

Tubulin post-translational modifications in developing dog primary neurons obtained with methods according to the 3Rs principles

Questa è la versione Post print del seguente articolo:

Original

Tubulin post-translational modifications in developing dog primary neurons obtained with methods according to the 3Rs principles / Gadau, Sergio Domenico. - In: RESEARCH IN VETERINARY SCIENCE. - ISSN 0034-5288. - 122:(2019), pp. 56-63. [10.1016/j.rvsc.2018.11.015]

Availability:

This version is available at: 11388/217635 since: 2022-05-23T15:40:40Z

Publisher:

Published

DOI:10.1016/j.rvsc.2018.11.015

Terms of use:

Chiunque può accedere liberamente al full text dei lavori resi disponibili come "Open Access".

Publisher copyright

note finali coverpage

(Article begins on next page)

Tubulin post-translational modifications in developing dog primary neurons obtained with methods according to the 3Rs principles

Sergio Domenico Gadau*

Department of Veterinary Medicine, University of Sassari, Via Vienna 2, 07100, Italy

* Corresponding author.

E-mail address: sgadau@uniss.it.

<https://doi.org/10.1016/j.rvsc.2018.11.015>

Received 30 May 2018; Received in revised form 19 October 2018; Accepted 12 November 2018

ABSTRACT

Microtubules play a crucial role during neuronal morphogenesis regulating many functions. In the study of these phenomena in vitro cellular models have been employed, mainly resorting to housed experimental animals. Among alternative models in neurobiological study, recently dog caught particular attention. In fact, the complexity of the canine brain, the lifelong span and the neurodegenerative pathologies render the dog a species closer to humans than rodents. Lately, growing interest in the limitation of the use of experimental animals, has stimulated the search for alternative experimental protocols. Starting from fetal dog brain, obtained by alternative way of sampling, we set neuronal primary cultures. Through immunofluorescence, we examined the presence and the cellular distribution of tubulin post-translational modifications as tyrosinated and acetylated α - tubulin, as markers of dynamic and stable microtubule respectively. In addition, we evaluated the pattern of two associated proteins which may slide on these two tubulin modifications, i.e. CLIP-170 and Kinesin-1. A clear positivity for tyrosinated and acetylated α -tubulin, was found. As far as the motor proteins are concerned, we detected a prevalence of CLIP-170 compared to kinesin-1 with a better overlapping between tyrosinated α - tubulin and CLIP-170. Our findings highlighted some original data about the role of the microtubular network during early phases of canine neuronal morphogenesis. In addition, the experimental protocol underlined the utility of this alternative model that allows to bypass both the scarcity of commercial canine neuronal cell lines and the need to resort to experimental dogs, respecting the 3Rs principles (reduction, refinement, and re- placement).

Keywords:

Tubulin post-translational modifications; Neuronal morphogenesis; Dog Primary neuronal culture; 3Rs principles

1. Introduction

Microtubules (MTs), cellular polymers composed by the assembly of α - and β -tubulin heterodimers, may exhibit a high complexity and crucial importance in neurons which are involved in cargo trafficking, neuronal polarization and morphogenesis during the early phases of neurogenesis (Janke and Kneussel, 2010). These functions are made possible thanks to at least three main MTs patterns: i) the presence of different encoded isoforms; ii) the action of specific motor proteins associated with them (MAPs); iii) several post-translational modifications (PTMs) generating on a microtubule a complexity of signals that known as tubulin code (Janke, 2014; Gadadhar et al., 2017). Tubulin PTMs include acetylation, tyrosination, detyrosination, Delta 2 ($\Delta 2$) modification, polyglutamylation, polyglycylation, palmitoylation, and phosphorylation (Song and Brady, 2015; Magiera and Janke, 2014; Westermann and Weber, 2003). Most of PTMs take place in the carboxy-terminal tubulin tail and seem to affect the α -tubulin (acetylation, tyrosination/detyrosination and $\Delta 2$ modification), whereas glutamylation glycylation may target both α - and β -tubulin (Li and Yang, 2015). In addition, some PTMs are more present on stable MTs (acetylation, detyrosination and $\Delta 2$ modification), whereas others, like tyrosination, feature on more recent and more dynamic MTs (Fukushima et al., 2009). Among other, the role of PTMs seems to be crucial during the neuronal morphogenesis. Indeed, although it was thought that MTs had a secondary role in neurogenesis for several years, it is now established which MTs are essential regulators of neuronal morphogenesis phenomena (Poulain and Sobel, 2010; Yu et al., 2001). It seems to be now asserted that axonogenesis and dendritogenesis, the essential processes by which neurons acquire their typical functional morphology, comes into play with a mix of stable and dynamic MTs (Burnette et al., 2008; Shea, 1999). Moreover, at this stage, the activity of MTs is regulated by a large number of associated proteins (MAPs), some of which may characterize the plus end of the most dynamic microtubules (like CLIP-170) while others such as the motor protein Kinesin-1, prefer to associate with stable microtubules (Galjart, 2010; Reed et al., 2006; Witte et al., 2008; Gomis-Ruth et al., 2008; Hammond et al., 2010; Verhey and Hammond, 2009). Many of the advances in the study of neurogenesis have been made possible by the use of in vitro experimental models, most part of which are based on murine embryo cultures (Dotti et al., 1988; Yu et al., 2001; Dehmelt et al., 2003). Despite the vast use of the murine experimental model, it presents some limitations compared to high mammals (humans included) such as the inbred nature of certain rodent strains, a short life span and size brain limitations (Lim et al., 2012). In recent years, several experimental models have been suggested in the study of many neurobiological aspects, pointing to other animal species, much closer to the human than the murine model, such as cow, sheep and dog (Cummings et al., 1993; Hashimoto et al., 2000; Duittoz and Hevor, 2001). The use of these alternative models for in vitro study have shown unquestionable advantages. Firstly, it allows some physiological aspects, typical of some species, to be studied directly on the cells obtained from that same species (think for example of neuronal cultures from bovine brains to study biological aspects related to BSE). Secondly, many of these experimental models are set up with materials taken from slaughterhouses or removed during surgery for

other reasons (therefore destined for destruction), allowing to set up any kind of experimental protocol, without however, resorting to housed experimental animals (Peruffo and Cozzi, 2014; Panin et al., 2015). Thirdly, by doing so it is often possible to obtain cell lines from species and organs, which are not always present even in the most popular commercial cell banks. Among other alternative species for experimental models, over the last years dogs have been considered an excellent translational model for human medical research. Indeed, the canine nervous system is much more similar in size to that of humans than to that of rodents and it may develop several neurological diseases overlapping with those observed in the human brain (Milward et al., 1997; Kirk, 2003; Starkey et al., 2005; Thomas et al., 2009). The aim of this work was to assess the suitability of dogs' primary neuronal cells obtained through alternative methods of sampling to study the early phases of canine neuronal morphogenesis. The pattern of tubulin acetylation and tyrosination, as markers of stable and unstable microtubules respectively was monitored. In addition, in order to better evaluate the behavior of posttranslational modifications of the tubulin during neuronal morphogenesis, we evaluated the pattern of distributions of some associated proteins that preferentially may slide on dynamic and stable microtubules, like CLIP-170 and Kinesin-1 respectively.

2. Materials and Methods

2.1. Primary Cell Culture

The sampling of the canine fetuses was made thanks to the collaboration between the Normal Anatomy Section and the Clinical Obstetrics of the Veterinary Teaching Hospital of our department. During routine ovariohysterectomy procedures, whenever pregnant uteri were found, they would be immediately refrigerated and provided to our laboratory. Isolation of canine primary neuronal cells was performed as previously described (Mura et al., 2016). Briefly, cryopreserved brain tissues obtained from 25 gestation days dog fetuses were thawed, grossly minced and treated with Earle's balanced salt solution (EBSS) containing papain and DNase I for 40 min at 37 °C and centrifuged. The pelleted cells were resuspended in Dulbecco's modified Eagle's medium/Ham's F12 (DMEM/F12; Euroclone,) supplemented with penicillin (30 mg/l) with streptomycin (50 mg/l), sodium bicarbonate (2.4 g/l), insulin (10 µg/ml), transferrin (10 µg/ml), sodium selenite (10⁻⁸ M), 10% fetal calf serum. As neuronal growth promoter we added 10 ng/ml GDNF (glial cell line derived neurotrophic factor- Sigma, St.Louis, MO, USA) and 2 ng/ml of BDNF (brain derived neurotrophic factor- Sigma, St.Louis, MO, USA) to the medium 100 ng NGF (nerve growth factor- Sigma, St.Louis, MO, USA). Cells were plated into Petri dishes with a cover-glass slide on the bottom, previously coated with polylysine (Sigma, St.Louis, MO, USA) and placed in incubator (37 °C; 5% CO₂).

2.2. Immunofluorescence Staining

Single and double indirect immunofluorescence were performed. After 16 days of culture, cells were fixed in cold 100% methanol for 20 min. After washing with PBS, fixed cells were incubated overnight with the following antibodies diluted with PBS containing: 3% bovine serum albumin (BSA) and 0,1% tryton X-100) anti β III-tubulin (monoclonal, clone DM1A, 1:1000, Merck KGaA, Darmstadt Germany); 2) anti-total α -tubulin (monoclonal, clone DM1A, 1:1000, Merck KGaA, Darmstadt Germany); 3) anti-tyrosinated α -tubulin (monoclonal, clone TUB-1A2, 1:1000, Merck KGaA, Darmstadt Germany); 4) anti-acetylated α -tubulin (monoclonal, clone 6-11B-1, 1:1000, Merck KGaA, Darmstadt Germany); 5) anti kinesin-1 (polyclonal, Merck KGaA, Darmstadt Germany); 6) anti-Clip 170 (polyclonal, Merck KGaA, Darmstadt Germany). After rinsing with PBS, cells were incubated for 1 h at 37 °C with secondary anti-rabbit and anti-mouse fluorescein/tetramethylrhodamine isothiocyanate-conjugated antibodies (AlexaFluor 488, AlexaFluor 594, 1:400, Termo Fisher, Waltham, MA, USA). Images were obtained through a confocal laser scanning microscope from Leica (TCS SP5 DMI 6000CS, Leica Microsystems GmbH, Wetzlar, Germany) using a 40/60 \times oil objective. FITC was excited at 488 nm and emission was detected between 510 and 550 nm. Rhodamine was excited at 568 nm and emission was detected between 585 and 640 nm. Nuclear counterstaining was performed using Hoechst blue-33,342 (1:5000, Merck KGaA, Darmstadt Germany). During the acquisition process we hold constant the laser intensity, gain, and offset (Pinhole [airy] 1.00; Zoom 1.0; Digital offset: 0; Power Laser Line UV [405] 21.00%; Power Laser Line Visible [488] 38.00%; Power Laser Line Visible [543] 35.00%).

2.3. Fluorescent Intensity and Colocalization

The quantitative analysis of fluorescence intensity was carried out through the Leica LAS AF Lite image analysis software package (Leica Microsystems GmbH, Wetzlar, Germany). On the images taken with confocal microscope, converted to grayscale and by appropriate magnifications we designed a ROI on cell profiles (or on the cell processes or on the cell body) turning off the channel 1 (Hoechst blue) so that the software read the pixel average value on the remaining channel 2 and 3 which were switched on (AlexaFluor 488 or 594) and we recorded the mean values of pixel, to which we subtracted the value of the possible background. The trend of colocalization was performed using the same software package as indicated above. Choosing the picture of double immunofluorescence the software made automatically a scatterplot of the pixel intensity values of the two channels (red and green labeling), calculating the Pearson's correlation coefficient, the percentage of colocalization rate and the Mander's overlap coefficient (M1 and M2). As indicated by Dunn et al. (2011) the more the value of the Pearson's coefficient approaches to 1, the more the two molecules are colocalizing.

2.4. Statistical Analysis

Statistical analyses were carried out through the software program Statgraphics (Statpoint Technologies, Warrenton, VA). Data are expressed as a mean \pm standard error (SEM) and the inter-group analysis was done by Student's t-test or ANOVA. Statistical significance was accepted when $p < 0.05$.

3. Results

The brain tissue with 25 days of gestation chosen for this study provided a large amount of proliferating neural cells. Indirect immunofluorescence was performed on fixed cells after 16 days of culture. The anti- β III antibody, a well-known neuronal marker (Dráberová et al., 1998), revealed high immunopositivity, confirming the neuronal character of the majority of the cells obtained in the culture. Also, the total α -tubulin antibody homogeneously marked the neuronal cells with equal distribution in the cell body and cytoplasmic prolongations (Fig. 1). The characterization of tubulin post-translational modifications through single immunofluorescence labeling revealed well detectable immunopositivity for both tyrosinated and acetylated α -tubulin (Fig. 2). In order to better understand the pattern of cellular distribution of the two PTMs examined, we performed a quantification of the fluorescence intensity on cytoplasmic processes and around the cell body region. We detected slightly higher immunopositivity in cytoplasmic prolongations than in the cell body for tyrosinated α -tubulin, although this difference did not appear significant ($P = .8$). On the contrary, the analysis of the cellular distribution of acetylated α -tubulin showed significant fluorescence intensity in cellular prolongations in comparison with that detectable in the cell body region ($P = .02$; Fig. 3). When we compared tyrosinated and to acetylated distribution, acetylation resulted significantly higher ($P = .004$) than tyrosination, both close to the cell body and along cytoplasmic processes (Fig. 4). Regarding the proteins associated with microtubules, immunofluorescence for CLIP-170 and Kinesin-1 highlighted a significant ($P = .002$) signal emission for CLIP in comparison with Kinesin immunopositivity (Fig. 5). Colocalization estimation on double immunostaining with tyrosinated α -tubulin and CLIP-170 antibodies showed intense immunopositivity throughout the cell prolongation with a good degree of overlapping (PCC = 0.760; M1 Red/Green = 0.993; M2, Green/Red = 0.998; Fig. 6). Diversely, double immunofluorescence for acetylated α -tubulin and Kinesin-1 highlighted a low colocalization trend between the two molecules (PCC = 0.430; M1, Red/Green = 0.445, M2, Green/Red = 0.600) (Fig. 7).

4. Discussion

Primary dissociated neurons can be considered a useful methodology to perform several studies on morphology, functions, survival, and toxicology on large number of homogeneous cell (Gibbons and Dragunow, 2010; Schock et al., 2010; Humpel, 2015). As far as the studies on neuronal development and differentiation are concerned, scientific literature is rich in *in vitro* work conducted in primary culture of various species, e.g. rats, mice, fish (Grondona et al., 2013; Darbinyan et al., 2013). Over these past years, particularly when dealing with studies on the biology of the nervous system, the need to seek an experimental model closer to humans has increased, especially considering some aspects such as brain size and complexity, life span expectancy and presence of pathologies similar to those present in humans (Mak et al., 2014; Hofman, 1985). In this context, the dog has lately started to represent an ideal candidate as a useful experimental model (Studzinski et al., 2005; Cotman and Head, 2008). In the present work we found interesting data both regarding the pattern of the microtubular network and some associated motor protein during dog neuronal morphogenesis, as well as data regarding the utility of an alternative experimental model without the use of housed experimental dogs. In our experiment, we focused our attention on two tubulin PTMs patterns such as tyrosination and acetylation since they are distinctive of dynamic and stable microtubules, respectively, and play a fundamental role during neuronal morphogenesis (Westermann and Weber, 2003; Poulain and Sobel, 2010). Immunofluorescence revealed a marked immunopositivity for tyrosinated and acetylated α -tubulin. Although it is well known that tyrosinated tubulin is present in most dynamic regions of the neuron (growth cone) and the cellular body (Marcos et al., 2009) while not abundant in cell prolongations, our data showed a good level of fluorescence intensity both towards the cellular body and along the neurites. This is a behavior that we have already observed in other types of neural cells (Gadau, 2015). That pattern of tyrosinated distribution may be in accordance with the fact that tyrosination is a modification that characterizes the plus end of the most dynamic microtubules, which are not only present in the growth cone (Webster et al., 1987). Dynamic instability characterizes microtubules that tend to evolve rapidly by exploring three-dimensional space in order to allow fast adaptation of the cytoskeleton network (Cai et al., 2009). Moreover, evidences reported that subset of dynamic microtubules are present along the neurites during the early stages of morphogenesis before their stabilization (Stiess and Bradke, 2011). Together with tyrosination, we wanted to evaluate the presence and distribution pattern of a microtubule-associated motor protein, the CLIP-170. CLIP-170 is part of a family of +TIPs protein accumulating at the end of the growing microtubules (Arnal et al., 2004; Folker et al., 2005). Double fluorescence and quantification showed intense marking for CLIP-170 and a perfect overlay with tyrosinated tubulin. This data is consistent with what has already been shown about CLIP-170. Indeed, that +TIP displays a tendency to bind microtubules that are growing and therefore dynamic, and has a high affinity to the richly tyrosinated

microtubules (Bieling et al., 2008). In regards with the second PTMs evaluated, the acetylated α -tubulin, we found a strong fluorescence intensity along the shaft of neuronal cells in contrast with the lesser intensity close to the cell body. It is well known which acetylated microtubules are more present in neuronal compartment that require more stability like the axons, where long-lived MTs are abundant (Fukushima et al., 2009). The pattern of distribution of acetylated α - tubulin, i.e. the presence of stabilized MTs along the neuronal processes may confirm both an early polarization during neuronal development and a need for the developing neurons to possess stable MTs during morphogenesis (Hammond et al., 2008; Witte et al., 2008; Peris et al., 2009). Still referring to the tubulin acetylation, we also found another interesting result. Indeed, the neurons used in our experiment were grown in culture until the day 16 before being fixed for immunofluorescence. So, observing our data on fluorescence intensity, we can assume which acetylated α -tubulin levels were still high on that day.

This is somewhat contradictory to what reported in Audebert et al. (1994) where in primary neurons from mouse, a decrease of acetylated tubulin after day 12 was found. This data surely deserves further insights but may suggest that the developmental pattern of PTMs may be different in different species. Even for acetylated tubulin we wanted to evaluate the behavior of a motor protein that seems to have a high affinity with it, i.e. Kinesin 1. Kinesin-1 is part of the large family of kinesins, motor protein involved in axonal transport (Hirokawa et al., 2009). It is well known which Kinesin-1 preferentially moves on to stable microtubules (Vale, 2003). Moreover, acetylation of tubulin seems to promote the linkage and transport of kinesin 1 (Reed et al., 2006). Our results have confirmed the good distribution of Kinesin-1 but without a high grade of overlay with acetylated tubulin and with a low quantification of fluorescence, especially when compared to CLIP-170 data. It would seem that on the 16th day of culture, compared to the high intensity of acetylated tubulin fluorescence, we have seen a decrease in Kinesin-1 activity. We know from the literature that Kinesin-1 is crucial during axonogenesis and that its scarcity may be fatal during neurogenesis as it may cause a defects growth in axons (Lu et al., 2013; Winding et al., 2016). In addition, authors have pointed out that a decrease in Kinesin-1 in neurons may occur due to a Tau competition with microtubule protofilament. The more tau binds to the microtubule, the more the kinesin levels may decrease (Dixit et al., 2008; McVicker et al., 2011). Unfortunately, we did not consider these aspects in our study, so we are absolutely aware that the pattern of Kinesin-1 observed deserves further insights.

Our experimental protocol has revealed some aspects of tubulin PTMs and motor proteins such as CLIP-170 and Kinesin-1 during dog neuronal development. Although some data are not entirely original (the presence of tyrosinated and acetylated α -tubulin and motor proteins are certainly not a novelty in neural cells), they have highlighted the patterns of distribution and amount of tubulin PTMs and certain associated protein, not previously evaluated in dog neurons. In addition, we have confirmed the utility of our experimental model for several reasons. Indeed, considering that the ideal animal model for studies on human diseases does not

exist (Hartung, 2017; Daneshian et al., 2015; Gregory et al., 2012), it is always advisable to choose an animal model that is closer to the human species so as to avoid failures in translating the results obtained, the dog seems to be a good candidate for this (Patterson, 2000; Pasquali, 2018). Moreover, thanks to cryo-preservation and starting from occasionally sampling, we have been able to store canine fetal brain tissues, which can be easily cultivated even after a long time from storage. This method certainly allows advantages such as not having to resort to the use of housed experimental animals as hard to manage as the dog and to bypass the difficulty of finding commercial neuronal primary/continuous canine cell lines. Our experimental model would also allow the study on neurodegenerative pathologies of the dog, shedding light on cellular molecular aspects, otherwise not evaluable with other types of clinical analysis. Finally, work like the present can highlight the possibility of integration between veterinary practice and basic experimental research, too often considered quite far from each other.

Conflict of interest

The author declares that there are no conflicts of interest.

Acknowledgements

This work was supported by grant CRP-25879/2011, from the Sardinia Region Research Support.

The author is grateful to Mrs. Nicole Nasgowitz for the revision of the English language in the whole manuscript.

References

- Arnal, I., Heichette, C., Diamantopoulos, G.S., Chrétien, D., 2004. CLIP-170/tubulin- curved oligomers coassemble at microtubule ends and promote rescues. *Curr. Biol.* 14, 2086–2095. <https://doi.org/10.1016/j.cub.2004.11.055>.
- Audebert, S., Koulakoff, A., Berwald-Netter, Y., Gros, F., Denoulet, P., Eddé, B., 1994. Developmental regulation of polyglutamylated alpha- and beta-tubulin in mouse brain neurons. *J. Cell Sci.* 107, 2313–2322.
- Bieling, P., Kandels-Lewis, S., Telley, I.A., van Dijk, J., Janke, C., Surrey, T., 2008. CLIP- 170 tracks growing microtubule ends by dynamically recognizing composite EB1/ tubulin-binding sites. *J. Cell Biol.* 183, 1223–1233. <https://doi.org/10.1083/jcb.200809190>.
- Burnette, D.T., Ji, L., Schaefer, A.W., Medeiros, N.A., Danuser, G., Forscher, P., 2008. Myosin II activity facilitates microtubule bundling in the neuronal growth cone neck. *Dev. Cell* 15, 163–169. <https://doi.org/10.1016/j.devcel.2008.05.016>.
- Cai, D., McEwen, D.P., Martens, J.R., Meyhofer, E., Verhey, K.J., 2009. Single molecule imaging reveals differences in microtubule track selection between Kinesin motors. *PLoS Biol.* 7, e1000216. <https://doi.org/10.1371/journal.pbio.1000216>.
- Cotman, C.W., Head, E., 2008. The canine (dog) model of human aging and disease: dietary, environmental and immunotherapy approaches. *J. Alzheimers Dis.* 15, 685–707.
- Cummings, B.J., Su, J.H., Cotman, C.W., White, R., Russell, M.J., 1993. Beta-amyloid accumulation in aged canine brain: a model of early plaque formation in Alzheimer's disease. *Neurobiol. Aging* 14, 547–560.
- Daneshian, M., Busquet, F., Hartung, T., Leist, M., 2015. Animal use for science in Europe. *ALTEX* 32, 261–274. <https://doi.org/10.14573/altex.1509081>.
- Darbinyan, A., Kaminski, R., White, M.K., Darbinian, N., Khalili, K., 2013. Isolation and propagation of primary human and rodent embryonic neural progenitor cells and cortical neurons. *Methods Mol. Biol.* 1078, 45–54. https://doi.org/10.1007/978-1-62703-640-5_5.
- Dehmelt, L., Smart, F.M., Ozer, R.S., Halpain, S., 2003. The role of microtubule-associated protein 2c in the

reorganization of microtubules and lamellipodia during neurite initiation. *J. Neurosci.* 23, 9479–9490.

Dixit, R., Ross, J.L., Goldman, Y.E., Holzbaur, E.L., 2008. Differential regulation of dynein and kinesin motor proteins by tau. *Science* 319, 1086–1089.

Dotti, C.G., Sullivan, C.A., Banker, G.A., 1988. The establishment of polarity by hippocampal neurons in culture. *J. Neurosci.* 8, 1454–1468.

Dráberová, E., Lukás, Z., Ivanyi, D., Viklický, V., Dráber, P., 1998. Expression of class III β -tubulin in normal and neoplastic human tissues. *Histochem. Cell Biol.* 109, 231–239.

Duittoz, A.H., Hevor, T., 2001. Primary culture of neural precursors from the ovine central nervous system (CNS). *J. Neurosci. Meth.* 107, 131–140.

Dunn, K.W., Kamocka, M.M., McDonald, J.H., 2011. A practical guide to evaluating co-localization in biological microscopy. *A.J.P. Cell Physiol.* 300, 723–742.

Folker, E.S., Baker, B.M., Goodson, H.V., 2005. Interactions between CLIP-170, tubulin, and microtubules: implications for the mechanism of Clip-170 plus-end tracking behavior. *Mol. Biol. Cell* 16, 5373–5384. <https://doi.org/10.1091/mbc.E04-12-1106>.

Fukushima, N., Furuta, D., Hidaka, Y., Moriyama, R., Tsujiuchi, T., 2009. Post-translational modifications of tubulin in the nervous system. *J. Neurochem.* 109, 683–693. <https://doi.org/10.1111/j.1471-4159.2009.06013>.

Gadadhar, S., Bodakuntla, S., Natarajan, K., Janke, C., 2017. The tubulin code at a glance. *J. Cell Sci.* 130, 1347–1353. <https://doi.org/10.1242/jcs.199471>.

Gadau, S.D., 2015. Detection, distribution and Amount of Posttranslational α -Tubulin modifications in Immortalized Rat Schwann Cells. *Arch. Ital. Biol.* 153, 255–265. <https://doi.org/10.12871/00039829201542>.

Galjart, N., 2010. Plus-end-tracking proteins and their interactions at microtubule ends. *Curr. Biol.* 20, 528–537. <https://doi.org/10.1016/j.cub.2010.05.022>.

Gibbons, H.M., Dragunow, M., 2010. Adult human brain cell culture for neuroscience research. *Int. J. Biochem. Cell Biol.* 42, 844–856. <https://doi.org/10.1016/j.biocel.2009.12.002>.

Gomis-Rüth, S., Wierenga, C.J., Bradke, F., 2008. Plasticity of polarization: changing dendrites into axons in neurons integrated in neuronal circuits. *Curr. Biol.* 18, 992–1000. <https://doi.org/10.1016/j.cub.2008.06.026>.

Gregory, M.H., Capito, N., Kuroki, K., Stoker, A.M., Cook, J.L., Sherman, S.L., 2012. A review of translational animal models for knee osteoarthritis. *Arthritis*. 764621. <https://doi.org/10.1155/2012/764621>.

Grondona, J.M., Granados-Durán, P., Fernández-Llebrez, P., López-Ávalos, M.D., 2013. A simple method to obtain pure cultures of multiciliated ependymal cells from adult rodents. *Histochem. Cell Biol.* 139, 205–220. <https://doi.org/10.1007/s00418-012-1008-2>.

Hammond, J.W., Cai, D., Verhey, K.J., 2008. Tubulin modifications and their cellular functions. *Curr. Opin. Cell Biol.* 20, 71–76. <https://doi.org/10.1016/j.ceb.2007.11.010>.

Hammond, J.W., Huang, C.F., Kaech, S., Jacobson, C., Banker, G., Verhey, K.J., 2010. Posttranslational modifications of tubulin and the polarized transport of kinesin-1 in neurons. *Mol. Biol. Cell* 21, 572–583.

Hartung, T., 2017. Opinion versus evidence for the need to move away from animal testing. *ALTEX* 34, 193–200. <https://doi.org/10.14573/altex.1703291>.

Hashimoto, A., Onodera, T., Ikeda, H., Kitani, H., 2000. Isolation and characterization of fetal bovine brain cells in primary culture. *Res. Vet. Sci.* 69, 39–46.

Hirokawa, N., Noda, Y., Tanaka, Y., Niwa, S., 2009. Kinesin superfamily motor proteins and intracellular transport. *Nat. Rev. Mol. Cell Biol.* 10, 682–696 (doi 10.1038/nrm2774).

Hofman, M.A., 1985. Size and shape of the cerebral cortex in mammals. I. the cortical surface. *Brain Behav. Evol.* 27, 28–40.

Humpel, C., 2015. Organotypic brain slice cultures: a review. *Neuroscience* 305, 86–98. <https://doi.org/10.1016/j.neuroscience.2015.07.086>.

Janke, C., 2014. The tubulin code: molecular components, readout mechanisms, and functions. *J. Cell Biol.* 206, 461–472. <https://doi.org/10.1083/jcb.201406055>.

Janke, C., Kneussel, M., 2010. Tubulin post-translational modifications: encoding functions on the neuronal microtubule cytoskeleton. *Trends Neurosci.* 33, 362–372. <https://doi.org/10.1016/2010.05.001>.

Kirk, A.D., 2003. Crossing the bridge: large animal models in translational transplantation research. *Immunol. Rev.* 196, 176–196.

Li, L., Yang, X.J., 2015. Tubulin acetylation: responsible enzymes, biological functions and human diseases. *Cell. Mol. Life Sci.* 72, 4237–4255. <https://doi.org/10.1007/s00018-015-2000-5>.

Lim, J.H., Koh, S., Olby, N.J., Piedrahita, J., Mariani, C.L., 2012. Isolation and characterization of neural progenitor cells from adult canine brains. *Am. J. Vet. Res.* 73, 1963–1968. <https://doi.org/10.2460/ajvr.73.12.1963>.

Lu, W., Fox, P., Lakonishok, M., Davidson, M.W., Gelfand, V.I., 2013. Initial neurite outgrowth in *Drosophila* neurons is driven by kinesin-powered microtubule sliding. *Curr. Biol.* 23, 1018–1023. <https://doi.org/10.1016/j.cub.2013.04.050>.

Magiera, M.M., Janke, C., 2014. Post-translational modifications of tubulin. *Curr. Biol.* 24, 351–354. <https://doi.org/10.1016/j.cub.2014.03.032>.

Mak, I.W., Evaniew, N., Ghert, M., 2014. Lost in translation: animal models and clinical trials in cancer treatment. *Am. J. Transl. Res.* 6, 114–118.

Marcos, S., Moreau, J., Backer, S., Job, D., Andrieux, A., Bloch-Gallego, E., 2009. Tubulin tyrosination is required for the proper organization and pathfinding of the growth cone. *PLoS One.* <https://doi.org/10.1371/0005405>.

McVicker, D.P., Chrin, L.R., Berger, C.L., 2011. The nucleotide-binding state of microtubules modulates kinesin processivity and the ability of Tau to inhibit kinesin-mediated transport. *J. Biol. Chem.* 286, 42873–42880. <https://doi.org/10.1074/jbc.M111.292987>.

Milward, E.A., Lundberg, C.G., Ge, B., Lipsitz, D., Zhao, M., Duncan, I.D., 1997. Isolation and transplantation of multipotential populations of epidermal growth factor-responsive, neural progenitor cells from the canine brain. *J. Neurosci. Res.* 50, 862–871.

Mura, A., Serra, E., Gadau, S.D., 2016. Setting up of primary Cultures from Fetal Dog Brain: an Alternative Method in Line with the 3Rs Principles. *Austin Biol.* 1, 1–5.

Panin, M., Corain, L., Montelli, S., Cozzi, B., Peruffo, A., 2015. Gene expression profiles of estrogen receptors α and β in the fetal bovine hypothalamus and immunohistochemical characterization during development. *Cell Tissue Res.* 359, 619–626. <https://doi.org/10.1007/s00441-014-2023-5>.

Pasquali, P., 2018. The importance of animal models in research. *Res. Vet. Sci.* 118, 144–145. <https://doi.org/10.1016/j.rvsc.2018.02.001>.

Patterson, D.F., 2000. Companion animal medicine in the age of medical genetics. *J. Vet. Intern. Med.* 14, 19.

Peris, L., Wagenbach, M., Lafanechère, L., Brocard, J., Moore, A.T., Kozielski, F., Job, D., Wordeman, L., Andrieux, A., 2009. Motor-dependent microtubule disassembly driven by tubulin tyrosination. *J. Cell Biol.* 185, 1159–1166. <https://doi.org/10.1083/jcb.200902142>.

Peruffo, A., Cozzi, B., 2014. Bovine brain: an in vitro translational model in developmental neuroscience and neurodegenerative research. *Front. Pediatr.* 2, 1–4. <https://doi.org/10.3389/fped.2014.00074>.

Poulain, F.E., Sobel, A., 2010. The microtubule network and neuronal morphogenesis: Dynamic and coordinated orchestration through multiple players. *Mol. Cell. Neurosci.* 43, 15–32. <https://doi.org/10.1016/j.mcn.2009.07.012>.

Reed, N.A., Cai, D., Blasius, T.L., Jih, G.T., Meyhofer, E., Gaertig, J., Verhey, K.J., 2006. Microtubule acetylation promotes kinesin-1 binding and transport. *Curr. Biol.* 16, 2166–2172. <https://doi.org/10.1016/j.cub.2006.09.014>.

Schock, S.C., Jolin-Dahel, K.S., Schock, P.C., Staines, W.A., Garcia-Munoz, M., Arbuthnott, G.W., 2010. Striatal interneurons in dissociated cell culture. *Histochem. Cell Biol.* 134, 1–12. <https://doi.org/10.1007/s00418-010-0707-9>.

Shea, T.B., 1999. Selective stabilization of microtubules within the proximal region of developing axonal neurites. *Brain Res. Bull.* 48, 255–261.

Song, Y., Brady, S.T., 2015. Post-translational modifications of tubulin: pathways to functional diversity of microtubules. *Trends Cell Biol.* 25, 125–136. <https://doi.org/10.1016/j.tcb.2014.10.004>.

Starkey, M.P., Scase, T.J., Mellersh, C.S., Murphy, S., 2005. Dogs really are man's best friend-canine genomics has applications in veterinary and human medicine! *Brief Funct. Gen. Proteom.* 4, 112–128.

Stiess, M., Bradke, F., 2011. Neuronal polarization: the cytoskeleton leads the way. *Dev. Neurobiol.* 71, 430–444. <https://doi.org/10.1002/dneu.20849>.

Studzinski, C.M., Araujo, J.A., Milgram, N.W., 2005. The canine model of human cognitive aging and dementia: pharmacological validity of the model for assessment of human cognitive-enhancing drugs. *Prog. Neuro-Psychopharmacol. Biol. Psychiatry* 29, 489–498. <https://doi.org/10.1016/j.pnpbp.2004.12.014>.

Thomas, R., Duke, S.E., Wang, H.J., Breen, T.E., Higgins, R.J., Linder, K.E., et al., 2009. Putting our heads together': insights into genomic conservation between human and canine intracranial tumors. *J. Neuro-*

Oncol. 94, 333–349. <https://doi.org/10.1007/s11060-009-9877-5>.

Vale, R.D., 2003. The molecular motor toolbox for intracellular transport. *Cell* 112, 467–480.

Verhey, K.J., Hammond, J.W., 2009. Traffic control: regulation of kinesin motors. *Nat. Rev. Mol. Cell Biol.* 10, 765–777. <https://doi.org/10.1038/nrm2782>.

Webster, D.R., Gundersen, G.G., Bulinski, J.C., Borisy, G.G., 1987. Differential turnover of tyrosinated and detyrosinated microtubules. *Proc. Natl. Acad. Sci. U. S. A.* 84, 9040–9044.

Westermann, S., Weber, K., 2003. Post-translational modifications regulate microtubule function. *Nat. Rev. Mol. Cell Biol.* 4, 938–947. <https://doi.org/10.1038/nrm1260>.

Winding, M., Kelliher, M.T., Lu, W., Wildonger, J., Gelfand, V.I., 2016. Role of kinesin-1- based microtubule sliding in *Drosophila* nervous system development. *Proc. Natl. Acad. Sci. U. S. A.* 113, 4985–4994. <https://doi.org/10.1073/pnas.1522416113>.

Witte, H., Neukirchen, D., Bradke, F., 2008. Microtubule stabilization specifies initial neuronal polarization. *J. Cell Biol.* 180, 619–632. <https://doi.org/10.1083/jcb.200707042>.

Yu, W., Ling, C., Baas, P.W., 2001. Microtubule reconfiguration during axogenesis. *J. Neurocytol.* 30, 861–875.

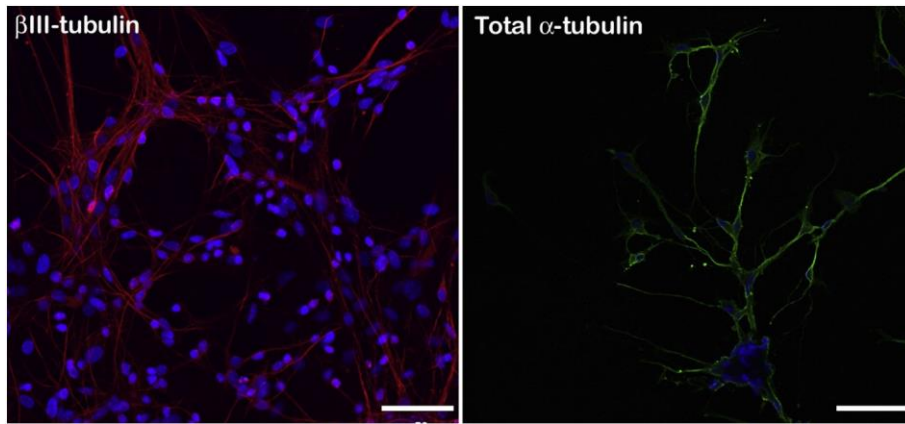


Fig. 1. Immunofluorescence staining to tubulin β -III and total α -tubulin on 16 days dog primary neuronal cultures. Bars = 50 μ m.

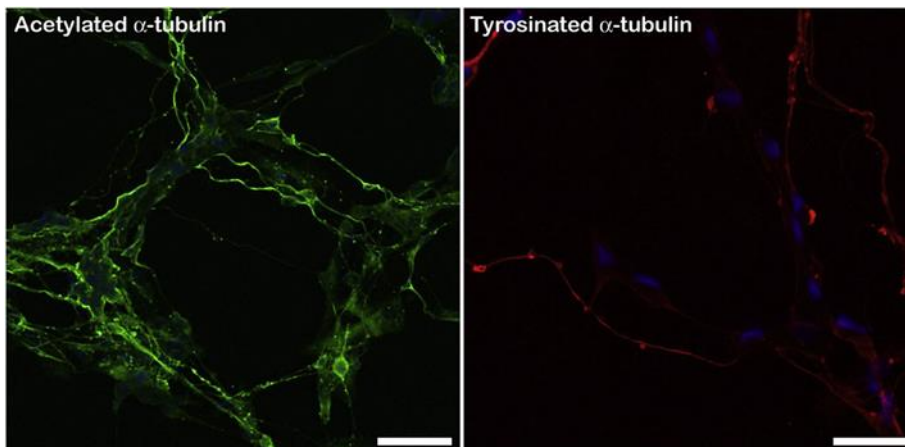


Fig. 2. Immunolabeling with acetylated and tyrosinated α -tubulin antibodies. Bars = 50 μ m.

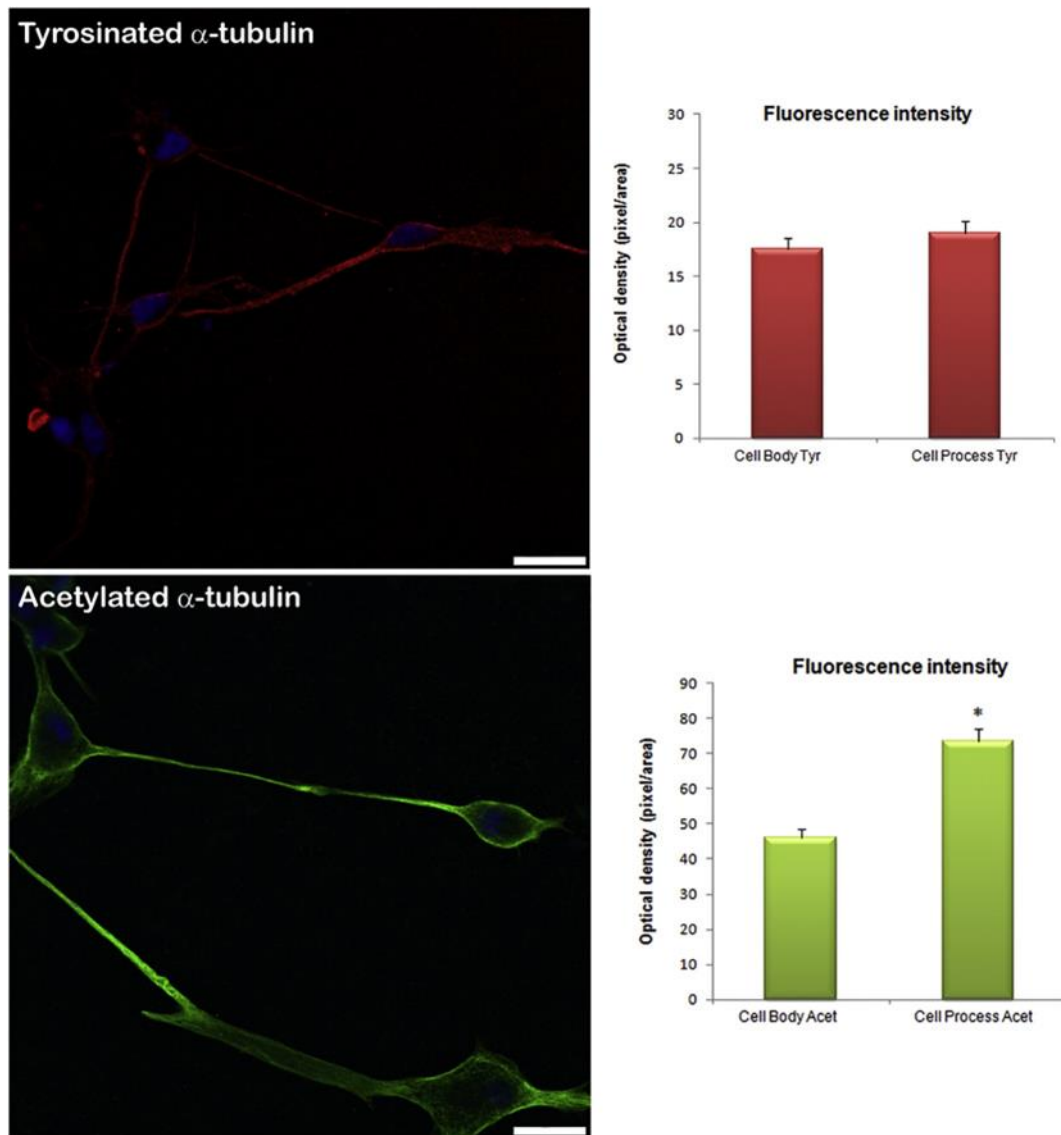


Fig. 3. Confocal images. Immunofluorescence staining revealed different cellular distribution of tubulin PTMs. By fluorescent intensity quantification (diagrams), tyrosinated α -tubulin (white arrows) showed no immunostaining differences in both cellular processes and cell body. On the contrary, acetylated α -tubulin intensity was stronger in cytoplasmic processes than the cell body. Data are expressed as means \pm SEM of five experiments. * = $p < 0.0001$. Bars = 25 μ m.

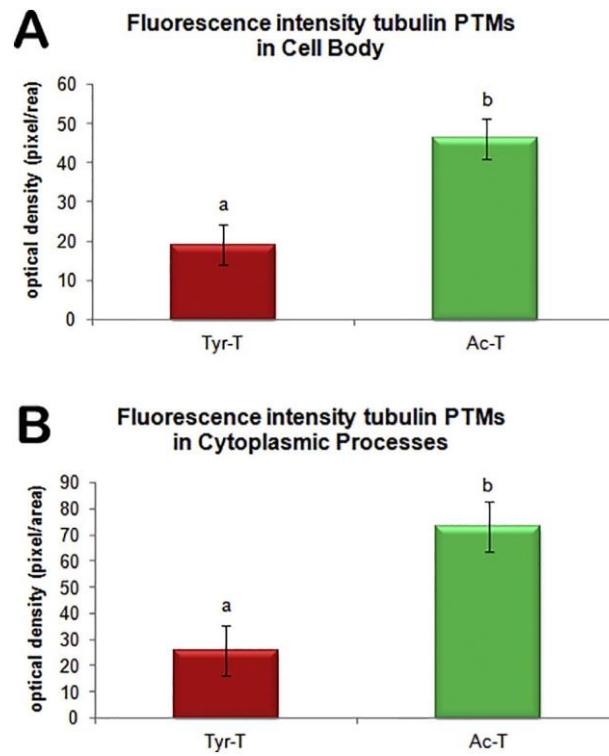


Fig. 4. Anova one way. Diagrams underlined a prevalence of acetylated α -tubulin respect to tyrosinated in both cell body (A) and cytoplasmic processes (B). Lower case letters indicate statistical difference among tyrosinated and acetylated α -tubulin (ANOVA $p < 0.01$). Data are expressed as means \pm SEM of five experiments. Bars = 25 μ m.

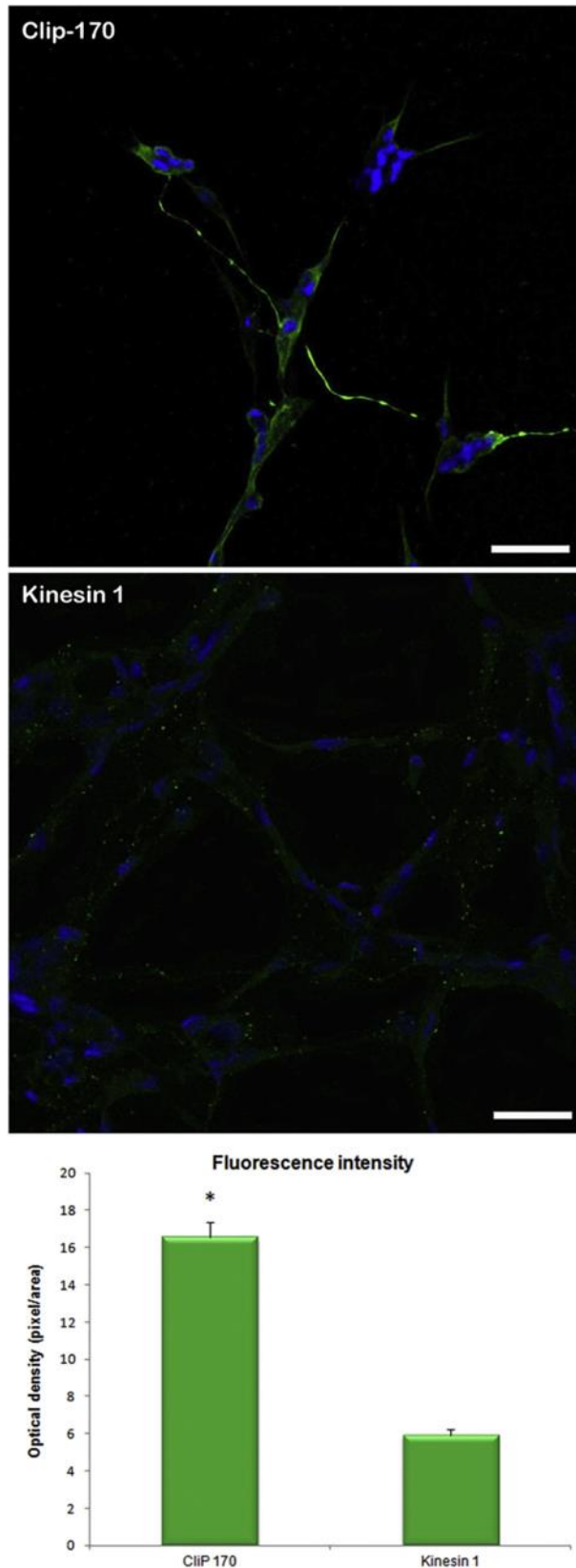


Fig. 5. Confocal images of immunofluorescence staining for CLIP-170 and Kinesin 1 microtubule associated protein. The diagram displayed a significant prevalence of fluorescence intensity for Clip -170 respect to Kinesin 1. Data are expressed as means \pm SEM of five experiments. * = $p < 0.002$. Bars = 25 μ m.

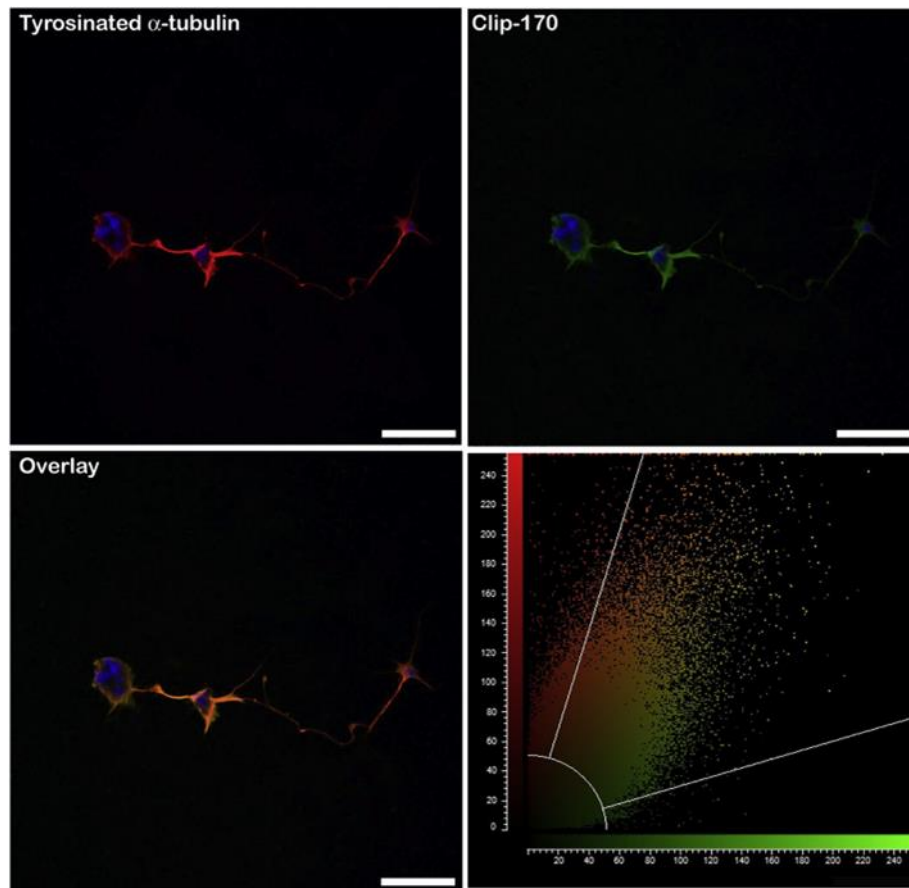


Fig. 6. Immunofluorescence staining to tyrosinated α -tubulin (top, on the left) and Clip-170 (top on the right) and overlay of both (bottom on the left). The diagram represents the degree of colocalization between the tubulin PTMs and the associated protein. Data are expressed as means \pm SEM of five experiments. Bars = 25 μ m.