolated, incubated with trypsin (0.25% w/v) and DNase (50 μg/ml), triturated, and then transferred to plating medium comprising 5% heat-inactivated horse serum (HS), 5% fetal bovine serum, and B-27 (1 μl/ml) prepared in minimum essential medium (MEM) (Invitrogen) supplemented with 0.6% glucose, 20 μg/ml gentamicin, and 2 mM glutamate (enriched MEM).

Using 24-well plates, ~10⁵ hippocampal neurons were plated in 1 ml of medium/well onto a hippocampal glial feeder layer. The feeder layer was grown on poly-lysine-coated glass cover slips for 2 weeks before transferring the neurons. On day 3, the medium was changed to enriched MEM containing 10% HS and a mixture of 5′-fluoro-2-deoxyuridine/uridine (20 μg/ml and 50 μg/ml, respectively, Sigma) to block glial cell proliferation. On day 7, the medium was switched to MEM containing 10% HS with no further modifications until cells were used for experiments.

Intracellular Ca²⁺ Imaging—Postnatal cultures 2–3 weeks after plating were used for Ca²⁺ imaging. First, cells were washed in serum-free cell-culture media containing 129 mM NaCl, 4 mM KCl, 1 mM MgCl₂, 2 mM CaCl₂, 10 mM glucose, and 10 mM HEPES (pH 7.4) with osmolarity adjusted to 320 mOsm.

Cells were incubated for 1 h at 23 °C in the dark in the same serum-free media containing 2 μM Fluo-4AM (Invitrogen/Molecular Probes). The cells were then extensively washed for 5 min and imaged using an upright Zeiss PASCAL confocal microscope with an Olympus ×63 water immersion lens (0.9 numerical aperture) and ×1–2 scan zoom in birefringent scan mode. Laser power, pinhole diameter, and detector gains were adjusted and standardized to avoid photo damage and pixel saturation. Each field was recorded for 5 min without signs of cellular photo toxicity or changes in spontaneous firing rates.

As all Aβ40 preparations initially were prepared in MOPS buffer, we tested their effects on the spontaneous activity of cultured neurons in 10 mM MOPS (pH 6.9 ± 0.1). We found that MOPS, which served as a control, did not affect the rate or the amplitude of Ca²⁺ activity or [Ca²⁺]ᵢ (p > 0.05, Student’s t test). Sequential images were taken at t = 0, 5, 30, 60, 90, and 120 min for each Aβ40 preparation, followed by a 30-min wash step.

Cell Viability Analysis—In initial experiments, we added 10 μM of each Aβ40 preparation (Zn²⁺–free Aβ40, Aβ40 fibrils or Zn²⁺–Aβ40 oligomers), MOPS, or Zn²⁺ to hippocampal neurons and measured neuronal viability after 48 h incubation. The incubation conditions were serum-containing culture media (MEM containing 10% HS) at 37 °C and 5% CO₂. Under these conditions, no toxicity was observed for any of the Aβ40 preparations. Comparison of Zn²⁺–Aβ40 oligomers and control conditions is shown in supplemental Fig. S6.

In a modified protocol, four equal aliquots of Zn²⁺–free Aβ40, Zn²⁺–Aβ40 oligomers, or Aβ40 fibrils were added to primary hippocampal neurons every 12 h without changing the incubation conditions (1 ml MEM containing 10% HS at 37 °C, 5% CO₂). The final Aβ40 concentration was 10 μM in each case. Cell survival was evaluated 72 h after the last application by assaying neuron-specific enolase or directly by phase-contrast microscopy.

Immunocytochemistry—Glass cover slips with treated cells were removed from the wells and washed briefly with the standard recording medium. The cells were fixed in 4% paraformaldehyde and 4% sucrose in 0.1M PBS (pH 7.4) for 20 min and then washed thoroughly with PBS, incubated for 1 h in PBS containing 10% normal goat serum and 0.1% Triton X-100 to reduce nonspecific reactivity, and incubated with rabbit anti-neuron-specific enolase at 4 °C for 24 h. The cells were then washed, incubated with Alexa Fluor 568-labeled caprine anti-rabbit secondary antibody (1:200, Molecular Probes, Eugene, OR) for 1 h, and washed. The coverslips were transferred onto glass slides and mounted in an anti-fading mounting medium comprising 90% glycerol and 0.1% p-phenylenediamine (Sigma) in 20 mM PBS (pH 8.5) for visualization. Confocal image stacks were recorded using a Zeiss LSM 510 laser-scanning microscope with a Zeiss ×40 oil-immersion objective (1.4 numerical aperture) and ×1 scan zoom. Detector gain and amplifier were initially set to obtain pixel densities within a linear range.

Quantification, Statistics, and Digital Images—Time lapse, immunostaining, and phase contrast images were analyzed using Zeiss LSM 510 or Zeiss PASCAL software (Carl Zeiss). The fluorescence signal was measured by producing regions of
interest related to the shapes of cell bodies. Alternatively, profiles of fluorescence intensity were generated using ImageJ. Cells were measured and counted using a double-blinded procedure by an independent observer. [Ca2+]i events were counted automatically using a home-made Matlab program (The MathWorks, Inc., Asheboro, NC) and controlled manually.

Statistical analyses were performed by Student’s t tests or analysis of variance using Matlab or KaleidaGraph (Synergy Software, Reading, PA). In each experiment, 4–6 cultures were used per group.

Figures were prepared using Photoshop CS2 (Adobe, San Jose, CA). Image brightness and contrast were adjusted uniformly across the entire image.

RESULTS

Morphology of Zn2+-Aβ40 Oligomers in Serum-free Culture Media—The rapid interaction of Zn2+ ions with Aβ40 induced aggregation mainly into quasi-spherical morphologies as observed previously in MOPS buffer (14). The experimental conditions used to assess Aβ morphologies by TEM and AFM were similar to conditions used for neuron cultures. Aβ morphologies were assessed at room temperature in serum-free culture media. Under these conditions, our preparations contained ~5 μM of unbound Zn2+. In fresh Zn2+-Aβ40 preparations, a distribution of predominantly quasi-spherical particles with 7–15-nm diameter was observed by TEM (Fig. 1, a and b). These Zn2+-Aβ40 assemblies resembled those of toxic spherical oligomers of Zn2+-free Aβ40 (22) stabilized at 4°C for 30–60 h, although the latter had larger diameters (15–35 nm). The majority of the Zn2+-Aβ40 complexes appeared to have stable size and morphology for at least 2 h at room temperature, whereas ~20% of these structures increased in size after 2 h (supplemental Fig. S3). In contrast, the morphology and diameter/length of structures observed in Zn2+-free Aβ40 preparations (supplemental Fig. S1, a and b) increased substantially in the first 2 h of incubation. Thus, morphological changes in Zn2+-free Aβ40 occur considerably faster than in Zn2+-stabilized oligomers.

Height analyses of the Zn2+-Aβ40 oligomers by AFM revealed distinct populations with heights of 1, 2, or 4 nm (Fig. 1, c and d). This suggests that aggregates are arranged in mono-, bi-, or tetrilayers, assuming ~1-nm-thick monolayers within which Aβ40 molecules have a hairpin conformation (14).

Height-diameter correlation analysis of native neurotoxic amylospheroids (23) and Zn2+-free cross-linked Aβ40 (24) yielded correlation coefficients of \( r^2 = 0.87 \) and \( r^2 > 0.95 \), respectively. A similar height-diameter correlation analysis of Zn2+-Aβ40 populations gave a correlation coefficient of \( r^2 = 0.055 \), demonstrating that heights and diameters were not correlated. Further analysis showed that the low correlation coefficient resulted from the existence of a relatively narrow population of diameters and three distinct populations of heights (Fig. 1, b–d). This suggests that Zn2+-Aβ40 assemblies in defined conformational protein blocks possessing an irregular structural organization in the horizontal plane and a regular organization in the vertical direction. This organization may be induced by stable hairpin conformation of Aβ40 and nonspecific intermolecular Zn2+ coordination (14, 25).

Secondary and Tertiary Structures of Zn2+-Aβ40—The secondary and tertiary structures of Zn2+-Aβ40 oligomers were analyzed by far-UV CD spectroscopy and x-ray powder diffraction (Fig. 2). At \( t = 0 \), the CD spectrum of Zn2+-Aβ40 oligomers measured in serum-free media exhibited a minimum at 214 nm, indicating a high β-sheet content which was stable during 2 h of incubation at room temperature (Fig. 2a). Similar CD experiments assessing Zn2+-free Aβ40 preparations at \( t = 0 \), the CD spectrum of Zn2+-Aβ40 oligomers measured in serum-free media exhibited a minimum at 214 nm, indicating a high β-sheet content which was stable during 2 h of incubation at room temperature (Fig. 2a).
0 or \( t = 2 \) h also showed the presence of \( \beta \)-sheets (supplemental Fig. S1c). Yet, the \( \beta \)-sheet content in these preparations increased substantially during the first 2 h of incubation, in agreement with the TEM data discussed above.

X-ray powder diffraction was used to elucidate the long-range order of metastable Zn\(^{2+}\)–A\(\beta\)40 oligomers (Fig. 2b). Fresh preparations of Zn\(^{2+}\)–A\(\beta\)40 in MOPS buffer were rapidly concentrated prior to x-ray measurements (see “Experimental Procedures”). The diffraction pattern collected in reflection mode exhibited three peaks with \( d \) spacings at 10.25, 4.67, and 3.7 Å, characteristic of amyloid fibrils (26–30) (Fig. 2b). This result was intriguing in view of the non-fibrillar, quasi-spherical morphology observed for the metastable Zn\(^{2+}\)–A\(\beta\)40 oligomers in both MOPS (14) and in serum-free culture media (Fig. 1). The most pronounced reflection peak corresponded to a distance of 4.67 Å and was attributed to intermolecular hydrogen bond distances. The coherence length of this reflection is \( \sim 20 \) Å, corresponding to approximately four molecules of A\(\beta\)40 in a crystallite along the axis of hydrogen bonding. The reflection referring to 10.25 Å was attributed to the mean distance between peptides in neighboring sheets of A\(\beta\)40 molecules with a U-shaped hairpin conformation. This distance is in good agreement with the 1-nm height for monolayer arrangements of Zn\(^{2+}\)–A\(\beta\)40 oligomers measured by AFM (Fig. 1, c and d). The calculated coherence length for the 10.25 Å diffraction peak is \( \sim 42 \) Å, corresponding to a tetra-layer of A\(\beta\)40, also in agreement with our AFM height analysis, which indicates a height of 4 nm (Fig. 1d). The low-intensity, broad reflection peak (\( > 6 \)) corresponding to \( \sim 3.7 \) Å indicates a low degree of order of the pleated \( \beta \)-sheets. Similar peaks were observed in fibrils of glucagon (3.77 Å) (26), A\(\beta\)1–28 (3.8 Å) (27), and A\(\beta\)40 (3.8 Å) (28) and was interpreted by Glenner et al. (26) as average spacing between \( \text{C}_\text{n} \) atoms in neighboring polypeptide chains. Our CD and x-ray powder diffraction data indicate that binding of Zn\(^{2+}\) to A\(\beta\)40 peptide does not interfere with the hairpin conformation observed in A\(\beta\)40 fibrils yet induces non-fibrillar morphologies, possibly via intermolecular Zn\(^{2+}\) coordination.

**Seeding A\(\beta\)40 with Zn\(^{2+}\)–A\(\beta\)40 Oligomers Inhibits Fibril Growth**—Our results indicate that Zn\(^{2+}\)–A\(\beta\)40 oligomers possess structural characteristics similar to those found in fibrils but do not have fibrillar morphology (14, 17, 18). To explore the overall effect of Zn\(^{2+}\)–A\(\beta\)40 oligomers on A\(\beta\)40 fibril formation, we analyzed their nucleation power by conducting time-dependent ThT fluorescence experiments in serum-free media. The ThT fluorescence assay quantitatively measures formation of cross-\( \beta \)-sheet structures (31) and is commonly used for monitoring A\(\beta \) assembly kinetics (32). The ThT fluorescence signal was recorded over 72 h at 25 °C without agitation in Zn\(^{2+}\)-free A\(\beta\)40 (comprising monomers and low-molecular-weight oligomers (19), Zn\(^{2+}\)–A\(\beta\)40 oligomers, or mixtures of the two preparations at 9:1, or 4:1 concentration ratio (Fig. 3). Ten \( \mu \text{M} \) Zn\(^{2+}\)-free A\(\beta\)40 displayed a rapid increase in ThT fluorescence in serum-free culture medium. The linear part of the fluorescence curve had a slope of 0.81 ± 0.08 arbitrary units/h. Such a fast increase in ThT fluorescence relative to measurements in hypotonic buffers is typically observed in serum-free medium because of the relatively high concentration of Na\(^+\) and Ca\(^{2+}\) salts, which are known to accelerate A\(\beta \) aggregation and fibril formation (33–36).

Seeding Zn\(^{2+}\)-free A\(\beta\)40 with 10 or 20% Zn\(^{2+}\)–A\(\beta\)40 oligomers affected both the slope and the plateau value of the ThT fluorescence specifically. The slopes decreased to 0.44 ± 0.05 arbitrary units/h for 10% and 0.33 ± 0.03 arbitrary units/h in the presence of 20% Zn\(^{2+}\)–A\(\beta\)40 oligomers, respectively. The ThT fluorescence at the plateau decreased by \( \sim 35 \%) and \( \sim 45 \)% relative to the plateau signal of A\(\beta\)40 in the presence of 10 and 20% Zn\(^{2+}\)–A\(\beta\)40 oligomers, respectively, suggesting a reduction of aligned cross-\( \beta \)-sheet content. The sample containing 10 \( \mu \text{M} \) Zn\(^{2+}\)–A\(\beta\)40 oligomers showed little increase in ThT fluorescence relative to Zn\(^{2+}\)-free A\(\beta\)40. These data suggest that Zn\(^{2+}\)–A\(\beta\)40 oligomers attenuate the nucleation step of A\(\beta\)40 fibrillation and interfere with fibril growth. The ThT results are in agreement with TEM images presented in supplemental Figs. S3 and S4. Thus, our results indicate that not only Zn\(^{2+}\) but also Zn\(^{2+}\)–A\(\beta\)40 oligomers interfere with A\(\beta\)40 assembly.

**Metastable Zn\(^{2+}\)–A\(\beta\)40 Oligomers Irreversibly Suppress Spontaneous Neuronal Activity**—The most common forms of spontaneous neuronal activity in vivo and in vitro are synchronous intracellular calcium ([Ca\(^{2+}\)]\(_i\)) transients and bursts of action potentials in large populations of neurons involved in local circuits. Typically, in serum-free media, synchronous [Ca\(^{2+}\)]\(_i\) bursts can be recorded at stable rates and amplitudes for 2–3 h at room temperature (21, 37). To evaluate how fresh Zn\(^{2+}\)–A\(\beta\)40 oligomers affect neuronal function, we added them to primary rat hippocampal neurons in serum-free culture media.
and measured spontaneous Ca\textsuperscript{2+} activity using the fluorescent Ca\textsuperscript{2+}-binding dye Fluo-4AM (38). The control conditions included freshly prepared Zn\textsuperscript{2+}-free A\textsubscript{B}40, A\textsubscript{B}40 fibrils, and Zn\textsuperscript{2+}. An additional control was MOPS (pH 6.9) diluted in serum-free cell-culture medium at the same concentration used for preparing Zn\textsuperscript{2+}-A\textsubscript{B}40 oligomers. We found that MOPS did not significantly affect the rate or the amplitude of Ca\textsuperscript{2+} activity or basal [Ca\textsuperscript{2+}]	extsubscript{i} (data not shown).

The effect of Zn\textsuperscript{2+}-A\textsubscript{B}40 oligomers on Ca\textsuperscript{2+} transients in a typical field of cultured hippocampal neurons is shown in Fig. 4, a and b. Initially, the fluorescence intensity of resting [Ca\textsuperscript{2+}]	extsubscript{i} was consistently below 10 relative fluorescence units. On average, 5–8 transient Ca\textsuperscript{2+} events per minute were measured, reaching up to 80 relative fluorescence units. After 60 min of incubation with 10 \( \mu \text{M} \) Zn\textsuperscript{2+}-A\textsubscript{B}40 oligomers, the mean Ca\textsuperscript{2+} firing rate gradually decreased to \( \sim 3–5 \text{ min}^{-1} \) (Fig. 4, a and b, and supplemental Fig. S5, a and b), and the net number of Ca\textsuperscript{2+} events was almost completely suppressed by 120 min (Fig. 4c and supplemental Fig. S5). An early indicator of neuronal damage is a gradual rise in basal [Ca\textsuperscript{2+}]	extsubscript{i}. In our experiments, an increase in [Ca\textsuperscript{2+}]	extsubscript{i} was observed \( \sim 30 \text{ min} \) after adding freshly prepared Zn\textsuperscript{2+}-A\textsubscript{B}40 oligomers (Fig. 4, a, b, and d) with further increase by a factor of 4–5 by 120 min. Extensively washing out the Zn\textsuperscript{2+}-A\textsubscript{B}40 oligomers did not reverse the change in basal [Ca\textsuperscript{2+}]	extsubscript{i}, nor did it affect the steady increase in the basal [Ca\textsuperscript{2+}]	extsubscript{i} signal (Fig. 4d). This suggests that Zn\textsuperscript{2+}-A\textsubscript{B}40-induced alterations of cell physiology were irreversible for at least 60 min after washing.

Of all the treatment conditions, only Zn\textsuperscript{2+}-A\textsubscript{B}40 oligomers induced a marked decrease in firing rates and in resting [Ca\textsuperscript{2+}]	extsubscript{i} fluorescence. Treatment with Zn\textsuperscript{2+}-free A\textsubscript{B}40 induced a slight, transient increase in the neuronal firing rate at \( \sim 10 \text{ min} \) (Fig. 4c) that became statistically insignificant by 30 min and completely waned after 60 min. Importantly, when the same preparations of Zn\textsuperscript{2+}-A\textsubscript{B}40 oligomers were stored for at least 16 h at room temperature before application, they did not affect spontaneous Ca\textsuperscript{2+} activity. TEM images of these Zn\textsuperscript{2+}-A\textsubscript{B}40 oligomer preparations revealed large amorphous aggregates extending more than 100 nm (supplemental Fig. S4), which likely formed by association of
the small quasi-spherical oligomers observed at earlier time points (Fig. 1a).

Two other Ca²⁺-binding dyes, Fura-2AM and Oregon Green BAPTA-2AM yielded very similar results (data not shown), suggesting that the observations were unrelated to the use of Fluo-4AM.

Metastable Zn²⁺-Aβ40 Oligomers Cause Neuronal Death—Alterations in neuronal activity and basal [Ca²⁺], following treatment with Zn²⁺-Aβ40 oligomers indicated neuronal dysfunction, which might lead to neuronal death. To test this prediction, we applied Zn²⁺-Aβ40 oligomers, freshly prepared Zn²⁺-free Aβ40, or fibrillar Aβ40 to primary hippocampal neurons and measured their viability by immunoassaying for neuron-specific enolase, a standard assay for specifically detecting neuronal, rather than glial, cell death. The cell viability experiments were performed in serum-containing medium at 37 °C. We could not assess the morphology of Aβ40 under these conditions because they were indistinguishable from those of serum proteins.

In initial experiments, we added 10 μM of each Aβ40 preparation, 10 mM MOPS, or 20 μM Zn²⁺ to the neurons and measured neuronal viability following incubation for 48 h. Under these conditions, we observed little or no toxicity induced by the Zn²⁺-Aβ40 oligomers (supplemental Fig. S6) or any of the other conditions (data not shown).

This result was inconsistent with the toxic effect of the Zn²⁺-Aβ40 oligomers on spontaneous Ca²⁺ activity and basal [Ca²⁺], levels. A potential explanation for this apparent discrepancy was rapid self-association of the metastable Zn²⁺-Aβ40 oligomers in serum-containing medium into large, nontoxic aggregates, similar to those shown in supplemental Fig. S4. In contrast to serum-free medium, this medium has a complex composition, including serum proteins and growth factors, which likely affect the rate of Aβ40 aggregation.

To test this hypothesis, we changed our protocol. Instead of adding 10 μM of any Aβ40 preparation in one portion at t = 0, the same total amount of each preparation was added in four freshly prepared aliquots (2.5 μM each) at t = 0, 12, 24, and 36 h. Remarkably, under these conditions, the Zn²⁺-Aβ40 oligomers reduced neuronal survival by 85% ± 3% (Fig. 4e). In contrast, no statistically significant difference was observed between the viability of untreated neurons and those treated with MOPS buffer, Aβ40 fibrils, or 20 μM Zn²⁺. 10 μM Aβ40 caused 20 ± 8% decrease in neuronal viability (p < 0.05), in agreement with many previous observations. Overall, our results indicate that freshly prepared Zn²⁺-Aβ40 oligomers are highly toxic to cultured neurons, induce changes in normal cellular physiology within minutes, and cause neuronal death within hours. Importantly, the apparent toxicity of Zn²⁺-Aβ40 strongly depends on the assembly state of the metastable oligomers, giving weight to their structure-toxicity interplay (Fig. 4 and supplemental Figs. S3, S4, and S6). Although the quasi-spherical Zn²⁺-Aβ40 assemblies (⌀ = 7–15 nm, Fig. 1) were highly toxic, their large aggregates (⌀ ≥ 100 nm, supplemental Fig. S4) were benign.

DISCUSSION
The reported results provide a detailed structure-toxicity study of early-forming, metastable, toxic Zn²⁺-Aβ40 oligomers. Our experiments in primary hippocampal cultures showed that the small Zn²⁺-Aβ40 oligomers inhibited spontaneous neuronal activity and caused neuronal death. Destabilization of neuronal network activity is thought to cause the cognitive impairment associated with AD (39, 40). Dysregulation of [Ca²⁺] is a prominent feature of AD. It is involved both in neuronal excitotoxicity and in apoptosis (41). Our experiments in primary hippocampal neurons showed that the Zn²⁺-Aβ40 oligomers inhibited spontaneous neuronal activity (Fig. 4a–c), induced a time-dependent elevation in basal Ca²⁺ levels (Fig. 4d), and, at later time points, caused neuronal death (Fig. 4e).

The formation of Zn²⁺-Aβ40 oligomers may disrupt Ca²⁺ metabolism and synaptic communication, and persistent insults may contribute to neuronal apoptosis.

The small (7–15 nm) Zn²⁺-Aβ40 assemblies have unique structural characteristics. Our TEM, AFM, CD, and X-ray diffraction data indicate that these oligomers are organized in a cross-β arrangement typical of mature amyloid fibrils (42), yet they exhibit quasi-spherical morphologies characteristic of Aβ oligomers (43). Furthermore, we show that the small quasi-spherical oligomers decrease the rate of fibril growth and, thus, may increase the steady-state concentration of toxic Zn²⁺-free Aβ forms. Our detailed structure-toxicity characterization of the Zn²⁺-Aβ40 oligomers indicates that only the early-forming small (7–15 nm) assemblies are toxic. Upon incubation (>16 h), the initial Zn²⁺-Aβ40 oligomers coalesce into larger structures (supplemental Fig. S4) and concomitantly lose their toxicity (supplemental Fig. S6). Our data provide mechanistic insights into the work of Deshpande et al. (11), who highlighted the role of Zn²⁺ in the formation and accumulation of toxic Aβ oligomers, and of Cuajungco et al. (44), who observed loss of Aβ toxicity upon prolonged incubation with Zn²⁺. Though apparently, Zn²⁺ binding prevents Aβ fibrillogenesis, the toxic behavior of the Zn²⁺-Aβ40 oligomers prepared here is akin to that of Zn²⁺-free Aβ oligomers, which become less toxic upon transformation into fibrils (45, 46).

Similarly to native amylopoploids (23), toxic Zn²⁺-Aβ40 oligomers may be considered off-pathway with regard to fibril formation (14). Other quasi-spherical toxic oligomers exhibiting β-sheet-rich structures have recently been reported for Aβ40 oligomers in the absence of Zn²⁺ (22). These oligomers formed following 30–60 h incubation at 4 °C. In contrast, the Zn²⁺-Aβ40 oligomers reported here were obtained within seconds at room temperature and retained their quasi-spherical morphologies for at least 2 h in serum-free medium. It is tempting to hypothesize that Zn²⁺ binding accelerates formation of oligomers similar to those reported by Chimont et al. (22), although testing this hypothesis will require detailed, side-by-side comparison of the two species.

On the basis of the data obtained here, we propose a structure-kinetic model for Zn²⁺-Aβ40 assembly spanning from the earliest metastable toxic oligomers to aged, benign morphologies (Fig. 5). Fig. 5a presents putative arrangements of Zn²⁺-Aβ40 in mono- to multilayer assemblies rich in β-sheet and

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cross-β assemblies as depicted by our CD, ThT, and x-ray diffraction analyses (Figs. 2 and 3). X-ray diffraction analysis also implies that the major conformation of Aβ40 in the aggregates resembles a hairpin, similar to the one described in Aβ fibrils by Petkova et al. (47, 48). However, our data cannot reveal the super-structural organization of molecules (i.e., symmetry of organization or registry of Aβ40) in multilayered Aβ40 assemblies (Fig. 5a). Combined AFM and x-ray diffraction analyses showed mostly abundant monolayers as well as bilayers and tetralayers but not trilayer arrangements. We propose that monolayers have kinetic and/or thermodynamic preference for arrangement in bilayers, ultimately forming tetralayers, which may be mediated by intermolecular coordination of Zn^{2+} ions (14, 25). This may result in enhanced Aβ40 C-terminal dynamics, as reported recently (49).

We estimate a total number of 20 molecules of Aβ40 in Zn^{2+}-Aβ40 monomeric oligomers (110 Å/4.67 Å) (Fig. 5b), where 110 Å is the average diameter per oligomer derived from TEM (Fig. 1, a and b) and 4.67 Å is the cross-β-sheet distance measured by x-ray powder diffraction (Fig. 2b). Each oligomer is composed of small crystalline assemblies of ~4 Aβ40 molecules, as indicated by the x-ray diffraction analysis. These Zn^{2+}-Aβ40 oligomers are distinct in their three-dimensional structures from analogous, toxic oligomers formed in the absence of Zn^{2+} (43). Fig. 5c presents a comparative scheme of Aβ40 oligomerization pathways in the presence or absence of Zn^{2+}. Metastable Zn^{2+}-Aβ40 oligomers form quasi-spherical mono-, bi-, or tetralayer toxic structures that strongly interfere with fibril formation. Aged Zn^{2+}-Aβ40 oligomers exhibit benign activity, similar to Zn^{2+}-free Aβ40 fibrils, but differ in their morphologies.

In conclusion, our results provide quantitative structural, spectroscopic, and functional analyses of metastable and toxic Zn^{2+}-Aβ40 oligomers in cultured hippocampal neurons. We show that binding of stoichiometric Zn^{2+} concentrations modulates Aβ neurotoxicity via structural organization mechanisms mediated by coordination chemistry. Hence, carefully targeted, Zn^{2+}-specific chelators may be beneficial for treatment of diseases associated with Aβ oligomerization (50–52).

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