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**Modelling human diseases in *Caenorhabditis elegans***

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44 **Abbreviations:** A β , β -amyloid peptide; AD, Alzheimer's disease; ALS, Amyotrophic
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46 Lateral Sclerosis; APP, Amyloid Precursor Protein; ASPs, aspartyl proteases; α -syn, α -
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48 synuclein; CFP, cyan fluorescent protein; CHIP, carboxyl-terminus of Hsc70 interacting
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50 protein; CLPs, calpain proteases; CNS, Central Nervous System; DA, dopaminergic
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52 neurons; DAPC, Dystrofin-Associated Protein Complex; DAT-1, Dopamine transporter -1;
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54 DGC, Dystrofin-Glycoprotein Complex; DMD, Duchenne Muscular Dystrophy; DR, Dietary
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56 restriction; Drp-1, Dynamin-related protein 1; dVAP; Drosophila VAP; ER, endoplasmic
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58 reticulum; FALS, Familiar Amyotrophic Lateral Sclerosis; FTDP-17 tau, Fronto-Temporal
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6 Dementia and Parkinsonism tau linked to chromosome 17; HIF-1, Hypoxia-Inducible
7 Transcription factor -1; HSF-1, Heat Shock Transcription Factor 1; Htt, Huntingtin; HD,
8 Huntington's disease; hVAP, human VAP; ILS, insulin-like signaling pathway; LRRK2,
9 leucine-rich repeat kinase 2; MAPK, Mitogen-Activated Protein Kinase; miRNAs,
10 microRNAs; MSP, Major Sperm Protein; NTFs, intracellular neurofibrillary tangles;
11 OPMD, Oculopharyngeal Muscular Dystrophy; PABPN1, Poly(A) Binding Protein Nuclear
12 1; PD, Parkinson's disease; PHP tau, pseudohyperphosphorylated tau; ROS, Reactive
13 Oxygen Species; RTK, Receptor Tyrosine Kinase ; SMA, Spinal Muscular Atrophy; SMN,
14 survival motor neuron gene; SOD1, Cu/Zn Superoxide dismutase 1; snb-1, synaptobrevin
15 gene -1; TGF β , Transforming growth factor- β ; ts, temperature-sensitive; VAMP,
16 (Synaptobrevin) Associated Protein B (VAPB); V- ATPase, vacuolar-ATPase; YFP, yellow
17 fluorescent protein
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Abstract

Genes linked to human diseases often function in evolutionary conserved pathways, which can be readily dissected in simple model organisms. Because of its short lifespan and the well known biology coupled with a completely sequenced genome that shares extensive homology with that of mammals, *Caenorhabditis elegans* is one of the most versatile and powerful model organisms. Research in *C. elegans* has been instrumental for the elucidation of molecular pathways implicated in many human diseases. In this review, we introduce *C. elegans* as a model organism for biomedical research and we survey recent relevant findings that shed light on the basic molecular determinants of human disease pathophysiology. The nematode holds promise of providing clear leads towards the identification of potential targets for the development of new therapeutic interventions against human diseases.

1 Introduction to *Caenorhabditis elegans* biology

The roundworm *Caenorhabditis elegans* (*C. elegans*) was selected as a simple metazoan model in the early 1960's by Sydney Brenner for pursuing research in developmental biology and neurobiology. Since its introduction as a model organism, *C. elegans* has been widely used to investigate important biological processes most of which have remained essentially unchanged during evolution [1]. *C. elegans* is a free-living, non-parasitic nematode, with a life cycle of 3.5 days at 20°C and a lifespan of about 2 to 3 weeks under suitable living conditions. The adult is about 1mm in length and 80µm in diameter; it feeds on bacteria such as *Escherichia coli* in liquid medium or on agar plates and can be easily cultivated in large numbers. *C. elegans* has five pairs of autosomes and one pair of sex chromosomes. It has two sexes, hermaphrodites and males; the ratio of sex chromosomes to autosomes determines its sex. A single hermaphrodite produces ~300 progeny by self-fertilization and more if it mates with males which arise occasionally at a frequency of 0.1%. Wild-type individuals consist of 959 somatic cells, 302 of which are neurons. The animal body is transparent so it is easy to track cells and follow cell lineages and biological processes [2]. The genome size of *C. elegans* is about a hundred million base pairs, is completely sequenced and surprisingly similar to that of humans; it is estimated that 60-80% of the genes have a human counterpart [3]. Viable mutant strains, strains that overexpress a gene or lack a gene function can be efficiently generated and the resulting phenotypes can be rapidly identified [4]. Comprehensive information concerning gene structure, expression patterns, protein-protein interactions, mutant or RNAi phenotypes and microarray data, is available in Wormbase, the online resource for nematode-related information (<http://www.wormbase.org/>) [5]. Nematode strains can be stored indefinitely in liquid nitrogen allowing for generating large mutant collections and public mutant repositories. *C. elegans* is amenable to unbiased forward and reverse genetic screens and particularly susceptible to gene inactivation by RNA interference [6, 7]. Due to its value as a research tool, a large set of methods that include advanced high resolution imaging techniques have been developed.

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C. elegans has emerged as a powerful experimental system to study the molecular and cellular aspects of human disease *in vivo*. It has been estimated that about 42% of the human disease genes have an orthologue in the genome of *C. elegans* including those genes associated with Alzheimer disease, juvenile Parkinson's disease, spinal muscular atrophy, hereditary non-polyposis colon cancer, and many others age-related disorders [8-10]. Modelling a human disease in a simple invertebrate, such as *C. elegans* allows the dissection of complex molecular pathways into their component parts and thus provides meaningful insight into the pathogenesis of a complex disease phenotype. Here, we survey nematode models of human disease, highlighting recent discoveries that shed light on the molecular mechanisms underlying disease pathogenesis.

2 *C. elegans* models of neurodegenerative disorders

Neurodegeneration has a profound effect on human health, yet the mechanisms underlying neuronal injury and death remain unclear. *C. elegans* models of neuronal dysfunction have been established for a number of neurodegenerative diseases, including Alzheimer disease, Parkinson disease and polyglutamin-expansion disorders. These models typically involve the transgenic expression of human disease genes.

2.1 Alzheimer's disease (AD)

Alzheimer's disease (AD) is a progressive neurologic disease that results in the irreversible loss of neurons particularly in the neocortex. The brain of AD affected patients is characterized by the accumulation of intracellular neurofibrillary tangles (NFTs) composed of the microtubule-associated protein tau that stabilizes microtubules when phosphorylated [11] and of extracellular senile plaques primarily composed of the β -amyloid peptide (A β) [12]. Compelling evidence supports the causative role of (A β)₁₋₄₂,

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which derives from the proteolysis of Amyloid Precursor Protein (APP) by β - and γ -secretase, in AD. Similarly, mutations in the tau gene lead to familiar tauopathies.

Autosomal dominant mutations in APP are correlated with rare cases of early-onset AD. Determining the *in vivo* functions of APP is difficult because mammals have an APP gene family containing two APP-related genes. *C. elegans* has a single APP-related gene, the *apl-1* mapped on the X chromosome. *Apl-1* is expressed in multiple cell types and is necessary for many developmental processes, including proper molting and morphogenesis. Loss of *apl-1* causes larval lethality which can be rescued by neuronal expression of the extracellular domain of APL-1. Similarly, the overexpression of APL-1 causes defects in movement, brood size and larval viability of transgenic nematodes. *Apl-1* overexpression-induced lethality is partially rescued by the reduced activity of *sel-12*, a *C. elegans* homologue of the human γ -secretase gene component presenilin 1, suggesting that SEL-12, like mammalian PS1, regulates either directly or indirectly the activity of APL-1 [13].

C. elegans AD models were developed that express A β variants under the control of male-specific, body wall muscle-specific and neuronal-specific promoters. Only transgenic lines carrying the *unc-54/A β ₁₋₄₂* minigene accumulate intracellular A β and show a progressive paralysis beginning in young adulthood. Co-immunoprecipitation studies coupled with mass-spectrometry reveal that chaperone-related proteins (two human HSP70, 3 HSP-16 homologous to α B-crystallin and a putative negative regulator of HSP70 function) interact with A β *in vivo*. This interaction is considered as part of a cellular protective response since the overexpression of either HSP-16.2 or a human HSP70 partially suppresses the A β -induced paralysis in worms [14]. Heat shock treatment reduces A β oligomeric protein and delays paralysis in transgenic A β worms probably through the activation of heat shock proteins regulated by the HSF-1 transcription factor [15]. HSF-1 has been coupled to normal ageing and age-related

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6 diseases [16]. Previous studies showed that constituents of *Ginkgo biloba* leaf extract
7 (EGb 761 and ginkgolides) delay beta amyloid-induced paralysis in transgenic *C. elegans*
8 [17]. This effect was not additive to protective heat shock suggesting a shared
9 mechanism of action by two treatments [15]. Microarray analysis in a transgenic worm
10 strain, that accurately expresses a temperature inducible A β ₄₂ in body wall muscle,
11 reveals that the gene encoding the arsenite-inducible protein (*aip-1*) is upregulated as
12 part of a cellular protective response. Worms overexpressing AIP-1 show decreased
13 accumulation of A β ₄₂ peptide and attenuated paralysis. The AIP-1 human homologue,
14 AIRAPL, but not AIRAP when expressed under the control of *myo-3* promoter also
15 confers protection against A β toxicity [18]. Both AIP-1 and AIRAPL contain a predicted
16 farnesylation site known to be critical for the AIP-1 mediated longevity in *C. elegans* [19].
17 AIP-1 and AIRAPL enhance at least partially general protein turnover by acting as
18 positive regulators of proteosomal function and thus protect against A β -induced toxicity
19 [18]. The effects of tetracycline and its analogues doxycycline and minocycline on A β ₄₂-
20 induced toxicity were assayed [20] using the worms expressing a temperature inducible
21 A β ₁₋₄₂ transgene [21]. Tetracyclines successfully protected transgenic worms from the A β
22 insult by reducing the concentration of oligomers considered to be responsible for the
23 toxic phenotype. These effects were specific, dose-dependent and not linked to any
24 antibiotic activity. Furthermore, tetracyclines protect A β -expressing nematodes from
25 oxidative stress by reducing the superoxide production suggesting a potential use of
26 these drugs in targeting A β aggregates.
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49 2.2 Tauopathies

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51 Abnormal phosphorylation, aggregation and ultimately functional alteration of the main
52 microtubule-associated protein, tau, is the major cause of neurodegenerative disorders
53 known as tauopathies [22, 23]. Tau aggregates are found in AD, Pick's disease,
54 corticobasal degeneration, Down's syndrome and FTDP-17 (frontotemporal dementia
55 with parkinsonism chromosome 17 type) [24]. The most common tauopathy is
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6 Alzheimer's disease. To analyze the role of tau modification during AD progression,
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8 human tau and a pseudohyperphosphorylated (10 serine/threonine residues were
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10 changed to glutamates) PHP tau, that mimics AD- relevant tau modification, were brought
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12 under the control of a pan neuronal (a 3.4 kb upstream of the gene F25B3.3) promoter.
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14 Transgenic worms expressing either tau or PHP tau develop a phenotype of
15
16 uncoordinated (*Unc*) locomotion, characteristic of a variety of *C. elegans* nervous system
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18 defects. However, only PHP tau- expressing worms show a defective pattern of motor
19
20 neuron development suggesting that PHP tau may better mimic the stable disease-like
21
22 tau modification which interferes with mechanisms of axonal outgrowth and path finding
23
24 [25]. To identify specific modifiers for the tau-induced pathologic phenotype, a genome-
25
26 wide RNAi screen was conducted using transgenic worms expressing mutations in tau
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28 (FTDP-17 tau) driven by the *aex-3* pan neuronal promoter. 60 enhancer genes modified
29
30 only the tau-induced *Unc* phenotype. These genes normally function in protein
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32 phosphorylation, protein folding, stress response, nucleic acid function, proteolysis and
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34 neurotransmission [26]. In addition, random mutational screens on these transgenic
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36 animals resulted in the identification of two novel tauopathy-associated genes, *sut-1* and
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38 *sut-2* (suppressor of tauopathy) [27, 28]. SUT-1 requires the activity of UNC-34 which
39
40 plays a role in the correct neuronal cell migration and axonal guidance. SUT-2 encodes a
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42 CCCH zinc finger protein, primarily expressed in the nucleus of neuronal cells, which
43
44 binds ZYG-12, a protein of the HOOK family. In turn, ZYG-12 acts as a linker connecting
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46 membrane compartments with the microtubule cytoskeleton protein.
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49 **2.3 Polyglutamine-expansion disorders**

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51 Numerous human neurodegenerative disorders including Huntington's disease (HD),
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53 several spinocerebellar ataxias and Kennedy's disease [29, 30] are associated with
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55 misfolded and aggregation-prone proteins that interfere with protein homeostasis leading
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57 to cellular dysfunction. Polyglutamine diseases are caused by a CAG triplet expansion in
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6 the coding regions of seemingly unrelated genes resulting in a pathogenic protein with
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8 abnormally expanded track of glutamines (Fig.1) [31].
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11 To address the mechanisms underlying the impact of aggregation-prone proteins
12 on cellular function, transgenic *C. elegans* lines expressing different lengths of polyQ-
13 YFP (yellow fluorescent protein) or CFP (cyan fluorescent protein) from integrated arrays
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15 in muscle (polyQm) [32] or neuronal (polyQn) [33] cells have been utilized in genetic
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17 screens. These polyglutamine aggregation models show polyQ-length dependent
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19 aggregation and toxicity. *C. elegans* polyQm or polyQn strains were crossed with animals
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21 expressing temperature- sensitive (ts) mutations considered to be sensitive indicators of
22
23 a disruption in protein homeostasis. These experiments have shown that chronic
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25 expression of an aggregation-prone protein interferes with the function of multiple
26
27 structurally and functionally unrelated proteins in a polyQ-length dependent manner.
28
29 PolyQ expansions uncover the folding defect of proteins harbouring mildly destabilizing
30
31 temperature-sensitive mutations, which in turn modify polyQ aggregation and toxicity and
32
33 enhance the disruption of cellular folding homeostasis. Thus, mild folding mutations in the
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35 genetic background can modify the toxic phenotypes of polyglutamine diseases [34].
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41 Protein aggregation and cellular dysfunction can occur at a threshold of
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43 approximately 40 glutamine residues. However, the threshold for polyQ aggregation and
44
45 toxicity is dynamic and ageing-dependent in *C. elegans*. At 3 days of age or less, only
46
47 worms expressing Q40 or greater exhibit aggregates, while in older animals aggregates
48
49 appear even in Q33 and Q35 expressing worms (32).
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52 A link between molecular determinants of ageing and aggregation-mediated
53
54 proteotoxicity was established in *C. elegans*. Polyglutamine toxicity was dependent on
55
56 the activity of *daf-16*, a forkhead transcription factor of the FOXO family functioning
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58 downstream of *age-1* (a phosphoinositide-3 kinase) in the insulin-like signalling pathway
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6 (ILS) [35]. Work on polyQ suppression shows that TOR-2, the worm ortholog of the
7 mammalian torsinA, is an ER-associated protein with chaperone activity which
8 suppresses polyglutamine aggregation in *C. elegans* [36].
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Huntington's disease (HD) is the most frequent autosomal dominant inherited
polyQ disorder caused by an expansion of a CAG trinucleotide sequence in the huntingtin
(Htt) protein. Normal Huntington alleles encode up to 37 CAG repeats, whereas HD-
affected individuals consist of more than 40.

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Previous work has shown that ubiquilin is an interactor of presenilin, a protein
associated with Alzheimer's disease. Ubiquilin proteins contain multiple ubiquitin related
domains and are linked to the ubiquitin-proteasome system of protein degradation
because both their ubiquitin-like domain and the ubiquitin-associated domain have been
shown to bind the proteosomal subunit S5a [37]. The role of ubiquilin in HD pathogenesis
was investigated using *C. elegans* expressing GFP-Htt-polyQ fusion proteins in body wall
muscle. Transgenic worms display a polyQ length-dependent motility defect which is
suppressed by ubiquilin overexpression through a mRFP-tagged ubiquilin fusion protein.
Conversely, knockdown by RNAi of *C. elegans* ubiquilin gene exacerbated the motility
defect associated with the expression of GFP-Htt (Q55) fusion protein. These findings
show that, similar to AD, ubiquilin protects against polyglutamine-induced toxicity and
they suggest a general role for ubiquilin in regulating a number of different
neurodegenerative disorders [38]. The motility defect that these *C. elegans* HD models
display is reduced by the knockdown of the gene encoding the dynamin-related protein 1
(Drp-1) which controls mitochondrial fission. This result establishes a link between HD
pathogenesis and mitochondrial dysfunction [39]. A role for insulin-like signaling pathway
(IIS) in the amelioration of Huntington's-associated proteotoxicity has been reported [16].

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Two different *C. elegans* models of human disease were used to explore the effects of dietary restriction (DR) on polyglutamine-associated age-related diseases. A HD model in which 35 glutamine residues were fused to YFP (Q35YFP) and expressed in the body wall muscles [32] and a transgenic model expressing a 42-amino acid amyloid-beta peptide (A β ₄₂) under the control of the *unc-54* promoter [40]. The results demonstrate that DR suppresses age-associated paralysis in these worms. To test if DR acts as a general suppressor of proteotoxicity, the effects of food deprivation on transgenic worms expressing an aggregation-prone form of GFP (GFP-degron) were also examined. It was shown that both environmental and genetic (represented by the RNAi inhibition of *eat-2* and the knockdown of *rab-10*, *sams-1* or *drr-1* genes that act downstream of food consumption) models of DR confer protection against proteotoxicity in *C. elegans*. Compelling evidence was presented that the general protective effect of DR is mediated by the activity of the heat shock transcription factor, *hsf-1* [41].

2.4 Parkinson's disease

Parkinson's disease (PD) is the second most common neurodegenerative disorder characterized by involuntary movements including bradykinesia and difficulty in balance and muscle rigidity due to the progressive loss of dopaminergic (DA) neurons from the substantia nigra. At cellular level, PD is characterized by cytoplasmic protein inclusions called Lewy bodies that are the pathological feature of PD and other neurodegenerative disorders known as synucleopathies [42]. α -synuclein (α -syn), a major constituent of Lewy bodies, is causatively related to PD since missense mutations in the α -syn gene or duplications and triplications of the α -syn locus cause familial forms of PD [43-45]. Sporadic PD affecting 1-4% of those over 65 years of age appears to be unrelated to mutations or multiplications of the α -syn locus and implicates a combination of environmental factors. How α -syn inclusions are formed and how this links to disease is poorly understood. Synucleopathies have been associated with mitochondria dysfunction,

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6 defective autophagy, impairment of the ubiquitin-proteasome system, production of
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8 reactive oxygen species (ROS), stress within the ER [46].
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11 The worm genome includes orthologs of all established familiar PD genes
12 (*Parkin*, *DJ-1*, *PINK1*, *UCHL-1*, *LRRK2*, *PARK9* and *NURR1*) except the α -syn. A
13
14 transgene bearing Rab1 guanosine triphosphate, a GTPase involved in endoplasmic
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16 reticulum to Golgi transport, under the control of the dopamine transporter (*DAT-1*) gene
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18 promoter was used to drive the expression of Rab1 along with α -syn in DA neurons in a
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20 worm PD model. Human α -syn overexpression in *C. elegans* leads to the formation of
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22 misfolded α -syn aggregates that increase with age. Coexpression of Rab1 significantly
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24 rescued the neurodegeneration caused by the expression of α -syn alone. Considering
25
26 that Rab1 plays an essential role in ER-Golgi vesicles trafficking and its enhanced
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28 expression protects against α -syn pathology, these combined results indicate that the
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30 accumulation of α -syn inhibits the ER-Golgi trafficking [47]. Once coexpressed, TOR-2
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32 [48] ameliorated the formation of these aggregates by associating with α -syn in Lewy
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34 bodies [49].
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39 Worms expressing both α -syn::GFP and TOR-2 in body wall muscles were used
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41 in a large-scale RNAi screen for modifiers of α -syn misfolding and neurodegeneration.
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43 868 candidate genes potentially associated with existing PD genes and pathways were
44
45 targeted for knockdown. 20 gene products that enhance misfolding of human α -syn upon
46
47 depletion were isolated. The neuroprotective genes, F32A6.3, the *C. elegans* ortholog of
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49 VPS41, a conserved vesicular protein, essential for lysosomal biogenesis, W08D2.5, the
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51 worm orthologue of *PARK9* and F55A4.1 (orthologue of *Sec22p*), a well characterized
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53 vesicular trafficking protein in yeast, were among those identified. The identification of *C.*
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55 *elegans* *ATG7* as a neuroprotective gene indicates the significant role of autophagy and
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57 lysosomal function in preventing the DA neurons loss caused by excess α -syn [48]. To
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59 further characterize the processes involved in inclusion bodies formation, a genome-wide
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6 RNAi screen was performed in transgenic worms expressing the α -synuclein-YFP
7 chimaera driven by the *unc-54* promoter. The screen identified 80 suppressors, of which
8 49 have an established human ortholog. Most of the genes are involved in protein quality
9 control and vesicle trafficking between the ER-Golgi as well as other vesicular
10 compartments. Moreover, this screen uncovered several regulators of life span (the
11 NAD⁺ dependent protein deacetylase *sir-2.1*, the sphingolipid synthase *lagr-1*) as
12 modifiers of inclusion formation suggesting a link between the molecular mechanisms of
13 ageing and α -synuclein pathology [50].
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23 Mutations in GTPase (R1441C/G) and kinase (G2019S) domains of leucine-rich
24 repeat kinase (LRRK2) are the most frequent cause of autosomal dominant and
25 idiopathic PD [51, 52]. Expression of human LRRK2 in *C. elegans* neurons modifies the
26 response to mitochondrial inhibition, inferred by the increased survival of worms exposed
27 to rotenone or paraquat, which are agents that impair mitochondrial function. These
28 findings demonstrate the power of the nematode as a model to study the possible gain-
29 of-function phenotype acquired by LRRK2 mutations. *lrk-1* is the sole *C. elegans*
30 orthologue of LRRK2. *lrk-1* and LRRK2 seems to share similar functions since LRRK2
31 complements the sensitization to rotenone caused by the *lrk-1* knockdown. These results
32 indicate a role for LRRK2 and its worm orthologue in regulating mitochondrial dysfunction
33 [53]. R1441C/G and G2019S mutations increase kinase activity of LRRK2 *in vitro* [54,
34 55]. The role of LRRK2 in PD pathogenesis was investigated *in vivo* using transgenic *C.*
35 *elegans* overexpressing human LRRK2 wild type, R1441C/G and G2019S mutations and
36 a LRRK2-inactive mutation K1347A in dopaminergic neurons. All transgenic worms show
37 an age-dependent degeneration of DA neurons, locomotor dysfunction, behavioural
38 abnormalities and dopamine deficiency. In contrast, loss of endogenous LRRK-1 and the
39 GTP binding defective mutation, K1347A, ameliorated LRRK2-associated phenotypes
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2.5 Amyotrophic lateral sclerosis (ALS)

Amyotrophic lateral sclerosis (ALS), the most common motor neuron disorder, is characterized by dysfunction or death of motor neurons in the motor cortex, brain stem and spinal cord. Approximately 10% of ALS cases are familial with an autosomal dominant inheritance [57] and ~20% of familial ALS (FALS) are associated with mutations in the gene coding for Cu/Zn superoxide dismutase (SOD1) [58] that catalyzes the conversion of highly reactive superoxide anions into hydrogen peroxide [59]. While it is accepted that toxic gain of function mutations in SOD1 gene evoke the disease phenotype, the mechanisms of toxicity remain unclear.

Transgenic *C. elegans* expressing FALS- related mutant (A4V, G37R, G93A) human SOD1 are more sensitive to paraquat-induced oxidative stress than control worms expressing wild-type human SOD1. Moreover, the transgenic worms that harbour gain of function alleles show an aberrant accumulation and aggregate formation of mutant proteins under oxidative stress. Thus, oxidative damage during ageing might cause FALS by inhibiting degradation and enhancing aggregate formation of mutant SOD1 proteins [60].

G85R, an ALS-associated human mutant SOD1, causes a severe locomotor defect in transgenic *C. elegans* when expressed pan-neuronally under the control of the synaptobrevin (*snb-1*) gene promoter. Paralyzed animals have soluble oligomers and insoluble aggregates in neurons. The movement defect results from the dysfunction of synapses, the connections between neurons and between neurons and muscles. An RNAi screen identified molecular chaperones as critical modifiers of protein aggregation – mediated toxicity [61]. Expression of three distinct SOD1 mutations (G85R, G93A, 127X) in the body muscle cells of wild type (N2) worms cause only mild cellular toxicity. However, when SOD1 mutants are expressed in the background of destabilized protein polymorphisms, their toxicity is enhanced. These results suggest that the genetic

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6 background may intensify the specific toxic phenotypes of misfolded and aggregation-
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8 prone proteins that characterize conformational diseases [62].
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11 A recent study identified the gene ALS8 as a novel cause of ALS [63]. Mutations
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13 in ALS8, as in SOD, result in a wide range of defects which vary in the age of onset, the
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15 speed of progression and the motor neurons affected. This variation may be due to
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17 genetic modifiers, redundancy or environmental contribution. ALS8 codes for VAMP
18
19 (Synaptobrevin) Associated Protein B (VAPB) which is closely related to VAPA, a protein
20
21 associated with the cytoplasmic face of the endoplasmic reticulum (ER) and the Golgi
22
23 apparatus [64-66]. Many species have VAPs proteins characterized by the major sperm
24
25 protein domain (MSP) of about 125 residues in the amino (N)-terminal end [67], the
26
27 central region of coiled-form motif and the hydrophobic carboxy (C)-terminus which acts
28
29 as a membrane anchor. The MSP domain is named from its similarity to *C. elegans*
30
31 MSPs, the most abundant proteins in the worm sperm [68].
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35 MSP function in the oocyte maturation and sheath contraction in *C. elegans* [69].
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37 After secretion, extracellular MSP directly binds to the VAB-1 Eph receptor and other yet
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39 to be identified receptors on oocyte and ovarian cell surfaces [70].
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43 The biological function of VAPs and the mechanisms underlying their impact in
44
45 ALS pathogenesis is not well understood. To define the role of VAPs, *C. elegans* was
46
47 used together with other model systems. *C. elegans* has a single VAP homolog, the VPR-
48
49 1 and VAP MSP domains share a 25% identity in their primary sequences with MSPs.
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51 Injection of recombinant VPR-1 MSP stimulated oocyte maturation and sheath
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53 contraction in the gonads of worms lacking MSP and sperm, suggesting that *C. elegans*
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55 MSP and VAP MSP domains have evolutionary conserved extracellular signalling activity.
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57 Microinjection of *Drosophila* VAP (dVAP) and hVAP also induced both responses. It is
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59 shown that VAPs regulate Eph receptor signalling *in vivo*. MSP domains of VAP proteins
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6 are cleaved and secreted ligands for Eph receptors. Mutations in VAPs may result in a
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8 failure to secrete the MSP domain, accumulation of inclusions in the endoplasmic
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10 reticulum and an unfolded protein response. These findings provide insight into the
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12 disease mechanism [71].

13 14 15 **2.6 Spinal muscular atrophy (SMA)**

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17 Spinal muscular atrophy (SMA), the most common genetic cause of infant mortality, is an
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19 autosomal recessive neuromuscular disorder. SMA patients suffer from degeneration of
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21 lower motor neurons in the anterior horn of the spinal cord leading to atrophy of the
22
23 corresponding muscles [72]. The survival motor neuron gene (SMN) has been
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25 causatively linked with the SMA, but the mechanisms underlying the disease
26
27 pathogenesis are poorly understood. Given that SMN is widely expressed both within and
28
29 outside the nervous system [73], the specific motor neuron defect that the SMA patients
30
31 face may be rather linked to the gene function [74]. *C. elegans smn-1* gene has been
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33 identified as the orthologue of human SMN [75] with a widespread expression in various
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35 tissues including the nervous system and body wall muscles. The mutant *smn-1(ok355)*
36
37 harbours a deletion allele which removes most of *smn-1* including the translational start
38
39 codon. Having reduced SMN-1 levels throughout the organism, *smn-1(ok355)* is used for
40
41 modelling aspects of SMA. Mutant animals proceed through embryogenesis due to
42
43 maternally contributed SMN-1, but showed late larval arrest, decreased lifespan, defects
44
45 in motility and pharyngeal pumping. Neuronal, but not muscle-directed expression of full
46
47 length *smn-1* partially rescues the *smn-1(ok355)* phenotype [76]. A genome-wide RNAi
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49 screen and behavioural studies in the loss of function *smn-1(ok355)* mutant strain provide
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51 preliminary evidence that the TGF β /BMP signalling pathway plays a role in the SMN-
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53 mediated neuromuscular pathology in *C. elegans* [77].

54 55 56 **3 Stroke – Excitotoxicity**

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6 Necrotic cell death underlies the pathology of numerous human degenerative conditions
7 [78]. In *C. elegans*, non-apoptotic cell death (necrosis) is triggered by specific genetic
8 lesions or environmental conditions such as energy depletion, toxin exposure or extreme
9 temperatures. Severe deprivation of energy resources can rapidly develop during
10 ischaemic or hypoglycaemic episodes. Prolonged hypoxia, a condition of oxygen
11 deprivation that takes place in ischemic episodes and stroke, also induces cell death in *C.*
12 *elegans* [79]. The most thoroughly characterized necrosis-induced mutations in the
13 nematode are gain of function mutations in specific ion channel genes, such as degenerin
14 genes *deg-1* and *mec-4*, the acetylcholine receptor channel subunit gene *deg-3* and the
15 Gs protein α -subunit gene *gsa-1*, which result in necrotic cell death of neurons expressing
16 the mutant proteins [80]. Execution of necrotic cell death requires the activity of calcium-
17 regulated CLP-1 and TRA-3 calpain proteases and ASP-3 ASP-4 aspartyl proteases.
18 Perturbation of intracellular concentrations of calcium, either by extracellular calcium
19 influx or by release of endoplasmic reticulum stores, activates calpain proteases which in
20 turn engage executioner aspartyl proteases leading to cell destruction [81]. In mammalian
21 models of excitotoxicity, calpains increase Ca^{2+} concentration by mediating the cleavage
22 of specific glutamate receptors [82]. Aspartyl proteases are either cytoplasmic or
23 lysosomal that are released into the cytoplasm as a result of lysosomal rupture.
24 Acidification of the cytoplasm due to the action of hydrolytic enzymes deliberated during
25 the lysosomal rupture requires the vacuolar H^+ -V-ATPase (V-ATPases), a proton pump
26 that acidifies endocytic compartments. Similar mechanisms may underlying the extreme
27 acidosis that is observed during stroke in humans [83]. Evidence supports that lysosomes
28 contribute to execution of necrosis. Suppression of lysosome biogenesis and of
29 lysosome-mediated cytoplasmic acidification, that develops during necrosis and is
30 required for cell death, affects necrosis in *C. elegans* [84]. A working model for necrotic
31 cell death and cellular defense pathways such as autophagy that may underlie diverse
32 aspects of development, tissue homeostasis and disease pathogenesis in *C. elegans* is
33 outlined in Fig. 2.

4 Muscle-associated disorders

Dystrophin is a huge cytosolic protein that links the intracellular F-actin filaments to the members of the dystrophin-glycoprotein complex (DGC) [85, 86]. Genetic defects in the complex components cause a variety of pathological conditions including muscular dystrophy, cardiomyopathy and vasospasm. Determining the molecular function of the complex will increase our understanding of muscle diseases pathogenesis. *C. elegans* has a dystrophin complex (DAPC) and mutations in its components result in head bending and hypercontraction [87, 88]. Several lines of evidence couple defects in the DAPC with calcium homeostasis disruption through a mechanism involving the ISLO-1 which mediates the interaction of SLO-1 (the orthologue of the mammalian BK channel) with DAPC. A defect in either DAPC or ISLO-1 impacts SLO-1 channel localization resulting in muscle hyperactivity [89].

4.1 Duchenne muscular dystrophy (DMD)

Duchenne muscular dystrophy (DMD) is one of the most severe X-linked childhood diseases, characterized by progressive muscle wasting and weakness due to mutations in dystrophin gene [90]. A *C. elegans* DMD model carrying mutations in *dys-1* and *h1h-1*, the worm orthologues of the human dystrophin and MyoD respectively, was used to investigate the effects of *chn-1* on muscle degeneration. *Chn-1* encodes the homologue of the human E3/E4 ubiquitylation enzyme CHIP (carboxyl-terminus of Hsc-70 interacting protein) that is strongly expressed in both neurons and muscles [91]. Downregulation of *chn-1* by mutation, as well as by pharmacological treatment with a proteosomal inhibitor (MG132) improves the motility of DMD worms. Muscle-specific decrease of CHN-1 activity is sufficient to control muscle degeneration in dystrophin mutant animals. These data suggest a specific role of CHN-1/CHIP in the control of muscle degeneration through the ubiquitin-proteasome pathway [92].

4.2 Oculopharyngeal muscular dystrophy (OPMD)

Oculopharyngeal muscular dystrophy (OPMD) is a late-onset autosomal dominant myopathy characterized by eyelid ptosis, dysphagia and limb-girdle muscle weakness [93]. A short polyalanine (GCG-triplet) stretch from 10 alanines to at least 13 alanines in the gene encoding polyalanine binding protein 1 (PABPN1) on chromosome 14q cause gain of function mutations leading to misfolding, aggregate formation and dysfunction of the ubiquitin proteasome system [94-96]. However, the pathogenesis of disease remains unclear.

In a *C. elegans* OPMD model, loss of function mutations in *sir-2.1/SIRT1* and *daf-16* protect transgenic worms from the muscle decline and abnormal motility induced by expression of mutant (13 alanines) PABPN1 protein [97].

5 Cancer

Cancer is a major cause of human mortality and typically evolves as a multistep process from mutations in key cellular genes. Although *C. elegans* does not form tumours *per se*, other mutant phenotypes are linked to worm homologues of human cancer genes, which often function at distinct steps within evolutionary conserved pathways. Thus, identifying *C. elegans* genes that disrupt processes relevant to cancer could contribute importantly to our understanding of the cancer gene functions.

Several studies show that c-Met, a receptor tyrosine kinase (RTK) is overexpressed and amplified in many human cancers [98-102]. Mutations in the c-Met juxtamembrane domain as well as germline mutations have been identified in small cell lung cancer [103] and in non-small cell lung cancer [104] cases respectively.

Transgenic worms expressing wild type c-Met or the frequent human lung cancer specific c-Met mutants (R988C and T1010I) were generated in order to investigate a

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cancer gene function in a whole organism context. Mutant transgenic worms show locomotion defects, low fecundity and vulval hyperplasia, phenotypes intensified upon exposure to nicotine [105].

The RTK/Ras/Raf/MAPK signalling pathway is highly conserved and interfaces with many aspects of animal development. Work in *C. elegans* has greatly contributed in our understanding of this pathway and its regulation [106]. In *C. elegans*, Ras controls vulval induction and its hyperactivation interferes with vulval cell differentiation leading to a multivulval phenotype [107]. Vulval development provides a model system to understand cell proliferation and differentiation, deregulation of which is causatively linked to human tumours.

Recently, the role of miRNAs in human cancer is extensively studied. miRNAs are small non-protein coding RNA molecules of ~21-23 nucleotides which control gene expression at the post-transcriptional level acting as developmental timing regulators [108]. Many of the 112 miRNAs identified so far in *C. elegans* are conserved across phylogeny. Compelling evidence suggests that miRNAs are involved in the regulation of ageing and metabolism and provides insight into their function as tumour suppressor genes or oncogenes.

Several miRNAs act in the Notch and Ras signalling pathways [109-111]. miR-84, a *let-7* family miRNA, targets *let-60*, a *C. elegans* orthologue of HRAS, KRAS and NRAS, the human ras oncogenes. All of the human ras genes have complementary sites for human *let-7* family miRNAs in their 3'UTRs, suggesting a similar mode of regulation as the worm *let-60* [110]. Gain of function mutations in *let-60* result in a multivulval phenotype which is partially suppressed by mir-84 overexpression [112]. Accumulating evidence suggests that *let-7* acts as a tumour suppressor gene. Similarly, miR-61 which

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6 targets *vav-1*, a homologue of the Vav oncogene family in vertebrates [113] may
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8 influence cancer through the regulation of Notch signalling [111].
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11 The role of apoptosis in cancer treatment sensitivity is well established. Apoptosis
12 is a genetically regulated cell death mechanism that is required for normal development
13 and homeostasis. Defects in key apoptotic proteins can interfere with tumourigenesis and
14 chemotherapy [114]. Therefore, understanding at the molecular level the events that
15 affect DNA damage- induced apoptosis is important for cancer research. The apoptotic
16 molecular pathway is highly conserved [115].
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25 In *C. elegans*, germline apoptosis limits the number of oocytes competing for
26 nutrients in the gonad. It can also be activated in response to pathogenic microorganisms
27 invasion or DNA damageing agents and genotoxic stress [116]. The p-53/ CEP-1, CED-9
28 (Bcl-2), CED-4 (Apaf1) and CED-3 (caspase) proteins function in the checkpoint
29 machinery of DNA damage-induced germline apoptosis. A recent study reveals that the
30 hypoxia-inducible transcription factor (HIF-1) antagonizes the function of CEP-1 in DNA-
31 damage induced apoptosis. HIF-1 inhibits apoptosis by transcriptionally upregulating the
32 tyrosinase family member TYR-2 in the ASJ neurons. Then, TYR-2 is secreted and once
33 entering the gonad, it blocks apoptosis. These findings yield insight into a novel pathway
34 through which two single neurons regulate apoptotic fate in another tissue. Ultimately,
35 this pathway links hypoxia to apoptosis. Knock down of the TYR-2 homologue TRP2 in
36 human melanoma cells increases basal and cisplatin-induced p53 apoptosis, indicating
37 an evolutionary conserved function. TYR-2 would be a candidate target in new
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60 therapeutic strategies [117].

6 Metabolic diseases

The O-GlcNAc signalling pathway, one of the most evolutionary ancient pathways,
couples the nutrient-dependent synthesis of UDP-GlcNAc to O-GlcNAc modification of

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6 Ser/Thr residues of a large number of nuclear and cytoplasmic protein targets.

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8 Accumulating data suggest the involvement of O-GlcNAc cycling in age-associated
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10 human diseases such as insulin resistance, X-linked Dystonia Parkinsonism, cancer and
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12 disease of the immune system.

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16 Two highly conserved enzymes are responsible for the cycling of O-GlcNAc on
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18 Ser/Thr residues of target proteins. The glycosyltransferase, OGT and the O-GlcNAcase
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20 which mediate the addition and the removal of O-GlcNAc respectively. The identification
21
22 of the enzymes involved in O-GlcNAc cycling led to the detection of their interacting
23
24 partners. Two-hybrid screens reveal diverse proteins associated with vesicle and
25
26 organelle movements in neurons, mitochondrial movement or factors involved in the
27
28 control of gene expression that interact with OGT. In *C. elegans*, two-hybrid analysis
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30 indicates the interaction of OGT-1 with MAPK, PMK-1. The highly conserved hexosamine
31
32 biosynthetic pathway is upstream of O-GlcNAc cycling. Accumulating findings suggested
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34 a link between the hexosamine biosynthetic pathway, O-GlcNAc cycling and mammalian
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36 insulin resistance [118].

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39 *C. elegans* strains having putative null alleles of *ogt-1* (ortholog of O-GlcNAc
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41 transferase) or *oga-1* (ortholog of O-GlcNAcase) provide versatile platforms for studying
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43 the role of O-GlcNAc in cellular signaling and metabolism. Nuclear transport of
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45 transcription factors is normal in homozygous *ogt-1(ok430)* [119] and *oga-1(ok1207)*
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47 knockout animals [120], yet the *ogt-1(ok430)* mutant completely lack any detectable O-
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49 GlcNAc on nuclear pore proteins, whereas the *oga-1(ok1207)* accumulated O-GlcNAc.
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51 Both mutant strains show increased glycogen and trehalose levels and decreased lipid
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53 storage. The link of human OGT and OGA to insulin resistance, prompted the
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55 examination of the impact of *ogt-1* and *oga-1* deletions on the insulin- like- signaling
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57 pathway controlling nutrient storage, dauer formation, longevity and stress responses in
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59 *C. elegans*. *oga-1 (ok1207)* knockout enhances dauer formation induced by a
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6 temperature sensitive allele of the insulin-like receptor *daf-2* (*e1370*) [120] under
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8 conditions in which the *ogt-1(ok430)* null allele lowers dauer formation [119]. *C. elegans*
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10 is the first animal with viable and fertile knockout alleles of OGA or OGT, which provide
11
12 genetically amenable models of non-insulin dependent diabetes. Use of O-GlcNAc
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14 cycling mutants in high-throughput RNAi screening revealed the interaction of *ogt-1* with
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16 essential components of important signaling pathways such as β -catenin. In mammals, β -
17
18 catenin triggers key developmental switches including the formation of T-cells and B-cells
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20 in adaptive immunity [121].
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24 Accumulating evidence suggests that the enzymes of O-GlcNAc cycling may play
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26 a role in modulating transcription [122, 123]. The impact of null alleles of O-GlcNAc
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28 cycling genes on chromatin structure and gene expression can be globally examined in
29
30 *C. elegans*. Whole-genome chromatin immunoprecipitation (ChIP)-on- chip tiling arrays
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32 revealed over 800 promoters where O-GlcNAc cycling occurs including microRNA genes
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34 and multigene operons. Transcriptional profiling of O-GlcNAc knockout mutants
35
36 confirmed the deregulation of numerous genes associated with insulin-like signaling,
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38 ageing, stress response, innate immunity and carbohydrate/lipid metabolism [124]. These
39
40 findings suggest that altered O-GlcNAc cycling has important implications in the diseases
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42 associated with ageing, including obesity, type II diabetes mellitus, cardiovascular
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44 diseases, cancer and neurodegenerative diseases.
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48 In *C. elegans*, insulin and its signaling pathway is implicated in the regulation of
49
50 fat storage and reproduction and in modulating lifespan. *daf-2*, the homologue of the
51
52 mammalian insulin receptor, is part of a signal transduction cascade homologous to the
53
54 insulin pathway in mammals. DAF-2 knockout induces dauer formation and extends
55
56 lifespan. Restoration of DAF-2 function specifically in neurons is sufficient to restore
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58 lifespan and reproduction of *daf-2* knockouts to wild-type levels. Growing evidence
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60 suggests that impaired insulin signaling in the central nervous system (CNS) plays a

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fundamental role in the pathogenesis of common metabolic diseases, including obesity and type 2 diabetes [125].

C. elegans provides a versatile platform for dissecting the molecular mechanisms underlying glucose-mediated impact on cellular and mitochondrial function in diabetes. An intracellular glucose concentration of 14mmol/l, which is within the range observed in poorly controlled diabetes patients, results in methylglyoxal-derived modifications of mitochondrial proteins and increase in ROS formation thus reducing lifespan in *C. elegans*. These effects are independent of osmotic pressure and the pathways activated by caloric restriction in *eat-2* mutants and the insulin-like receptor *daf-2/daf-16* pathway. Conversely, high glucose-mediated lifespan reduction in *C. elegans* is dependent on glyoxalase -1-controlled mitochondrial complexes II and III. Further studies should delineate the relevance of these mechanisms described in *C. elegans* to the situation in diabetic patients [126].

MicroRNAs, have also been implicated in the regulation of glucose and lipid metabolism and hence in the initiation and progression of diabetes and its specific complications. miRNAs which play a critical role in the pathogenesis of the disease may serve as potential biomarkers for prognosis and diagnosis of diabetes. Furthermore, the altered expression profiles of miRNAs in the pancreas and insulin-targeted tissues in diabetic patients could provide insights for treating this complex metabolic disease [127].

7 Concluding remarks

Accumulating evidence demonstrates that most of the important pathways such as insulin signalling, Ras/Notch signalling, p53, many miRNAs have remain essentially unchanged during evolution. Many human diseases, including cancer, originate from mutations in genes functioning in pathways conserved in *C. elegans*. Although nematode disease models might not perfectly recapitulate the pathophysiology of human disease, the small,

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6 transparent worm enables the use of powerful genetic and molecular approaches to
7 dissect the toxicity mechanisms and determine the *in vivo* factors that exacerbate or cure
8 pathological conditions. Besides being an excellent model for drug target identification, *C.*
9 *elegans* is amenable to high-throughput screens for rapid and inexpensive drug
10 evaluation before embarking on expensive and elaborate animal models.
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Table 1. Selected human disease models in *Caenorhabditis elegans*.

Disease	Disease-associated protein	Characteristic pathology in <i>C. elegans</i>	<i>C. elegans</i> findings with potential therapeutic relevance
AD	β -amyloid peptide	Muscle-associated human $A\beta_{1-42}$ deposits [14] Neuronal $A\beta$ expression induces defect in chemotaxis [17]	Delay of $A\beta_{1-42}$ -mediated paralysis by heat shock treatment [14] and Ginkgolide A [17]
	APP/APL-1	Severe developmental defects induced by inactivation or overexpression of <i>apl-1</i> [13]	AIRAPL/AIP-1 suppresses $A\beta$ toxicity [18] Tetracycline and its analogues protect from β -amyloid- induced toxicity [20]
AD-relevant tau	PHP-tau	Insoluble highly phosphorylated tau aggregates in neurons linked to a defective pattern of motor neuron development [25]	
PG	polyQ aggregates	Muscle (polyQm) [32] or neuronal (polyQn) [33] induced toxicity	TOR-2 mediated suppression of polyQ aggregation [36]
HD	Expression of human Htt (Q>40) in body wall muscle	Motility defects [38]	Rescue of disease phenotype by ubiquitin overexpression [38] Amelioration of the motility defect by Drp-1 knockdown [39] Suppression of proteotoxicity by DR [41]
PD	Human α -syn expression in dopaminergic neurons W08D2.5/PARK9, B0432.2/DJ-1, EEED8.9/PINK1 LRRK2/LRK-1	Lewy body formation, selective degeneration of dopaminergic neurons [47] Knockdown by RNAi enhances misfolding of human α -synuclein [48] Enhanced loss of dopaminergic neurons [53]	Co-expression of Rab1 rescue the degeneration [47] Co-expression of TOR-2 ameliorates the aggregate formation [48] <i>sir-2.1</i> /SIRT1, <i>lagr-1</i> /LASS2 suppress α -synuclein inclusion formation [50] Autophagy confers neuroprotection [48]
ALS	SOD1 ALS8/VPR-1	Pan-neuronal expression caused severe locomotion defect [61] Mild body muscle toxicity influenced by the genetic background [62]	
SMA	SMN/SMN-1	Late larval arrest, decreased lifespan, defects in motility and pharyngeal pumping [76]	<i>smn-1(ok355)</i> deletion mutant as a useful platform for functional analysis of human SMN protein [77]

Stroke- Excitotoxicity	Specific ion channels (DEG-1, MEC-4, DEG-3, GSA-1 in nematode) Specific proteases (calpains CLP-1, TRA-3 and aspartyl proteases ASP-3, ASP-4 in nematode)	Neurodegeneration [80, 81]	Inhibition of executioner proteases (ASP-3, ASP-4) suppresses necrosis [81] Alterations of lysosome biogenesis and function by genetic or pharmacological treatment could affect necrotic cell death [84]
DMD	Dystrofin/dys-1	Muscle degeneration [90, 91]	<i>chn-1</i> /CHIP elimination in the musculature suppresses muscle degeneration [92]
OPMD	PABPN1	Muscle cell decline and abnormal motility [97]	Treatment with sirtuin inhibitors protect against mutant PABPN1[97, 128]
Cancer	c-Met	Locomotion defects, low fecundity and vulval hyperplasia [105] Anti-apoptotic factor, antagonizes p53/CEP-1, interferes with tumor progression and therapy [117]	
	<i>let-60</i> /ras oncogenes <i>vav-1</i> /Vav	Multivulval phenotype [109- 111]	
	<i>cep-1</i> /p53	Apoptotic defects interfere with tumorigenesis and resistance to chemotherapeutic drugs [114]	
	HIFa/HIF-1	Anti-apoptotic factor, antagonizes p53/ <i>cep-1</i> , interferes with tumour progression and therapy [117]	Target TYR-2/TRP2 [117]
Metabolic diseases (insulin resistance, type 2 diabetes)	<i>ogt-1</i> , <i>oga-1</i>	Null mutations cause alterations in carbohydrate and lipid metabolism [119, 120, 124]	Overexpression or inhibition of specific miRNAs may be a future tool for targeting diabetes [127]

Figure legends

Figure 1. Pathogenesis of polyglutamine diseases. Polyglutamine expansion disorders are caused by abnormally expanded tracks of polyglutamine residues (polyQ) in seemingly unrelated proteins. In many cases, abnormal proteolytic cleavage of the affected proteins could result in toxic folding intermediates, oligomers and aggregates which ultimately form intracellular inclusions. Damaged proteins cannot be degraded through the ubiquitin (proteosomal) and lysosomal degradation pathways. Thus, the accumulation of unwanted proteins may lead to neurodegeneration. Mitochondrial dysfunction has also been linked to polyglutamine-expansion proteotoxicity.

Figure 2. The complex interplay between autophagy, cell survival and cell death. Autophagy is a catabolic process responsible for the degradation of long-lived proteins, molecules and organelles. Cellular material to be degraded is engulfed in double-membrane vesicles, called autophagosomes, which undergo fusion with lysosomes to form autolysosomes where hydrolases degrade the cytoplasmic material. Free fatty acids and amino acids produced by this process can be reutilized by the cell to maintain ATP levels and protein synthesis, contributing to cell survival. Starvation or growth factor deprivation induces autophagy by inhibiting TOR signalling. Autophagy contributes to life span extension under caloric restriction in many organisms including yeast, nematodes, flies and mammals. Mutations in genes functioning in various steps of the autophagy pathway suppress cell death triggered by diverse stimuli. Pharmacological inhibitors block distinct steps of the autophagic pathway (red blocking lines). Autophagy is implicated in neurodegeneration in *C. elegans*. Diverse genetic or environmental insults lead to elevated cytoplasmic calcium concentration disturbing calcium homeostasis. Increased calcium concentration activates cytoplasmic calpain proteases causing lysosomal membrane rupture and release of lysosomal components into the cytoplasm which becomes acidified. The vacuolar H⁺ ATPase (V-ATPase) pump is responsible for lysosomal and

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6 subsequent cytoplasmic acidification. Low pH conditions favour the activation of
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8 cathepsin proteases contributing to cell death. Autophagy is up-regulated upon induction
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10 of necrosis directly and / or through calpain activation and synergizes with lysosomal
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12 cathepsin proteases to mediate cell death. Similarly impaired autophagy can be
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14 deleterious by allowing damaged organelles and proteins to accumulate. Expression of
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16 human disease genes in worms disturbs cellular homeostatic mechanisms and induces
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18 stress, which beyond a certain threshold, becomes detrimental. TCA: tricarboxylic acid; 3-
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20 MA: 3-methyladenine; $[Ca^{2+}]$: cytoplasmic calcium concentration; V-ATPase: vacuolar H⁺-
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22 ATPase; ER: endoplasmic reticulum; SERCA: sarco-endoplasmic reticulum; InsP3R:
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24 inositol triphosphate receptor; RyR: ryanodine receptor.
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8 **Bios**

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12 **Nektarios Bio**

14 Nektarios Tavernarakis is a Research Director at the Institute of Molecular
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25 European Molecular Biology Organisation (EMBO) Young Investigator award,
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27 award, and is member of EMBO.
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42 **Maria Bio**

44 Maria Markaki is a staff scientist in the *Caenorhabditis elegans* molecular genetics
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48 mechanisms that underlie the effects of autophagy on ageing.
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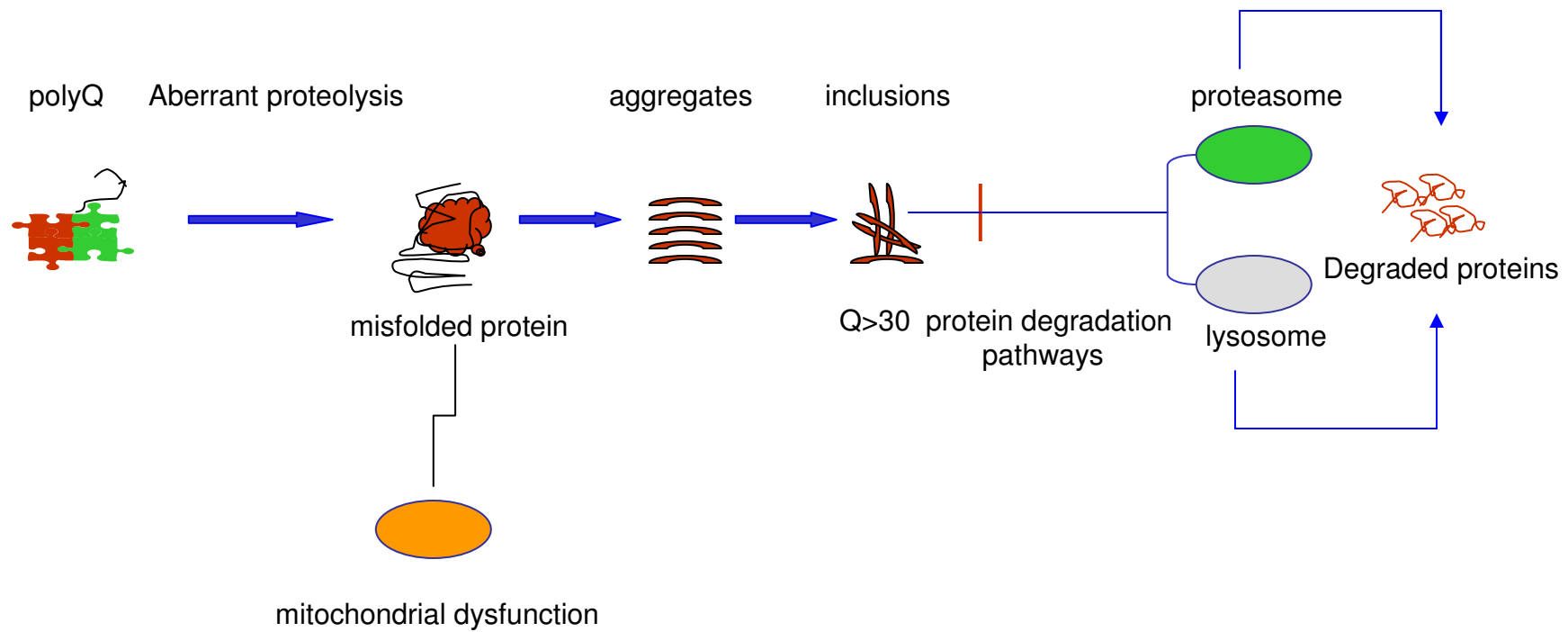


Figure 1 - Markaki & Tavernarakis

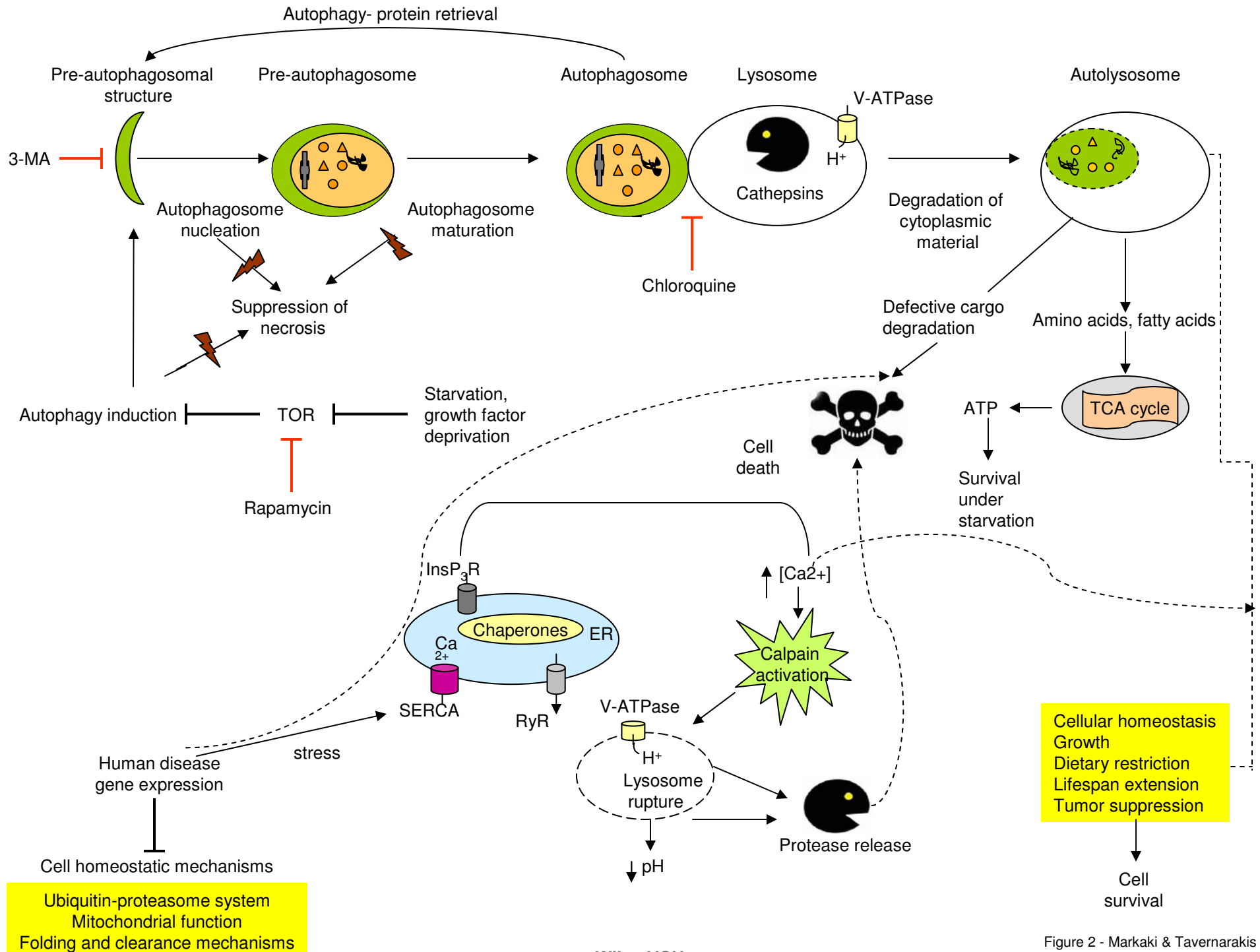


Figure 2 - Markaki & Tavernarakis

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