

Neuronal cell culture from transgenic zebrafish models of neurodegenerative disease

Jamie Rae Acosta^{1,2,3 #}, Maxinne Watchon^{3,4,5 #}, Kristy C. Yuan⁵, Jennifer Fifita⁵, Adam J. Svahn⁵, Emily K. Don⁵, Ian P. Blair⁵, Garth A. Nicholson^{4,5,6}, Nicholas J. Cole⁵, Claire Goldsbury^{1,2,3}, Angela S. Laird^{5 †}

¹The Brain & Mind Research Institute, University of Sydney, New South Wales, Australia

²The Bosch Institute, University of Sydney, New South Wales, Australia

³Discipline of Anatomy and Histology, University of Sydney, New South Wales Australia

⁴Sydney Medical School, University of Sydney, Sydney, New South Wales 2006, Australia.

⁵Centre for Motor Neuron Disease Research, Department of Biomedical Sciences, Faculty of Medicine and Health Sciences, Macquarie University, Sydney, New South Wales, Australia

⁶ANZAC Research Institute, Concord Repatriation Hospital, University of Sydney, New South Wales, Australia

These authors contributed equally

† Corresponding author: Dr Angela Laird, angela.laird@mq.edu.au Centre for Motor Neuron Disease Research, Department of Biomedical Sciences, Faculty of Medicine and Health Sciences, Macquarie University, Sydney, New South Wales, Australia

Keywords: primary neuronal cell culture, transgenic zebrafish, Amyotrophic Lateral Sclerosis (ALS), Spinocerebellar ataxia type-3, Fused in Sarcoma (FUS), ataxin-3 (ATXN3)

Declarations of interest: none

Summary statement:

This article describes the optimisation and validation of a protocol for culturing of neurons from transgenic zebrafish for the study of neurodegenerative diseases.

Abstract:

We describe a protocol for culturing neurons from transgenic zebrafish embryos to investigate the subcellular distribution and protein aggregation status of neurodegenerative disease-causing proteins. The utility of the protocol was demonstrated on cell cultures from zebrafish that transgenically express disease-causing variants, human FUS and ataxin-3 proteins, in order to study amyotrophic lateral sclerosis (ALS) and spinocerebellar ataxia type-3 (SCA3), respectively. A mixture of neuronal subtypes, including motor neurons, exhibited differentiation and neurite outgrowth in the cultures. As reported previously, mutant human FUS was found to be mislocalized from nuclei to the cytosol, mimicking the pathology seen in human ALS and the zebrafish FUS model. In contrast, neurons cultured from zebrafish expressing human ataxin-3 with disease-associated expanded polyQ repeats did not accumulate within nuclei in a manner often reported to occur in SCA3. Despite this, the subcellular localisation of human ataxin-3 protein seen in the cell cultures was similar to that found in the SCA3 zebrafish themselves. The finding of similar protein localisation and aggregation status in the neuronal cultures and corresponding transgenic zebrafish models confirms that this cell culture model is a useful tool for investigating the cell biology and proteinopathy signatures of mutant proteins for the study of neurodegenerative disease.

Introduction

The zebrafish (*danio rerio*) is increasingly used to successfully model neurodegenerative diseases [1-11] and holds promise for testing potential disease treatments [8, 12]. There are straightforward methods available for modulating gene expression in zebrafish [13-15] and female zebrafish spawn large numbers of embryos making it possible to perform behavioral testing and drug study screens with relatively high throughput [16]. Many proteins associated with neurodegenerative disease in humans are homologous in zebrafish, highlighting potentially conserved molecular-cellular functions that can be readily investigated in the zebrafish model [17].

Zebrafish cells, including neural cells, can be cultured directly from developing embryos [18-24]. The potential of this method for investigating differentiated neurons has previously been achieved with later-stage embryos (>19 hours post-fertilization; hpf) [21]. Here we focused on exploring the potential to study neurodegenerative diseases by applying and optimising the technique using transgenic zebrafish expressing mutated forms of the proteins fused in sarcoma (FUS) and ataxin-3 to model amyotrophic lateral sclerosis (ALS) and spinocerebellar ataxia type-3 (SCA3), respectively. ALS is a fatal neurodegenerative disease that causes progressive paralysis due to loss of motor neurons within the brain and spinal cord. ALS can be caused by either non-inherited (sporadic) and/or inherited causes, with more than 25 different genes currently identified to be linked with the disease [25-27]. One gene known to cause ALS is fused in sarcoma (FUS) [28]. FUS is a ubiquitous, predominantly nuclear, multifunctional DNA- and RNA-binding protein (reviewed in [29]). More than 50 different FUS mutations have been

discovered to cause familial ALS (fALS)[28-30]. SCA3 is a somewhat similar fatal neurodegenerative disease that results in gradual loss of control and coordination of muscles due to neuronal loss. The genetic cause of SCA3 is inheritance of an expanded CAG trinucleotide repeat region in the *ATXN3* gene [31]. Abnormal CAG nucleotide repeat expansions (>40 repeats) result in an ataxin-3 protein with a long polyglutamine (polyQ) repeat region that has multiple potential toxic effects [31]. We have recently reported that zebrafish expressing ataxin-3 with an expanded polyQ tract harbour disease hallmarks such as ataxin-3 positive cleavage fragments and impaired movement at 6dpf [32].

Both ALS and SCA3 are characterized by the mislocalization, accumulation and aggregation of the respective mutated proteins in neurons, accompanied by neural cell dysfunction and death [33, 34]. In this study, cell cultures derived from transgenic zebrafish larvae allowed investigation of the subcellular localization of mutated human FUS and ataxin-3 and the presence or absence of protein inclusions in different cell types, including differentiated neurons. We confirmed that the subcellular localization of the disease-causing proteins were the same in the cell cultures as in the living transgenic zebrafish for both models of neurodegenerative disease. These neuronal cell cultures, obtained from transgenic zebrafish lines of neurodegenerative diseases, have potential for use in drug screening assays for effectors of protein aggregation and mislocalization. In combination with zebrafish behavioural and physiological analysis, this is an additional tool to investigate the functional effects of cellular pathology in neurodegeneration.

Results

Optimization of zebrafish neural cell cultures

Cells harvested from transgenic zebrafish embryos that expressed GFP in motor neurons under the *islet1* promoter (*islet1:GFP*) were used to generate primary zebrafish cell cultures and optimize the growth of neurons. From this, we determined the percentage of cells that expressed GFP to give us an indication of the degree of motor neuron survival. Embryos up to 48 hpf were cultured with ease, whilst embryos up to 96 hpf required longer incubations in trypsin to achieve cell dissociation, which was detrimental to subsequent cell survival. For this reason, we predominantly worked with cultures from 24 hpf zebrafish embryos. Cell cultures derived from both 24 and 48 hpf embryos maintained motor neuron integrity, with GFP positive neurons representing 10-12% of the total cells in culture and exhibiting rapid neurite outgrowth after 1 day *in vitro* (div; Figure 1A). There was no difference in the percentage of GFP expressing cells or cellular morphologies when comparing cells grown at 28 °C (controlled temperature in captivity) and 37 °C (standard mammalian cell culturing temperature) (Figure 1B), suggesting that both temperatures are suitable for culturing zebrafish motor neurons. In an attempt to improve the cell dissociation step we tested the effect of de-yolking the embryos by microsuction prior to culturing [21]. We found that absence of the yolk gave rise to motor neurons with shorter neurites and widespread cell death after 2 div (although the percentage of motor neurons after 1 div remained unchanged relative to cultures from embryos with intact yolks) (Figure 1C). In cultures derived from larvae with intact yolk sacs, motor neurons were viable for up to 1 week. A schematic

representation of the optimised workflow required to derive this culture is summarised in Figure 2.

Demonstration of mixed neural subtypes in culture

As well as *islet1*:GFP-positive motor neurons, a variety of other neuronal subtypes were also present in the cultures, demonstrated by immunolabelling with neural cell antibodies obtained from the Developmental Studies Hybridoma Bank (University of Iowa). Anti-*islet1/2* antibodies (39.4D5) labelled all GFP positive motor neurons as expected and additionally some GFP negative neurons presumably representing those expressing *islet2* but not *islet1* transcription factors (Figure 3A). Some *islet1* expressing cells and other cells were also labelled with by Zn12 antibodies against L2/HNK-1, a neural cell adhesion molecule expressed by a variety of different neural subtypes (Figure 3B). In summary, a variety of motor neurons and other neural subtypes were evident in the mixed cultures.

Culturing cells from transgenic zebrafish expressing pathogenic human motor neuron disease associated proteins

We next cultured cells from transgenic zebrafish that expressed fluorescently tagged human neurodegenerative-disease related proteins (Figure 4). In post-mortem tissue, cytosolic mislocalization and aggregation of FUS occurs in motor neurons [30, 35]. In our zebrafish cell cultures, fALS mutant human FUS (FUS-R521C) fused to GFP showed greater cytosolic distribution than wild-type human FUS (Figure 4A). This is consistent

with mislocalisation seen in a FUS zebrafish model described previously [36] and with other cell model studies [37].

Cells were also cultured from a transgenic zebrafish model of SCA3 that express EGFP-fused to human ataxin-3 containing either a pathogenic (84Q) or non-pathogenic (23Q) polyglutamine tract. In the SCA3 zebrafish cell cultures, we did not detect any mislocalization or aggregation of EGFP-ataxin-3-84Q within the nucleus of neurons, a common phenotype reported in SCA3 patient brain and spinal cord samples [33]. No major qualitative differences were present in the neurons from EGFP-ataxin-3-84Q zebrafish compared to non-pathogenic EGFP-ataxin-3-23Q zebrafish after 2 div (Figure 4B). We did note some aggregation of the mCherry protein used as a neural cell reporter in our transgenic zebrafish, within cells cultured from both EGFP-ataxin-3-23Q and EGFP-ataxin-3-84Q zebrafish (Figure 4B,C).

To confirm that the EGFP displayed in the cultured neural cells was indicative of the expression of EGFP-fused to human ataxin-3 we performed immunolabelling with a polyglutamine (polyQ) antibody (Figure 4C). The polyQ staining pattern was found to be mostly cytoplasmic, and similar for the EGFP-ataxin-3-23Q and -84Q samples (Figure 4C). This subcellular localization was consistent with that found in the live transgenic zebrafish expressing either EGFP-ataxin-3-23Q or -84Q at 3 dpf (Figure 4D).

Discussion

Protocols exist for culturing cells from dissociated zebrafish embryos [18-24, 38]. A previous study demonstrated that differentiated zebrafish motor neurons can be cultured from embryos older than 19 hpf, up to 96 hpf and maintained, demonstrating the potential

for this technique to be used to investigate the development and cell biology of motor neurons *in vitro* [21, 24]. We adapted this method and used it to culture neurons from transgenic zebrafish models of neurodegenerative diseases. We show that zebrafish motor neurons grow neurites, differentiate and can be maintained in culture at either 28 °C or 37 °C. We found that de-yolking embryos prior to dissociation was detrimental to the survival of motor neurons in the cultures and led to stunted neurite outgrowth. This suggested the importance of endogenous factors and nutrients found in the yolk for growth and sustenance of differentiating neurons and other cell types [39]. Despite this, recent work in primary cell culture of zebrafish embryos has been successful in culturing a variety of neuronal cell types without the preservation of the yolk sac [24]. In previous work, selection of spinal cord neurons amongst a heterogeneous mixture of cells was achieved by performing larvae spinal cord dissections or fluorescent activated cell sorting (FACS) purification of neurons [21, 24]. However optimisation of this particular protocol is required due to high mortality rates [24]. Enhanced motor neuron purity could enable investigation of cell-autonomous factors that have been shown to be important for the degenerative mechanisms of other motor neuron disease-related proteins such as superoxide dismutase-1 (SOD1) [40]. On the other hand, co-culturing motor neuron together with other cell types is biologically relevant and advantageous to cell survival due to available trophic factors in culture [24]. Similar to previous studies related to culturing zebrafish cells [21, 24], passaging of cells was not attempted.

Cultures from human mutant FUS transgenic zebrafish demonstrate that mutant, but not wild-type human FUS is ubiquitously mislocalized in zebrafish cells, consistent with previous results in whole mount zebrafish larva and cell cultures [4, 36] and in mammalian cell lines [4, 41]. This model offers another tool for gathering insight into mechanisms of FUS-linked disease. In contrast, we did not see any nuclear mislocalization or aggregation of expanded polyQ human ataxin-3 in the neurons cultured from our EGFP-ataxin-3 zebrafish larva [32]. Instead, the non-pathological EGFP-ataxin-3-23Q showed the same cytosolic distribution in zebrafish cells as the EGFP-ataxin-3-84Q protein. Ataxin-3 proteins with expanded polyQ stretches (>40Q repeats) are often reported to accumulate within the nucleus, often within inclusions, in SCA3 patient brain autopsy samples and in many animal models [33, 42]. However, we did find aggregates of mCherry protein that did not localise with EGFP-ataxin-3. mCherry-positive protein aggregates have been reported previously to occur, with red fluorescent proteins showing an increased propensity to self-aggregate when exposed to light [43]. Nevertheless, these cell culture findings were consistent with what was seen in whole mount samples from the transgenic EGFP-ataxin-3 zebrafish larvae. This suggests that expanded polyQ ataxin-3, unlike human FUS, is not extensively mislocalized at this early age. Immunolabelling of transgenic zebrafish cells with ataxin-3 or polyQ specific antibodies confirmed that the exogenous protein and polyQ repeats maintained cytosolic distribution and did not accumulate within the nucleus. However, there was some nuclear GFP fluorescence not co-labelled with the polyglutamine antibody suggesting partial degradation of the EGFP-ataxin-3 fusion protein, resulting in some GFP separated from

the polyQ tract. These ataxin-3 expressing cell cultures provide an additional tool to complement the existing phenotypes already found in these SCA3 zebrafish.

Overall, the protocol described here adds a new tool for investigating neurodegenerative diseases using zebrafish. We developed an easily adaptable method for the culturing of neurons from dissociated zebrafish embryos and further demonstrated ways of characterizing these cells *in vitro*. We provide examples of cultured cells that transgenically express proteins linked to the neurodegenerative diseases ALS and SCA3 and were able to demonstrate that the cultured cells maintained similar protein localisation to the *in vivo* model from which they were generated. The zebrafish cell culture model offers another tool to gain insight into the molecular and cellular mechanisms underlying the diseases associated with these pathogenic proteins.

Materials and Methods

Transgenic Zebrafish

All experiments were carried out with approval from the University of Sydney Animal Ethics Committee (K00/3-2012/2/5709, K03/10-2010/3/5435 and K00/12-2010/3/5463) and Macquarie University (2016/04, 2015/034 and 2017/19). Transgenic zebrafish were bred on Tübingen/AB background and both male and female zebrafish were utilised. Transgenic zebrafish with GFP-expressing motor neurons driven by the *islet1* promoter Tg(*isll*:GFP)rw0Tg are described in [44]. Transgenic zebrafish Tg(*actb2*:Hsa.FUS-GFP)mq1Tg and Tg(*actb2*:Hsa.FUS_R521C-GFP)mq2Tg expressing human FUS conjugated to GFP driven by a β -actin promoter (called FUS-WT-GFP and FUS-R521C-

GFP in the text) were generated as described previously [36]. Transgenic zebrafish Tg(*elavl3*:Gal4-VP16; mCherry); Tg(UAS:dsRed,EGFP-ATXN3_Q23) and Tg(*elavl3*:Gal4-VP16; mCherry); Tg(UAS:dsRed,EGFP-ATXN3_Q84) expressing EGFP tagged human ataxin-3 (containing either a normal polyQ motif [23Q] or a disease-linked expanded polyQ motif [84Q]) were generated using the UAS/Gal4 system as described in [32].

Primary cell cultures

The cell culture protocol was based on a method developed by Sakowski and colleagues (2012) [21] as well as other methodology used for the culturing of mammalian and avian neurons [45]. Whole zebrafish embryos at 24 or 48 hpf were dechorionated manually with forceps, placed in microcentrifuge tubes, kept in ice-cold E3 medium with 16 μ M tricaine (anaesthesia for zebrafish). These embryos were then washed multiple times with ice-cold sterile E3 medium and kept on ice for 20 minutes. For the experiment comparing cell cultures including or excluding the yolk sac, embryos were de-yolked by slow microsuction via syringe. Embryos were then dissociated in 1x Trypsin diluted in PBS (Invitrogen) at 37 °C within a water bath for 30 minutes with periodic gentle swirling and pipetting to aid dissociation. Trypsinisation was arrested with DMEM supplemented with 10% FBS, L-alanyl-L-glutamine and antimycotic (Invitrogen). Cells were then pelleted by centrifugation at a relative centrifugal force of 180 (typically 1000 rpm) for 3 minutes. Coverslips were pre-coated with 0.1 mg/mL poly-D-lysine (Sigma Aldrich) for 1 hour and washed 3 times with PBS before plating. Cells were re-suspended in Hank's buffer salt solution (HBSS; Invitrogen) and plated at a density of 500,000 cells per 12 mm

coverslip via a hemacytometer. Cells were placed in neuron-enriching Neurobasal™ media supplemented with 2% B27, L-alanyl-L-glutamine and antimycotic (Invitrogen). Multi-well plates were incubated at 37 °C with 5% CO₂ throughout the experiment (2 div) with half of the media replaced daily. For the experiments comparing the effect of temperature, plates containing cell cultures from transgenic zebrafish with the GFP-expressing motor neurons driven by the *islet1* promoter were incubated at either at 28°C or 37°C with 5% CO₂ for 24 hours. Cells were then fixed with 4% PFA in PBS and processed for immunofluorescent staining as described below.

Immunofluorescence

Cells were fixed after 1 div for 15 minutes in 4% PFA in PBS pre-warmed to 37°C. Cells were then washed 3 times in PBS, permeabilized with 0.05% PBS/Triton-X-100 followed by another 3 PBS washes. Non-specific antibody binding was blocked by incubation by 5% goat serum (in PBS) prior to a 1 hour incubation with one of the following primary antibodies: for islet 1 and islet 2 homeobox, 39.4D5 (1:50) and neuronal cell surface marker Zn12 (1:50) all obtained from the Developmental Studies Hybridoma Bank; for human ataxin-3 (1:500; Millipore, clone 1H9[MAB5360) or anti-polyglutamine (PolyQ) (Millipore, clone 5TF1-1C2[MAB1574). Coverslips were then washed in PBS and then incubated for 1 hour with secondary antibodies Alexa Fluor 555 or 647 anti-mouse (1:200; Invitrogen, A32727 and A32728). Cells were counterstained with DAPI (1:1000; Sigma Aldrich) and the coverslips were mounted in Prolong-Gold antifade reagent (Molecular Probes).

Imaging and analysis

All cell cultures were imaged using a Zeiss Axio Observer inverted epifluorescence microscope equipped with a 40x Plan-Apochromat oil objective, xenon light source and Axiovision 4.8.2 acquisition software. Percentage motor neuron density (percent of *islet1:GFP* positive cells) from 3 independent experiments was calculated by the number of GFP-positive cells among the total number of DAPI-positive cells from ten images per coverslip taken of randomly selected regions (fragmented nuclei indicative of dead cells were not counted). Cross-section of the transgenic ataxin-3 zebrafish spinal cord at 3 dpf was imaged using the Leica TCS SP8 using a Leica HyD detector with a Leica 40x HC PL APO CS2 water immersion. DAPI was excited by a diode laser at 405nm whilst the GFP and mCherry were excited by an OPSL laser at 488nm and 552nm respectively. Images were prepared with ImageJ 1.51w and adjusted by a mean filter with radius 1. We compared the subcellular localisation of the disease causing proteins FUS and ataxin-3 by comparing the localisation of GFP expression with the DAPI stained nucleus.

Acknowledgements

The authors would like to thank Henry Paulson for the original EGFP-ataxin-3 plasmids and Reinhard Köster for the *elavl3:Gal4-VP16* and bidirectional UAS constructs. They thank staff members (past and present) of the zebrafish facilities at the Brain and Mind Centre, University of Sydney and Macquarie University for the care of the zebrafish described within this manuscript.

Competing interests

No competing interests declared.

Funding

This work was funded by the National Health and Medical Research Council of Australia (AP1069235, AP1146750 and Dementia Teams Grant 1095215), MJD Foundation, The Snow Foundation and Macquarie University (MQ Research Development Grant and MQ Safety Net Scheme). The Swedish SCA Network also provided donation support.

References

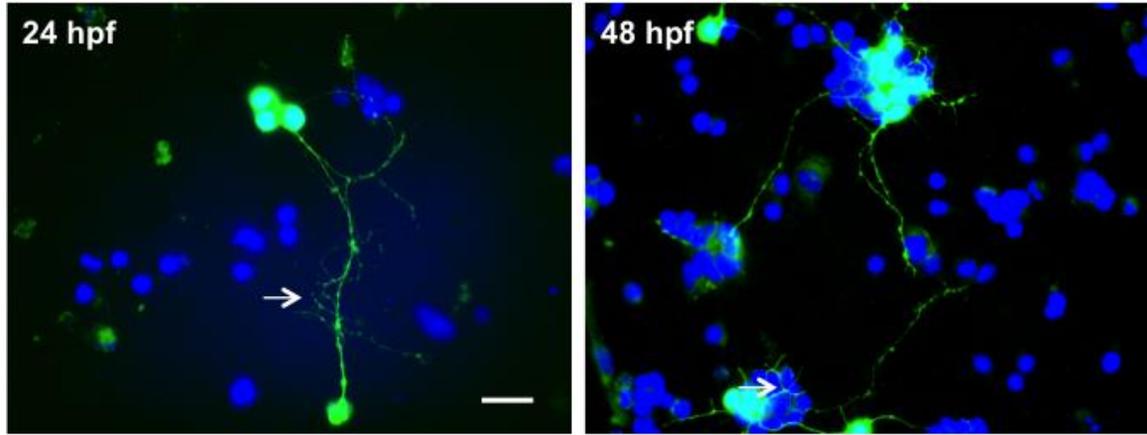
1. Babin, P.J., C. Goizet, and D. Raldua, *Zebrafish models of human motor neuron diseases: Advantages and limitations*. Prog Neurobiol, 2014.
2. Bai, Q. and E.A. Burton, *Zebrafish models of Tauopathy*. Biochim Biophys Acta, 2011. **1812**(3): p. 353-63.
3. Bandmann, O. and E.A. Burton, *Genetic zebrafish models of neurodegenerative diseases*. Neurobiol Dis, 2010. **40**(1): p. 58-65.
4. Bosco, D.A., et al., *Mutant FUS proteins that cause amyotrophic lateral sclerosis incorporate into stress granules*. Hum Mol Genet, 2010. **19**(21): p. 4160-75.
5. Kabashi, E., et al., *Gain and loss of function of ALS-related mutations of TARDBP (TDP-43) cause motor deficits in vivo*. Hum Mol Genet, 2010. **19**(4): p. 671-83.
6. Laird, A.S., et al., *Tissue-specific models of spinal muscular atrophy confirm a critical role of SMN in motor neurons from embryonic to adult stages*. Hum Mol Genet, 2016. **25**(9): p. 1728-38.
7. Lemmens, R., et al., *Overexpression of mutant superoxide dismutase 1 causes a motor axonopathy in the zebrafish*. Hum Mol Genet, 2007. **16**(19): p. 2359-65.
8. McGown, A., et al., *Early interneuron dysfunction in ALS: insights from a mutant sod1 zebrafish model*. Ann Neurol, 2013. **73**(2): p. 246-58.
9. Miller, V.M., et al., *CHIP suppresses polyglutamine aggregation and toxicity in vitro and in vivo*. J Neurosci, 2005. **25**(40): p. 9152-61.
10. Paquet, D., et al., *A zebrafish model of tauopathy allows in vivo imaging of neuronal cell death and drug evaluation*. J Clin Invest, 2009. **119**(5): p. 1382-95.
11. Ramesh, T., et al., *A genetic model of amyotrophic lateral sclerosis in zebrafish displays phenotypic hallmarks of motoneuron disease*. Dis Model Mech, 2010. **3**(9-10): p. 652-62.
12. Schiffer, N.W., et al., *Identification of anti-prion compounds as efficient inhibitors of polyglutamine protein aggregation in a zebrafish model*. J Biol Chem, 2007. **282**(12): p. 9195-203.
13. Don, E.K., et al., *A Tol2 Gateway-Compatible Toolbox for the Study of the Nervous System and Neurodegenerative Disease*. Zebrafish, 2017. **14**(1): p. 69-72.
14. Hruscha, A., et al., *Efficient CRISPR/Cas9 genome editing with low off-target effects in zebrafish*. Development, 2013. **140**(24): p. 4982-7.
15. Suster, M.L., et al., *Transgenesis in zebrafish with the tol2 transposon system*. Methods Mol Biol, 2009. **561**: p. 41-63.
16. Zon, L.I. and R.T. Peterson, *In vivo drug discovery in the zebrafish*. Nat Rev Drug Discov, 2005. **4**(1): p. 35-44.
17. Howe, K., et al., *The zebrafish reference genome sequence and its relationship to the human genome*. Nature, 2013. **496**(7446): p. 498-503.
18. Liu, W., Y. Guan, and P. Collodi, *A zebrafish cell culture assay for the identification of microRNA targets*. Zebrafish, 2010. **7**(4): p. 343-8.
19. Myhre, J.L. and D.B. Pilgrim, *Cellular differentiation in primary cell cultures from single zebrafish embryos as a model for the study of myogenesis*. Zebrafish, 2010. **7**(3): p. 255-66.

20. Robles, V., M. Marti, and J.C. Izpisua Belmonte, *Study of pluripotency markers in zebrafish embryos and transient embryonic stem cell cultures*. Zebrafish, 2011. **8**(2): p. 57-63.
21. Sakowski, S.A., et al., *A novel approach to study motor neurons from zebrafish embryos and larvae in culture*. J Neurosci Methods, 2012. **205**(2): p. 277-82.
22. Fassier, C., et al., *Zebrafish atlastin controls motility and spinal motor axon architecture via inhibition of the BMP pathway*. Nat Neurosci, 2010. **13**(11): p. 1380-7.
23. Ciarlo, C.A. and L.I. Zon, *Embryonic cell culture in zebrafish*. Methods Cell Biol, 2016. **133**: p. 1-10.
24. Sassen, W.A., et al., *Embryonic zebrafish primary cell culture for transfection and live cellular and subcellular imaging*. Dev Biol, 2017. **430**(1): p. 18-31.
25. Nguyen, H.P., C. Van Broeckhoven, and J. van der Zee, *ALS Genes in the Genomic Era and their Implications for FTD*. Trends Genet, 2018. **34**(6): p. 404-423.
26. Ling, S.C., M. Polymenidou, and D.W. Cleveland, *Converging mechanisms in ALS and FTD: disrupted RNA and protein homeostasis*. Neuron, 2013. **79**(3): p. 416-38.
27. Renton, A.E., A. Chio, and B.J. Traynor, *State of play in amyotrophic lateral sclerosis genetics*. Nat Neurosci, 2014. **17**(1): p. 17-23.
28. Vance, C., et al., *Mutations in FUS, an RNA processing protein, cause familial amyotrophic lateral sclerosis type 6*. Science, 2009. **323**(5918): p. 1208-1211.
29. Deng, H., K. Gao, and J. Jankovic, *The role of FUS gene variants in neurodegenerative diseases*. Nat Rev Neurol, 2014. **10**(6): p. 337-48.
30. Kwiatkowski, T.J., Jr., et al., *Mutations in the FUS/TLS gene on chromosome 16 cause familial amyotrophic lateral sclerosis*. Science, 2009. **323**(5918): p. 1205-8.
31. Costa Mdo, C. and H.L. Paulson, *Toward understanding Machado-Joseph disease*. Prog Neurobiol, 2012. **97**(2): p. 239-57.
32. Watchon, M., et al., *Calpain Inhibition Is Protective in Machado-Joseph Disease Zebrafish Due to Induction of Autophagy*. J Neurosci, 2017. **37**(32): p. 7782-7794.
33. Rub, U., et al., *Clinical features, neurogenetics and neuropathology of the polyglutamine spinocerebellar ataxias type 1, 2, 3, 6 and 7*. Prog Neurobiol, 2013. **104**: p. 38-66.
34. Saberi, S., et al., *Neuropathology of Amyotrophic Lateral Sclerosis and Its Variants*. Neurol Clin, 2015. **33**(4): p. 855-76.
35. Mackenzie, I.R., R. Rademakers, and M. Neumann, *TDP-43 and FUS in amyotrophic lateral sclerosis and frontotemporal dementia*. Lancet Neurol, 2010. **9**(10): p. 995-1007.
36. Acosta, J.R., et al., *Mutant human FUS Is ubiquitously mislocalized and generates persistent stress granules in primary cultured transgenic zebrafish cells*. PLoS One, 2014. **9**(6): p. e90572.
37. Dormann, D., et al., *ALS-associated fused in sarcoma (FUS) mutations disrupt Transportin-mediated nuclear import*. Embo j, 2010. **29**(16): p. 2841-57.
38. Andersen, S.S., *Preparation of dissociated zebrafish spinal neuron cultures*. Methods Cell Sci, 2001. **23**(4): p. 205-9.

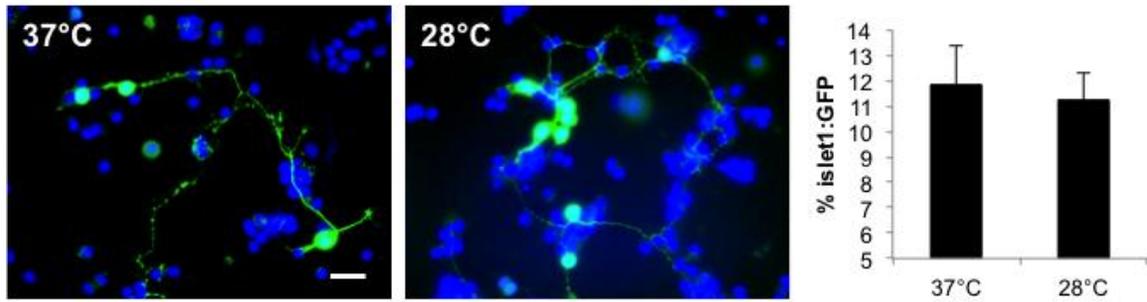
39. Carvalho, L. and C.P. Heisenberg, *The yolk syncytial layer in early zebrafish development*. Trends Cell Biol, 2010. **20**(10): p. 586-92.
40. Yamanaka, K., et al., *Mutant SOD1 in cell types other than motor neurons and oligodendrocytes accelerates onset of disease in ALS mice*. Proc Natl Acad Sci U S A, 2008. **105**(21): p. 7594-9.
41. Gal, J., et al., *Nuclear localization sequence of FUS and induction of stress granules by ALS mutants*. Neurobiol Aging, 2011. **32**(12): p. 2323.e27-40.
42. Simoes, A.T., et al., *Calpastatin-mediated inhibition of calpains in the mouse brain prevents mutant ataxin 3 proteolysis, nuclear localization and aggregation, relieving Machado-Joseph disease*. Brain, 2012. **135**(Pt 8): p. 2428-39.
43. Jakobs, S., et al., *EGFP and DsRed expressing cultures of Escherichia coli imaged by confocal, two-photon and fluorescence lifetime microscopy*. FEBS Letters, 2000. **479**(3): p. 131-135.
44. Higashijima, S.-i., Y. Hotta, and H. Okamoto, *Visualization of Cranial Motor Neurons in Live Transgenic Zebrafish Expressing Green Fluorescent Protein Under the Control of the Islet-1 Promoter/Enhancer*. Journal of Neuroscience, 2000. **20**(1): p. 206-218.
45. Whiteman, I.T., et al., *Rapid changes in phospho-MAP/tau epitopes during neuronal stress: cofilin-actin rods primarily recruit microtubule binding domain epitopes*. PLoS One, 2011. **6**(6): p. e20878.

Figures

A



B



C

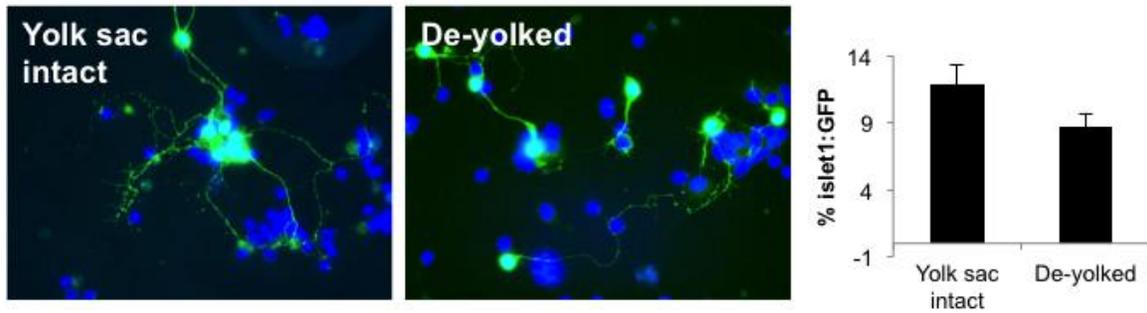


Figure 1 | Optimization of the zebrafish primary neural cell culture. **(A)** Images of cell cultures derived from 24 hpf and 48 hpf-aged embryos. Motor neurons in both cultures exhibited outgrowth of long processes (arrows). **(B)** No difference in motor neuron survival rate was evident for cells incubated at 37°C or 28°C after 1 day (cultures from 24 hpf larvae). **(C)** Motor neurons in cultures derived from de-yolked embryos exhibited shorter neurites compared to those derived from whole embryos. Note however that by 2 div (days *in vitro*), almost 100% of cells from the de-yolked cultures were non-viable (not shown). Scale bar = 10 μ m.

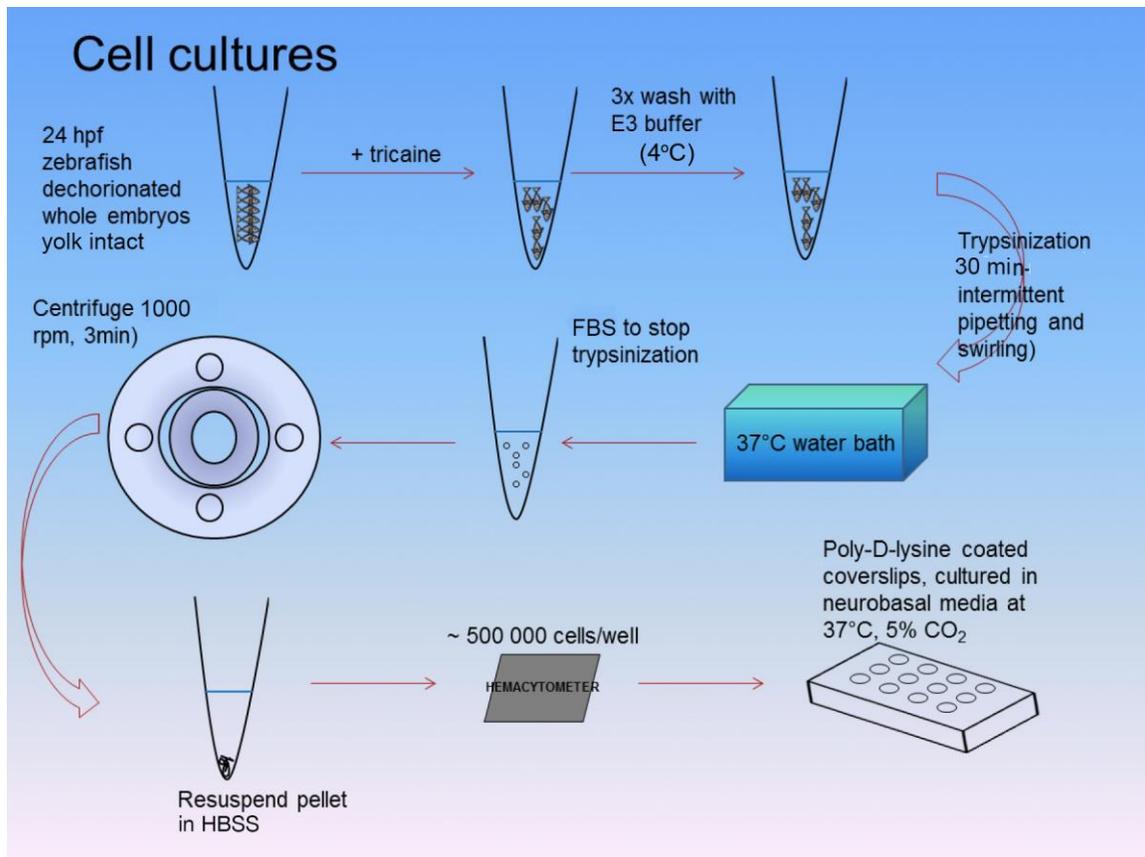


Figure 2 | Workflow for culturing zebrafish neurons. Zebrafish embryos from 24 hpf or 48 hpf aged embryos were collected, dechorionated (with fine forceps) and placed into microtubes with E3 medium and 16 μ M tricaine. Embryos were then washed 3 times with ice-cold E3 medium before being placed into 1x trypsin (in PBS) and pipetted intermittently for 30 minutes within a 37°C water bath. FBS was then added to stop dissociation and the tubes were then centrifuged for 3 minutes at 180 rcf (1000 rpm). The supernatant was removed and the cell pellet was resuspended in HBSS. Using a hemacytometer, approximately 500,000 cells were plated onto 12mm coverslips pre-coated with poly-D-lysine and cultured in neurobasal media. Half this media was changed daily.

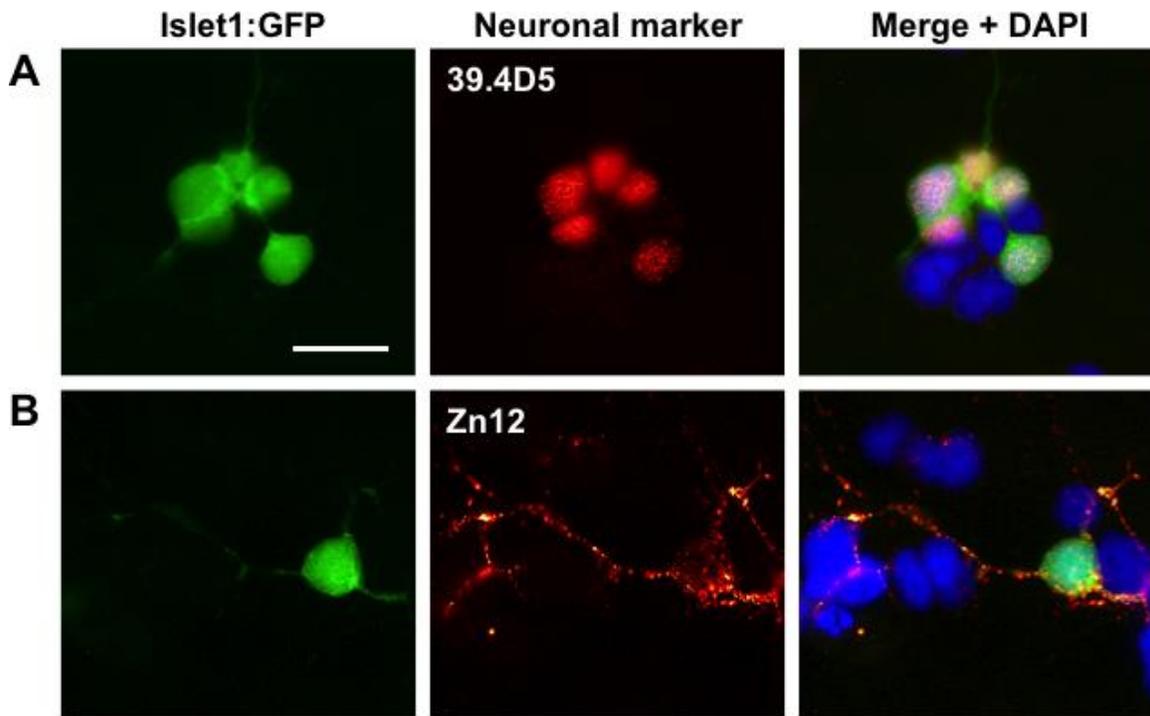


Figure 3 | Images of cultured 24 hpf Islet1:GFP zebrafish embryos stained with zebrafish-specific neuronal markers. (A) 39.4D5 (islet1 and islet2 homeobox); (B) Zn12 (neuronal cell surface marker). Scale bar = 10 μ m.

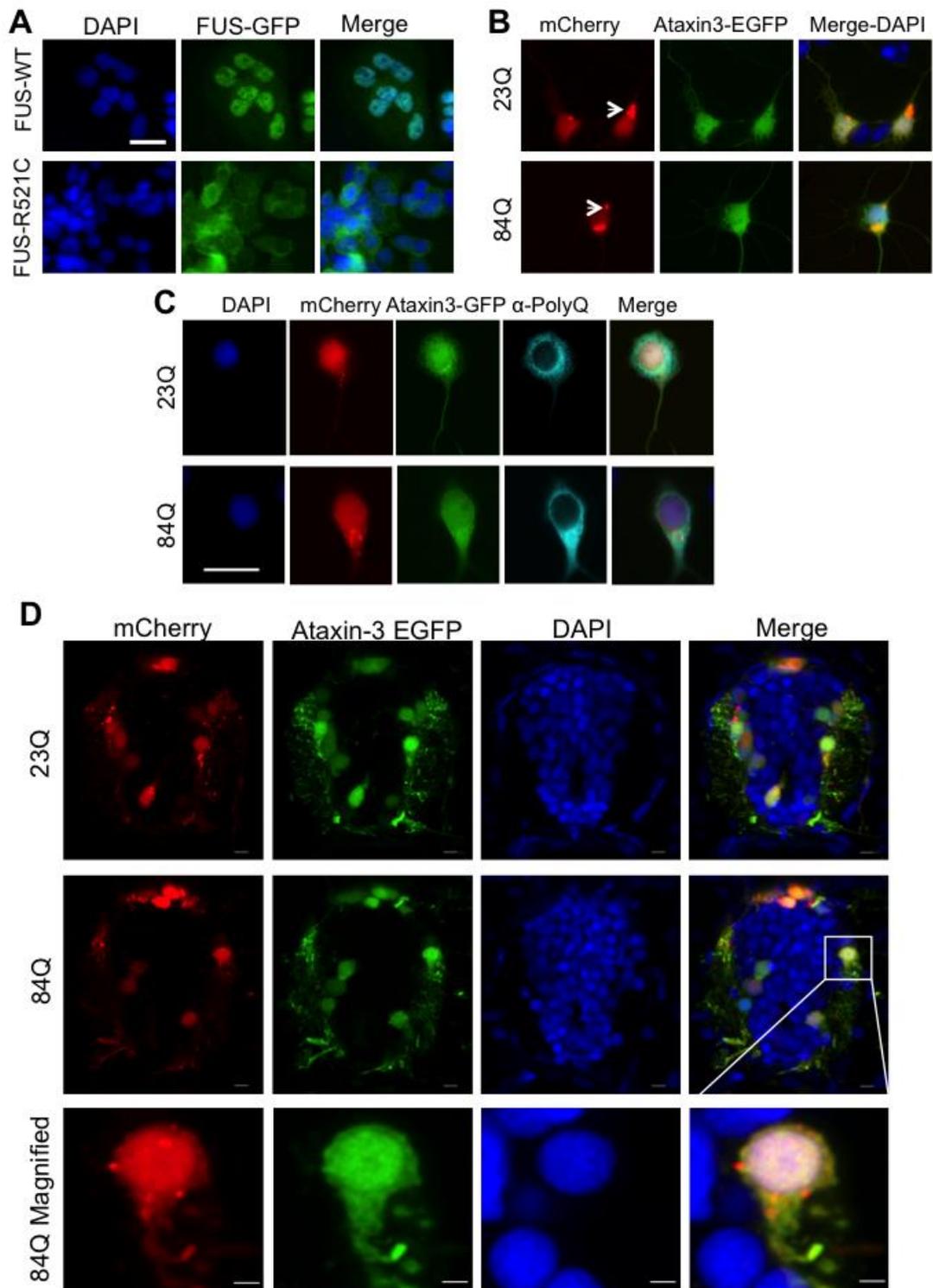


Figure 4 | Cultured cells derived from transgenic zebrafish larvae expressing neurodegenerative disease associated proteins FUS or ataxin-3. **(A)** In cells cultured from mutant human FUS-GFP (FUS-R521C) zebrafish the FUS-GFP protein was mislocalized to the cytosol whereas it remained predominantly nuclear in cells cultured from wild-type FUS-GFP zebrafish. **(B)** In cells cultured from double transgenic zebrafish expressing mCherry (red) and EGFP-ataxin-3-23Q/84Q (green) showed no obvious difference in fluorescent protein distribution in cells expressing non-pathogenic EGFP-ataxin-3-23Q and pathogenic EGFP-ataxin-3-84Q. Aggregates of mCherry-positive protein (arrows) were present in some neurons [43]. **(C)** Immunolabeling cell cultures with anti-polyQ (pale blue) demonstrated cytosolic distribution of the ataxin-3 protein in cells expressing either EGFP-ataxin-3-23Q or pathogenic EGFP-ataxin-3-84Q. Scale bars = 10 μ m. **(D)** Cross-sections of the spinal cord of 3dpf transgenic SCA3 zebrafish revealed a similar, predominately cytoplasmic, expression pattern of EGFP-ataxin-3 and mCherry to that seen in the cell cultures. Scale bars = 5 μ m.