Tau excess impairs mitosis and kinesin-5 function, leading to aneuploidy and cell death

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ABSTRACT

In neurodegenerative diseases such as Alzheimer’s disease (AD), cell cycle defects and associated aneuploidy have been described. However, the importance of these defects in the pathophysiology of AD and the underlying mechanistic processes are largely unknown, in particular with respect to the microtubule (MT)-binding protein Tau, which is found in excess in the brain and cerebrospinal fluid of affected individuals. Although it has long been known that Tau is phosphorylated during mitosis to generate a lower affinity for MTs, there is, to our knowledge, no indication that an excess of this protein could affect mitosis. Here, we studied the effect of an excess of human Tau (hTau) protein on cell mitosis in vivo. Using the Drosophila developing wing disc epithelium as a model, we show that an excess of hTau induces a mitotic arrest, with the presence of monopolar spindles. This mitotic defect leads to aneuploidy and apoptotic cell death. We studied the mechanism of action of hTau and found that the MT-binding domain of hTau is responsible for these defects. We also demonstrate that the effects of hTau occur via the inhibition of the function of the kinesin Klp61F, the Drosophila homologue of kinesin-5 (also called Eg5 or KIF11). We finally show that this deleterious effect of hTau is also found in other Drosophila cell types (neuroblasts) and tissues (the developing eye disc), as well as in human HeLa cells. By demonstrating that MT-bound Tau inhibits the Eg5 kinesin and cell mitosis, our work provides a new framework to consider the role of Tau in neurodegenerative diseases.

KEY WORDS: Alzheimer’s disease, Drosophila genetics, Eg5 (KIF11) kinesin, MAPT protein, Neurodegenerative diseases, Aneuploidy

INTRODUCTION

Alzheimer’s disease (AD) is a complex, progressive and irreversible neurodegenerative disease of the brain, and the most common form of dementia in the elderly. Symptoms start when neurons in brain regions involved in memory, cognition and neurogenesis are being damaged and ultimately die. The hallmark pathological lesions of the disease are extracellular senile plaques (SPs) and intraneuronal neurofibrillary tangles (NFTs). Whereas the SPs are composed of the microtubule (MT)-associated protein Tau (MAPT). Within the NFTs, the Tau protein is found hyperphosphorylated, with phosphorylation on many more residues than normally occurs (Grundke-Iqbal et al., 1986). More generally, neurodegenerative disorders with intracellular Tau filamentous deposits are referred to as tauopathies (Delacourte and Buée, 2000; Lee et al., 2001). These include, in addition to AD, progressive supranuclear palsy, corticobasal degeneration, Pick’s disease and argyrophilic grain disease, as well as the inherited frontotemporal dementia and parkinsonism linked to chromosome 17 (FTDP-17). The identification of mutations in Tau as the cause of some of these tauopathies (e.g. FTDP-17 frontotemporal lobar degeneration with Tau inclusions) has further indicated the important role of this protein in neurodegeneration (Frost et al., 2015).

Two decades ago, chromosome missegregation was proposed to be responsible for neurodegeneration in individuals with AD. Indeed, such individuals develop up to 30% aneuploid or polyploid cells both in brain and peripheral tissues, indicating the presence of widespread chromosome partitioning defects (Iourov et al., 2009; Migliore et al., 1997; Mosch et al., 2007; Yurov et al., 2014). Furthermore, the aneuploid and hyperploid neurons that arise in AD are particularly prone to degeneration and could account for 90% of the neuronal loss that characterizes late-stage AD (Arendt et al., 2010). Several causes could explain the excess of aneuploidy in AD brain: (i) lack of aneuploidy clearance during brain development, (ii) an increased propensity for chromosome missegregation during mitosis during development and in the adult or (iii) an aberrant attempt of cell cycle re-entry. The fact that peripheral blood lymphocytes of individuals with AD are prone to undergo aneuploidy spontaneously (Migliore et al., 1997) is in favour of the second hypothesis, i.e. an increased general propensity for chromosome missegregation. Further evidence for the potential involvement of cell cycle defects in AD comes from the fact that both APP and Tau are increasingly phosphorylated during mitosis (Pope et al., 1994, Preuss et al., 1995; Suzuki et al., 1994). This suggests that the physiological regulation of the phosphorylation of these proteins is important for the correct progression of mitosis. In accordance with this idea, it was recently shown that an excess of Aβ can actually induce mitotic spindle defects and consequent aneuploidy (Borysov et al., 2011). Such a deleterious role of an excess of Tau on mitosis was never shown, although recent data show an increased level of aneuploidy in splenic lymphocytes of transgenic mouse models of tauopathies (Rossi et al., 2014). It was also reported that individuals with the TauP301L mutation, which is associated with frontotemporal dementia, had several chromosome aberrations, such as aneuploidies in their fibroblasts and lymphocytes (Rossi et al., 2008), raising the question of the cellular mechanisms involved.

Here, we studied the effect of an excess of human Tau (hTau) protein on cell mitosis in vivo. Using the Drosophila developing
wing disc epithelium as a model, we show that an excess of hTau induces a mitotic arrest, with the presence of monopolar spindles. This mitotic defect leads to aneuploidy and apoptotic cell death. We studied the mechanism of action of hTau and found that the MT-binding domain of hTau is responsible for these defects. We also demonstrate that hTau effects occur via the inhibition of the function of the kinesin Klp61F, the Drosophila homologue of Eg5 (also known as KIF11). We finally show that this deleterious effect of hTau is also found in other cell types (neuroblasts) and tissues (the developing eye disc) as well as in cell culture. Altogether, our results show that an excess of hTau strongly impairs cell division and that this effect involves the hTau domain that binds to MT and the inhibition of Klp61F/Eg5 function.

RESULTS

hTau overexpression in epithelial cells induces mitotic defects

In order to study the effect of hTau on dividing cells, we focused on the Drosophila wing imaginal disc, which consists of one columnar epithelium. During the larval stages, many cell divisions take place in this epithelium as it grows in size to form the future adult wing. We overexpressed hTau, together with GFP, in a specific area of the wing disc (see the GFP staining in Fig. 1A,B and in Fig. S1), using the ptc-Gal4 driver. The hTau transgene that we used in this work is the 0N4R Tau splice variant (Andreadis et al., 1992; Goedert et al., 1989; Kosik et al., 1989), which we tagged with a flag tag at the C-terminus (Fig. S1). We first tested whether an excess of hTau in the ptc expression domain affected the cell cycle by looking at the number of cells undergoing mitosis (PH3-positive cells) in this area. There was a clear increase in PH3 staining in the ptc area (Fig. 1A), as measured by 14±2.1% of PH3-positive pixels in this area, compared to 2.7±0.6% of PH3-positive pixels outside this area within the wing pouch (n=5; P<0.001). This observed excess of cells undergoing mitosis in the presence of hTau could be due either to a change in the cell cycle duration (a shorter cell cycle would result in more cells undergoing mitosis) or to defects in mitosis (mitosis would take longer). We tested the first hypothesis by performing BrdU staining, which labels cells undergoing S phase. We could not see any clear increase in the number of BrdU-positive cells in the ptc domain where hTau is expressed (Fig. 1B), indicating that there is no shortening of the cell cycle duration.

**Tau excess disrupts the mitotic spindle by inducing monopolar spindles**

Hence, there might be a defect in mitosis, which we further studied in detail by looking at the mitotic spindle. We stained mitotic spindles using anti-tubulin antibodies. In normal conditions, cell divisions within the wing disc occur with a planar alignment of the mitotic spindle such that there is symmetric cell cleavage (Fig. 2A-A′ and Fig. S2). Here, in presence of an excess of hTau in the ptc domain, we could not see planar spindles and, in particular, we could only see one pole very clearly (Fig. 2A′). In order to test whether this was due to a change in the spindle orientation, we searched for the other spindle pole in serial confocal sections (Fig. 2B). This other pole was not visible, indicating that these cells actually have monopolar spindles (Fig. 2B). We tested whether this defect could be seen when using different Gal4 lines expressing in different areas of the wing disc. We could see this defect with dpp-Gal4, which expresses hTau in a broader area of the wing (Fig. S3). We could also see this defect when expressing hTau in the whole wing disc with MS1096 as a Gal4 driver (Fig. S3). This indicates that this defect can be observed when hTau is expressed at any place within the wing disc. In conclusion, an excess of human Tau induces a strong alteration of the mitotic spindle, which becomes monopolar.

**Tau excess induces poly and aneuploidy**

We then tested whether this had consequences on chromosome segregation. We looked at the chromosomes by staining them with PH3 and could see that some cells had an increased and...
abnormal number of chromosomes (Fig. 2C). Indeed, because imaginal disc cells are diploid (Fuse et al., 1994), the maximum number of chromosomes should be eight (four chromosomes segregating in each daughter cell). In the presence of hTau excess, several cells contained largely more than eight chromosomes. One example is shown in detail in Fig. 2C, in which chromosomes were counted one by one, with a spindle that seems mis-oriented compared to dividing cells present outside the ptc area (A”), because only one spindle pole is clearly visible in a confocal section. Scale bars: 30 µm in A, and 10 µm in A’-A”. (B) A z-series of confocal sections of the ptc area shows that the opposite spindle pole of hTau-overexpressing cells is never visible (see putative positions of opposite pole indicated by arrowheads for two selected cells). This indicates that these cells actually display abnormal monopolar spindles. Scale bar: 10 µm. (C) Immunostainings of mitotic spindles and mitotic chromosomes in third instar larval wing discs overexpressing hTau protein 0N4R in the ptc domain: Tubulin (green), PH3 (red) and phalloidin (blue). Left panel: the ptc area (delimited by dotted lines) contains many large cells with monopolar spindles and PH3-positive chromosomes. Middle panel: a higher magnification of the ptc area shows that those large cells with monopolar spindles contain a high number of chromosomes. Outside the ptc area are cells dividing normally (arrows), with a normal content of chromosomes. Right panels: a z-series of confocal sections of one cell within the ptc area (see arrowhead in the middle panel) allows the precise counting of chromosomes, each new chromosome on the next z-section being highlighted by a white star: the total number of chromosomes for the studied cell is 20, a number much larger that the eight chromosomes expected from a single DNA replication of the four Drosophila chromosomes. Scale bars: 20 µm in the left panel and 10 µm in the middle and right panels. These experiments were replicated at least three times in the laboratory.

abnormal number of chromosomes (Fig. 2C). Indeed, because imaginal disc cells are diploid (Fuse et al., 1994), the maximum number of chromosomes should be eight (four chromosomes segregating in each daughter cell). In the presence of hTau excess, several cells contained largely more than eight chromosomes. One example is shown in detail in Fig. 2C, in which chromosomes were counted one by one (each new chromosome that is visible on the next focal plane is labelled with a star). For the selected cell, the total number of chromosomes was 20. Knowing that there is no particular change in S phase, as assessed by BrdU staining, this indicates that some cells are mitotically blocked, but have undergone new S phase. The fact that the number of chromosomes is variable and is not a factor of four could be explained by the presence of some cytokinesis occurring in cells with an abnormal spindle, which would lead to daughter cells with an abnormal number of chromosomes. It is known that aneuploidy often leads to apoptotic cell death (Peterson et al., 2012). Also, it has been shown that defective alignment of the mitotic spindle in the wing disc correlates with cell delamination and apoptotic death at the basal face of the disc (Nakajima et al., 2013). Hence, if cytokinesis occurs in cells with a misaligned monopolar spindle, the most basal daughter cell will probably undergo apoptotic cell death. To see whether such cell death occurred in the hTau-overexpressing domain, we looked at transverse z-sections of the wing disc. We could indeed see apoptotic fragments of nuclei, as stained with DAPI, specifically

Fig. 2. hTau overexpression induces monopolar spindles and chromosomal aneuploidy. (A,B) Immunostainings of mitotic spindles in third instar larval wing discs overexpressing human Tau (hTau) protein 0N4R in the ptc domain: Tubulin (green), hTau (red) and phalloidin (blue). (A) Cells within the ptc domain are large, like dividing cells outside the ptc area, as seen with the phalloidin staining at low magnification. A higher magnification of the ptc area (A’) shows that those large cells correspond to mitotic cells, with a spindle that seems mis-oriented compared to dividing cells present outside the ptc area (A”), because only one spindle pole is clearly visible in a confocal section. Scale bars: 30 µm in A, and 10 µm in A’,A”. (B) A z-series of confocal sections of the ptc area shows that the opposite spindle pole of hTau-overexpressing cells is never visible (see putative positions of opposite pole indicated by arrowheads for two selected cells). This indicates that these cells actually display abnormal monopolar spindles. Scale bar: 10 µm. (C) Immunostainings of mitotic spindles and mitotic chromosomes in third instar larval wing discs overexpressing hTau protein 0N4R in the ptc domain: Tubulin (green), PH3 (red) and phalloidin (blue). Left panel: the ptc area (delimited by dotted lines) contains many large cells with monopolar spindles and PH3-positive chromosomes. Middle panel: a higher magnification of the ptc area shows that those large cells with monopolar spindles contain a high number of chromosomes. Outside the ptc area are cells dividing normally (arrows), with a normal content of chromosomes. Right panels: a z-series of confocal sections of one cell within the ptc area (see arrowhead in the middle panel) allows the precise counting of chromosomes, each new chromosome on the next z-section being highlighted by a white star: the total number of chromosomes for the studied cell is 20, a number much larger that the eight chromosomes expected from a single DNA replication of the four Drosophila chromosomes. Scale bars: 20 µm in the left panel and 10 µm in the middle and right panels. These experiments were replicated at least three times in the laboratory.
Protein domain of hTau is responsible for mitotic arrest

To get insight into the molecular mechanisms involved, and whether hTau binding to MTs was important for this effect, we tested which protein domain of hTau is responsible for this defect. hTau has different protein domains and can be subdivided into four regions: an N-terminal projection region, a proline-rich domain, an MT-binding domain (MBD) consisting of either three or four tandem repeat sequences (depending on alternative splicing) and a C-terminal region (Mandelkow et al., 1996). Tau’s ability to bind MTs depends on the MBD as well as on adjacent regions (Gustke et al., 1994). More precisely, the repeat sequences within the MBD are thought to directly bind MTs through their positive net charge, which interacts with negatively charged residues in tubulin (Jho et al., 2010; Kar et al., 2003). Here, we constructed two partial sequences of hTau (Fig. 3A), one consisting of the N-terminal half of the protein, including the proline-rich domain (hTau-Nter1-193) and one consisting of the C-terminal half of the protein (hTau-Cter141-383), including part of the proline-rich domain, which was shown to be required for proper MT-binding of the MBD (Elie et al., 2015). Hence, only the C-terminal construct can bind to MTs. Transgenic lines were obtained with both constructs inserted at the same genomic position as was the full-length hTau transgene, in order to obtain a similar level of transgene expression. Also, all constructs, including wild-type hTau, are flag-tagged in the C-terminal, enabling determination of expression level (Fig. S4). We tested the effect of both constructs, by expressing them with the ptc-Gal4 driver. When looking at adult wings, we could see that only the C-terminal domain induced a wing defect like that seen when overexpressing the full-length hTau (Fig. 4B-D). We further looked at larval wing discs overexpressing the C-terminal of hTau and could see the same monopolar spindle defects as those seen with full-length hTau (Fig. 4E). This suggests that hTau binding to MTs might be the cause of these spindle defects. We further verified this hypothesis by comparing the effect of two different full-length hTau transgenes, hTauS2A and hTauS11A. The corresponding hTau proteins are mutated on different phosphorylation sites and are known to differ in their ability to bind MTs (Chatterjee et al., 2009): contrarily to hTauS11A, the hTauS2A protein, which bears mutations within the MBD only, binds weakly to MTs. Hence, compared to hTauS11A, the expression of hTauS2A should be less deleterious for mitosis if MT binding is required for the effect of hTau. When expressed in the whole wing discs (Fig. S5), we observed abnormal mitosis with monopolar spindles in the presence of hTauS11A, as we previously noticed with wild-type hTau. Interestingly, there was no obvious defect in mitosis in the presence of an excess of hTauS2A (Fig. S5). This further confirms the importance of hTau binding to MTs as being the cause of the observed mitotic defects. hTau binding to MTs could affect mitosis in different ways: either hTau would overstabilize MTs and disrupt their normal dynamics during mitosis, or hTau would interfere with the function of other MT-binding proteins such as kinesins, which are important for normal cell division. In particular, hTau was shown to induce MT release from both kinesin-1 and Eg5 in gliding assays (Dixit et al., 2008; Ma et al., 2011). In addition, when testing the importance of more than 20 kinesin genes for cell division in Drosophila S2 cells (Goshima and Vale, 2003), it has been shown that loss of function of Klpl0A, Ncd, Klp67A or Klp61F/Eg5 cause monopolar spindles, which is reminiscent of what we observed in wing discs overexpressing hTau.

hTau C-terminal microtubule-binding domain is responsible for hTau-induced mitotic arrest

In order to investigate the hypothesis of hTau affecting kinesin function during mitosis, we looked at whether these specific kinesins...
are actually important for spindle dynamics in the wing disc. We tested the consequences of RNA interference (RNAi)-induced loss of function of these kinesins, using the MS1096 driver (Fig. 5A and Fig. S6). Similarly to what is observed in the presence of hTau overexpression, we observed enlarged cells with monopolar spindles in wing discs expressing RNAi for Klp61F/Eg5 (Fig. 5A). We did not detect such a phenotype in wing discs expressing RNAi for Klp10A, Ncd or Klp67A (Fig. 5A and Fig. S6). This result suggests that hTau excess might actually inhibit mitosis in the wing disc by inhibiting the function of the Klp61F/Eg5 kinesin. This Klp61F/Eg5 kinesin is a plus-end-directed tetrameric kinesin. Its antiparallel tetrameric organization is fundamentally different from the majority of other kinesins that are dimers, such as the well-characterized conventional kinesin-1. Because it is able to slide apart bundles of anti-parallel oriented MTs, this kinesin plays an important role during mitosis. In particular, it is important for the separation of duplicated centrosomes and their positioning at opposite poles of the dividing cells. In klp61F mutants, the centrosomes of dividing cells fail to migrate at each pole of the cell and are found adjacent to each other (Sharp et al., 1999). If hTau excess actually impairs mitosis by inhibiting Klp61F/Eg5 function, we should also see such defects of centrosome migration. We tested this by comparing centrosome position in wing discs expressing either hTau in excess or a Klp61F RNAi construct in the ptc area. Both conditions gave the same phenotype: cells within the ptc area displayed monopolar spindles with duplicated and unseparated centrosomes (Fig. 5B-C). This result further suggests that hTau blocking of mitosis might occur via Klp61F inhibition. We then tested whether we could find this negative interaction between hTau and Klp61F by genetic means.

Genetic interaction between Klp61F/Eg5 and hTau
We tested for a negative interaction between hTau and Klp61F, looking at adult wings obtained from individuals overexpressing hTau within the ptc area. In these conditions, the L3-L4 intervein area is reduced because of the important cell death that occurs consecutively to the mitotic blocking induced by hTau. We tested whether loss of one copy of the Klp61F gene could accentuate the hTau-induced reduction in intervein size. This was indeed the case, as shown in Fig. 6A. This genetic interaction further suggests that hTau-induced defects are the consequences of Klp61F/Eg5 inhibition and raises the question of the molecular mechanisms involved. Because previous work showed that hTau could induce MT release from Eg5 in gliding assays (Ma et al., 2011), we tested whether the hTau effect in the wing disc could actually be the consequence of Klp61F/Eg5 detachment from MTs.

**Fig. 4. Adult wing phenotypes induced by full-length or truncated hTau expression with ptc-Gal4 and their correlation with the presence of monopolar spindles at the larval stage.** (A) Description of the different 0N4R hTau constructs used. (B) Representative adult wing images from control (ptc/+) and flies overexpressing full-length 0N4R hTau (ptc>hTau): the L3-L4 intervein, where lies the domain of ptc-Gal4 expression, is smaller in presence of hTau. Higher magnification of the wing margin highlights this difference and also shows mis-oriented cell hairs near L4. (C) Representative adult wing images from flies overexpressing hTau-Nter (ptc>hTau-Nter) or hTau-Cter (ptc>hTau-Cter): the L3-L4 intervein size is unchanged in the presence of hTau-Nter, but is reduced in the presence of hTau-Cter. Higher magnification of the wing margin highlights the phenotypes and also shows mis-oriented cell hairs near L4 in the presence of hTau-Cter, similarly to what is seen with full-length hTau. (D) Quantification of the L3-L4 intervein size (margin), showing that overexpression of hTau-Cter gives the same significant phenotype as overexpression of full-length hTau (data expressed in % of control genotype). Histogram shows mean values±s.e.m. for the set of measurements. The number of wings measured for each genotype is indicated at the bottom of each histogram bar. Two-tailed Student’s t-test was performed to compare mutant genotypes with the control genotype. ***P<0.001. (E) Representative immunostaining of mitotic spindles in third instar larval wing discs overexpressing hTau-Cter in the ptc domain: Tubulin (green) and phalloidin (red). Similarly to what is observed in the presence of full-length hTau, the expression of hTau-Cter induces monopolar spindles in the ptc domain of expression. Scale bar for the top panels of E is 50 µm and 10 µm for the bottom panels. These experiments analyzing adult wing phenotypes were replicated at least three times, giving the same phenotypes. Corresponding measurements were made twice.
Klp61F/Eg5 localization is modified in the presence of an excess of hTau

The mechanism of interaction between Klp61F/Eg5 and hTau might be similar to the one described by Dixit et al. for kinesin-1 and hTau: kinesin-1 movement along MTs is stopped when encountering Tau protein bound to MTs, and this leads to the detachment of kinesin-1 from MTs (Dixit et al., 2008). If the situation were similar for Klp61F/Eg5, we should see less Klp61F/Eg5 bound to MTs during mitosis in the presence of hTau. We tested this by comparing Klp61F localization in dividing cells overexpressing mGFP or hTau or Klp61F-RNAi or Klp10A-RNAi in the whole wing pouch with the driver MS1096: Tubulin (green) and phalloidin (magenta). Left panel: control wing disc (with the expression of mGFP) shows no defects in cell division (some normal divisions are indicated by arrows). Middle left panel: when hTau is overexpressed with MS1096, many cells are blocked in mitosis with monopolar spindles (arrowheads). Middle right panel: when Klp61F expression is reduced in the whole wing disc by RNAi, there are many cells blocked in mitosis with monopolar spindles (arrowheads), a phenotype similar to the one obtained with hTau overexpression. Right panel: when Klp10A expression is reduced in the whole wing-disc by RNAi, there is no mitosis blocking with monopolar spindle and many normal cell divisions are present (see arrows).

hTau excess also affects mitosis in neuronal tissues

The question is now open to see whether such an effect of hTau excess in mitosis can be found in other tissues than the wing disc epithelium. To answer this question, and to focus on neuronal tissues, we first looked at whether hTau excess induced mitotic defects in another imaginal disc, the eye disc. This tissue gives rise to photoreceptors, which are neuronal cells. The cell division pattern within the eye disc is more complex than within the wing disc, with the presence of a morphogenetic furrow associated with two mitotic waves. It is known that inhibition of cell division within the eye disc (i.e. the second mitotic wave using the GMR promoter) leads to loss of bristles, fusion of ommatidias and eye roughness (Morris et al., 2001). Here, we tested whether the known eye roughness induced by overexpression of hTau in the developing eye disc with the GMR-Gal4 driver (Jackson et al., 2002; Wittmann et al., 2001) is due to Klp61F-related cell cycle defects. We tested whether loss of one copy of the klp61F
gene increased the eye phenotype. The expression of one dose of our hTau transgene gave a mild eye phenotype with only bristles missing, and almost no ommatidial disorganization (Fig. 7A, B), whereas the expression of two copies of the hTau transgene led to a stronger phenotype, with more bristles missing and ommatidial disorganization at the posterior side of the eye (Fig. 7C). Loss of one copy of klp61F in the presence of one dose of hTau leads to a phenotype that is similar to, and even stronger than, the one observed with two copies of the hTau transgene (Fig. 7D, E). This confirms the genetic interaction observed when expressing hTau in the wing disc. We further tested whether overexpression of Klp61F-GFP under the ubiquitin promoter could rescue the bristle phenotype observed in the presence of one copy of the hTau transgene. This was indeed the case, with almost no bristles missing in this genetic condition (Fig. 7F). Also, the MBD of hTau, but not the N-terminal projection domain, induced the same eye phenotype as full-length hTau (Fig. S8), as was expected from their effect on mitosis in the wing disc. Altogether, these results provide evidence that the effect of hTau on cell division, through Klp61F dysfunction, can also be found in the eye disc.

To further study the effect of hTau on mitosis in neuronal tissues, we focused on dividing neuroblasts in the larval brain. Note that it was previously shown that klp61F mutants presented mitotic defects in neuroblasts, with monopolar spindles and clear aneuploidy (Heck et al., 1993). We used the pan-neuroblast 1407 Gal4 driver (Luo et al., 1994) to overexpress hTau in neuroblasts and see whether this led to mitosis arrest with monopolar spindles and chromosome aneuploidy. We could indeed see these defects when comparing control brains (Fig. 7G) with brains overexpressing hTau (Fig. 7H): abnormal mitosis with monopolar spindles and chromosomal aberrations could only be seen in the
presence of hTau. This indicates that the toxic effect of hTau on mitosis is not specific to epithelial cells from imaginal discs but can also be found in dividing precursors of the central nervous system.

The interaction between Tau and Klp61F/Eg5 is conserved between Drosophila and humans

Altogether, our results indicate that hTau can inhibit Klp61F function in Drosophila cells. Although it was previously shown that hTau could actually inhibit Eg5 function in vitro (Ma et al., 2011), we further wanted to test whether this was indeed the case in human cells. Hence, we tested whether the expression of hTau in HeLa cells could actually enhance the monopolar spindle phenotype previously reported when Eg5 expression was inhibited with siRNAs (Zhu et al., 2005). Using siRNAs targeting Eg5 at increasing doses, we observed an increasing percentage of monopolar spindles among mitotic (PH3-positive) cells (Fig. 8A). There was no significant increase of mitotic cells with monopolar spindles when using control mutated siRNAs (Fig. 8A). When additionally transfecting hTau onto cells treated with the lowest doses of siRNA, we found an increase in the percentage of monopolar spindles, which was not the case in conditions using control siRNAs (Fig. 8B,C). This indicates that the presence of an excess of hTau actually enhances the defects induced by Eg5 knockdown, confirming that the interaction between hTau and Klp61F/Eg5 observed either in vitro or in Drosophila can also be detected in human cell lines.

Reciprocally, we tested whether the mitotic blockade induced by hTau in Drosophila dividing cells could also be induced by an excess of Drosophila Tau. When we overexpressed Drosophila Tau in the wing disc in the same conditions as hTau, we could also detect mitotic defects with monopolar spindles as well as a reduction of the wing size (Fig. S9). In addition, we found the same genetic interaction with Klp61F as seen between Klp61F and hTau (Fig. S9). This indicates that the interaction between Tau and Klp61F/Eg5 is conserved among species.

DISCUSSION

Here, we report for the first time that an excess of hTau in dividing cells leads to a mitotic arrest of these cells, associated with the presence of monopolar spindles, aneuploidy and cell death. hTau protein has two paralogous proteins in vertebrates, namely MAP2 (preferentially localized in the somatodendritic compartment of neurons) and MAP4, which is rather ubiquitously expressed (Morris et al., 2011). All of them are highly conserved in the sequence of their MBD (Dehmelt and
Halpain, 2005). A negative effect of MAP4 on mitosis was previously reported (Holmfeldt et al., 2003): when transiently induced in human K562 erythroleukemia cells, DG75 Burkitt’s lymphoma cells or Jurkat acute T-cells leukemia, MAP4 induced mitotic arrest with the presence of monopolar spindles. This conserved effect between MAP4 and hTau in blocking mitosis is in accordance with the implication of the MT-binding repeats, which are the most conserved sequences between the two proteins. It is surprising that this effect on mitosis was never reported for the protein hTau when transfected in cells in culture, considering the number of publications and teams having performed these experiments (Frost et al., 2015; Morris et al., 2011). One reason could be that very few studies actually focused on mitosis and the mitotic spindle in the presence of an excess of hTau. A recent study focused on the effect of an excess of Tau on S phase: there was no significant effect for all hTau isoforms tested, except a 10% reduction in S phase observed with an excess of the 1N3R isoform (Li et al., 2015). In our hands, using HeLa cells, we used low concentrations of hTau plasmid and could not detect any change in the amount of cell divisions with monopolar spindles at these concentrations. In addition, there is a negative correlation between the presence of hTau and the number of dividing cells visible within the well. The causes might be that hTau-expressing cells die before dividing or that hTau-expressing cells stay in the G0 or quiescent phase and do not enter the cell cycle. Thus, specific transient expression conditions would be required to observe hTau-induced mitotic blocking in culture before cell death or quiescence occurs.

Our study is, to our knowledge, the first one describing transgenic flies with transgenes expressing fragments of hTau, all inserted at the same genomic position using the PhiC31 integrase system (Bischof et al., 2007), with the aim to reduce the differential positional effects for each transgene and to be able to compare the phenotypes obtained between each transgene. Getting rid of positional effects was indeed shown to be particularly important when comparing the severity of phenotypes for full-length hTau overexpression (Povellato et al., 2014). We were thus able to show that the expression of the C-terminal half of hTau (141-383) was able, on its own, to induce the same mitotic blocking and the same adult wing or eye phenotype than the expression of full-length hTau overexpression (Povellato et al., 2014). We were thus able to show that the expression of the C-terminal part of 2N4R hTau (1-193) had no effect on mitosis and no wing or eye phenotype. This led us to conclude that hTau effect might be due to its binding to MTs. These results are in accordance with the recently published paper from Geng et al., in which hTau transgens were randomly inserted within the genome and the level of protein expression estimated by western blot (Geng et al., 2015). This study showed that GMR-driven expression of the C-terminal part of 2N4R hTau (231-441), which corresponds to the region 127-383 of 0N4R hTau, induced the same rough-eye phenotype as the GMR-induced expression of full-length 2N4R hTau protein. Altogether, this confirms the importance of the C-terminal moiety of hTau in the cellular toxicity of this protein.

Our description of the deleterious role of hTau on the mitotic spindle makes sense when considering the previously published results indicating that hTau is phosphorylated during mitosis.
Remarkably, hTau is phosphorylated, during mitosis, such as to give the same immunoreactive pattern as hyperphosphorylated ‘pathological’ Tau in AD, using the antibodies anti-AT8, -Tau-1, -T46 and -PHF-1 (Preuss et al., 1995). Some of the phosphorylated residues are T153, T181, S202/205, T212/217 and S214, the latter having been shown to be important for MT binding of Tau (Iellenberger et al., 1998). This hTau phosphorylation is associated to a change in protein localization: during mitosis, a substantial fraction of hTau is not bound to MTs, but retained in the cytoplasm. These results are in accordance with the idea that hTau binding to MTs is deleterious for mitosis, and that normal cellular physiology phosphorylates Tau during mitosis such as to avoid the mitotic blocking that we describe here. Whether mutating these phosphorylation sites would increase hTau-induced mitotic defects is an open question. Indeed, many mutations of Ser or Thr residues in Ala (either alone, or in combination) of hTau were tested for their deleterious effect when expressed in the Drosophila eye (Chatterjee et al., 2009; Fulga et al., 2007; Pavelli et al., 2014; Steinhilb et al., 2007a,b) or in other tissues (Ubhi et al., 2007). The obtained results suggested that many phosphorylation sites within hTau could compensate for the mutation of one or several sites normally phosphorylated during mitosis. This functional redundancy demonstrates how physiologically important Tau phosphorylation is for normal cell biology. Note that S262 and S356, which are mutated in hTauS2A, are not residues strongly phosphorylated during mitosis (Iellenberger et al., 1998). Hence, apart from being useful to correlate mitotic defects with hTau binding to MTs, this mutated construct has no relevance to the matter of endogenous phosphorylation of hTau during mitosis.

Our results show the presence of aneuploidy/hyperploidy in cells overexpressing hTau. This and other results are in favour of the chromosome missegregation/MT dysfunction hypothesis of AD, with the idea that, over a lifetime, defective mitoses lead to the accumulation of aneuploid cells throughout the body, including the brain, and that these aneuploid cells are more prone to neurodegeneration (Potter, 1991). These defective mitoses could occur during embryonic neurogenesis, or during adult neurogenesis. It is known that there is some constitutional polyploidy derived from chromosome missegregation during mitosis in neuronal progenitor cells (Iourov et al., 2009; Mosch et al., 2007): one study showed that about 10% of neurons from the entorhinal cortex have a DNA content between 2n and 4n in normal adult brains, while being negative for cyclin B1 staining (i.e. they were not undergoing an S-G2 transition phase) (Mosch et al., 2007). Several studies reported increased aneuploidy in the brain as well as in peripheral cells of individuals with AD (Iourov et al., 2009; Migliore et al., 1997; Mosch et al., 2007; Yurov et al., 2014). For example, Mosch et al. (2007) reported that individuals with AD had 20% of polyploid, cyclin-B1-negative neurons in the entorhinal cortex, raising the question of the mechanisms responsible for the increase in this population of neurons. Increased neuronal polyploidy was also observed in transgenic mice with mutated hTau (Rossi et al., 2014), as well as in APP and PS1 mouse models (Boeras et al., 2008; Granic et al., 2010). There are two hypotheses explaining this increase: the first one being that neurons undergo new S phase during the course of the disease, especially during aging; the second one being that neurogenesis (embryonic, adult or both) is affected, leading to daughter cells with missegregation of chromosomes. Our data support the second hypothesis.

Interestingly, the amyloid Aβ1-42 peptide was also shown to disrupt the mitotic spindle (Borysov et al., 2011), although differently compared to the phenotypes we observed with hTau: incubation of Xenopus egg extracts with Aβ1-42 peptide induced shorter or bent mitotic spindles. This phenotype was rescued when adding recombinant motor domains of Eg5, KIF4A or MCAK. Similarly to what we show here, the effect of Aβ1-42 was shown to be due to its localization to the spindle and its interference with the normal association of Eg5, KIF4A and, to a lesser degree, MCAK. In our study, we focused only on kinesins, which generated a ‘monopolar spindle’ phenotype when knocked down in S2 cells (Klp10A/KIF2, Klp67A/KIF18, Klp61F/Eg5/KIF11 and Ncd/KIFC1) (Goshima and Vale, 2003). We found that Klp61F/Eg5 was the only one giving, when inhibited in the wing disc, a phenotype similar to hTau overexpression. Similarly, from these four kinesins, only Eg5/KIF11 and KIF2 gave monopolar spindles when its expression was inhibited with siRNA in HeLa cells (Zhu et al., 2005). Also, Klp61F was found as an enhancer of hTau toxicity from a genetic screen performed in the Drosophila eye: a P-element mutant (different from the mutant we used) of Klp61F enhanced the eye phenotype induced by overexpression of 2N4R hTau (Ambegaokar and Jackson, 2011). This independent result allows the generalization of our conclusions to the different isoforms of Tau, in accordance with the fact that mitosis blocking is observed with the C-terminal part of hTau only. In conclusion, our results, together with the previous biochemical demonstration that hTau affects Eg5 function on MTs (Dixit et al., 2008; Ma et al., 2011), indicate that the hTau defect in vivo is, at least partly, due to interference with Klp61F/Eg5 normal function. Hence, Aβ- and Tau-induced defects both converge on Eg5 dysfunction. The importance of Eg5 dysfunction might be related to the fact that, from the different kinesins we considered, only Eg5/KIF11 lies in a genetic region associated with increased risk for AD (Ertken-Taner et al., 2004; Feuk et al., 2005; Prince et al., 2003; Reitz et al., 2012). Altogether, this suggests that Eg5/KIF11 dysfunction might play a role in AD and that protecting or increasing the activity of this kinesin could be one strategy to consider in order to modify the progression of the disease.

Because AD is not generally considered as a developmental disease, i.e. as a disease appearing in the aged individual as a consequence of developmental defects occurring during the division of neuronal precursors, but as a disease resulting from the aging and degeneration of post-mitotic neurons, it is important to also consider the Tau-Eg5 interaction in post-mitotic neurons. The study of Eg5 expression and localization in the brain did show that Eg5 was highly expressed during embryonic development, but was also found in the adult brain (Ferhat et al., 1998; Lin et al., 2011). In particular, it was found at higher levels in hippocampal neurons compared to sympathetic neurons (Ferhat et al., 1998). Two pieces of evidence suggest that Eg5 plays a role in intracellular transport or synaptic plasticity in post-mitotic neurons. The first one is that an excess of β-amyloid peptide reduces transport of neurotransphin and neurotransmitter receptors to the cell surface, via the inhibition of Eg5 function (Ari et al., 2014). In addition, inhibition of Eg5 with monastrol affects long-term potentiation (Ari et al., 2014). The second one is that Eg5 directly interacts with ZBP1, a protein involved in the transport of messenger ribonucleoproteins (mRNPs), resulting in abnormal transport of β-actin mRNA (Song et al., 2015). Knowing the importance of the actin cytoskeleton in synaptic plasticity processes (Bellot et al., 2014), this is another indication of a potential role of Eg5 in adult and aging post-mitotic neurons, which might be affected by the excess of Tau observed in individuals with AD.
In conclusion, our work, by demonstrating that MT-bound Tau inhibits kinesin-5 and cell mitosis, provides a new framework to consider the role of an excess of Tau either during neurogenesis or in unknown Eg5-dependent processes in post-mitotic neurons.

MATERIALS AND METHODS

Fly stocks
We used the following Gal4 activator strains: ptc-Gal4, dp-β-Gal4, MS1096-Gal4, GMR-Gal4 (gifts from Sophie Layalle, IGF, Montpellier, France) and 1407-Gal4 inscutable (ins)g4 (FBSt008751).

For the visualization of expression domains, we used a UAS-mCD8-GFP strain (FBSt0005137) and, for the visualization of the localization of Klp61F protein, the Ubi-Klp61F:GFP strains (FBSt0035509 and FBSt0035510). To test genetic interactions with Klp61F, we used the loss-of-function mutant Klp61Fv110355 (FBSt0035508). The UAS-hTauv225 (FBSt0051365) and UAS-hTaus11x (FBSt0051366) strains were used to confirm the importance of Tau binding to MTs in the studied phenotypes. All these lines were obtained from the Bloomington Drosophila Stock Center.

For RNAi experiments, we used lines obtained from the Vienna Drosophila RNAi Center (Dietzl et al., 2007) containing an RNAi construct targeting the following genes: Klp61F (v109280, v52105), ncd (v110355, v22570), Klp104a (v41534) or Klp67A (v108852, v52105).

In order to overexpress Drosophila Tau, the UAS-dtau strain was a gift from E. Skoulakis (Mershin et al., 2004).

Third instar larval larvae were used independently of their sex, except for crosses with the MS1096 driver (on the X chromosome), for which we selected males. Adults aged between 2 and 10 days old were selected for analysis of wing size and eye phenotypes. The phenotypes were similar in selected males. Adults aged between 2 and 10 days old were selected for MS1096 crosses with the from E. Skoulakis (Mershin et al., 2004).

(Continued)
GFP staining) and outside the ptc domain, with the ImageJ software. Total PH3-positive area was then divided by the size of the domain considered. Student’s t-test was performed to compare the percentages between the two domains. For the measurement of differences in wing size, sample size was calculated based on the measured standard deviation (4.7 for a mean of 100 for the control genotype) such as to be able to detect a 5% variation of wing size with a type I error of 5% and a power of 80%; 14 wings had to be measured. Measurements were made blind of the genotype and, after testing for normality, Student’s t-test was performed to compare the control and mutant genotypes. For the measurement of differences in the proportion of dividing cells with monopolar spindles, sample size was arbitrarily set up at minimum 30 dividing cells for the dose-response curves with increasing amounts of Eg5 siRNA. With this size, it was possible to detect an increase of the percentage of monopolar cells ranging from 5 to 80%. We used the same sample size to perform the dose-response curve with increasing concentrations of control siRNA and to test for the effect of co-transfection with ΔTau. Images of cells were taken randomly within the slide, scanning the slide, looking at PH3-positive spots and then taking pictures of the tubulin staining in order to see the spindle. Statistical tests used are chi-2 tests.

This article is part of a subject collection on Spotlight on Drosophila: Translational Impact. See related articles in this collection at http://dmm.biologists.org/lookup/collection/drosophila-disease-model.

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References


