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1 **Dynamic Modulation of Autophagy: Implications for aging and cancer**

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15 **Keywords**

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4 **23** ***ABSTRACT***

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6 **24** *Reduced autophagy has been implicated in aging, yet whether its loss can promote aging*
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8 **25** *phenotypes and pathologies in mammals, and how reversible this process is, has never been*
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10 **26** *fully explored. Using inducible short hairpin RNA (shRNA) mouse models, we have recently*
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12 **27** *shown that autophagy inhibition accelerates aging, and that even a temporary block in*
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14 **28** *autophagy can create irreversible damage that increases a cancer risk.*
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21 **30** Aging is associated with a loss of proteostasis, organelle homeostasis, as well as an
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23 **31** accumulation of damaged and misfolded aggregates¹ Thus, it is no surprise that increasing age
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25 **32** is associated with a corresponding decrease in autophagy. Whilst conventional and conditional
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27 **33** knockout mouse models of essential autophagy genes have provided important insights into
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29 **34** the role of autophagy in development and disease, aging studies have been difficult to perform
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31 **35** either due to the associated neonatal lethality, or the rapid adult neurotoxicity that inevitably
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33 **36** occurs with systemic autophagy loss.^{2,3}
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40 **38** Despite the technical limitations to explore autophagy and aging in mammalian systems,
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42 **39** numerous studies have provided supportive evidence that regimens intended to promote
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44 **40** autophagy, both through lifestyle (dietary restriction) and pharmacological modulation, can
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46 **41** promote health-span.^{4,5} However, these approaches are pleiotropic in nature, often promoting
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48 **42** autophagy through upstream mechanisms that impinge upon additional signaling cascades.
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50 **43** Recently, two genetic studies have shown that by promoting autophagy constitutively, mice
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52 **44** display an increased health-span and reduced rates of spontaneous tumorigenesis.^{6,7} Together
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54 **45** these data provide compelling evidence that pharmacological modulation of autophagy may
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56 **46** have broad-spectrum health benefits.
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4 48 In our recent publication, we attempted to provide answers to some of the outstanding questions
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6 49 that remain in the field of autophagy and mammalian aging. The first was simply, is a systemic
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9 50 reduction in autophagic flux enough to promote aging and age-related phenotypes in a
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11 51 mammalian system? Whilst the second was, if yes then are these effects reversible by
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13 52 restoration of autophagy? This latter point is of importance as it argues for the correct timepoint
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15 53 of intervention. Is it possible to reverse pathological phenotypes, or is it more effective to
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17 54 prevent the damage from ever accruing?
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23 56 To circumvent the limitations imposed by traditional (systemic) knockout mice, we employed
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25 57 doxycycline-inducible short hairpin RNA (shRNA) models to achieve body-wide temporal
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27 58 control of autophagy through the targeting of *Autophagy-related 5 (Atg5)*, an essential
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29 59 autophagy component (termed ‘Atg5i’ mice). A major caveat of our inducible system is that
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31 60 doxycycline is poorly permeable across the blood-brain-barrier and as such the system shows
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33 61 no activation in the brain, leaving autophagy intact in this organ.⁸ We realized that this
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35 62 discrepancy of system activation provided us with a unique opportunity to perform long-term,
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37 63 ‘systemic’ autophagy experiments without the associated neurotoxic effects seen in whole-
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39 64 body knockout models (e.g. systemic *Autophagy-related 7 [Atg7]* knockout in adult mice leads
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41 65 to death between 2 to 3 months³). Furthermore, we have developed two models with shRNAs
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43 66 of different inhibition efficiencies. The original Atg5i mice provided a knockdown efficiency
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45 67 that generated gross phenotypes akin to those seen in knockout mice (hepatomegaly and
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47 68 splenomegaly)⁸, whilst the second hairpin mouse line (termed Atg5i-2) was hypomorphic,
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49 69 leading to a reduction in autophagy without these obvious associated pathologies.⁹
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60 71 In our latest work, Atg5i mice were aged until eight-weeks old, to separate out developmental
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62 72 from tissues homeostatic effects, before being placed on a doxycycline-containing diet to
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4 73 inhibit autophagy.⁹ As expected, although they survive premature death due to the neuronal
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6 74 toxicity, mice with autophagy inhibition still displayed dramatically reduced life-spans
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8 75 compared to normal mice in both the shRNA's tested (Atg5i median survival 185 days).
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10 76 Furthermore, they displayed evidence of phenotypes that occur with increasing age such as
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12 77 greying, kyphosis, loss of muscle mass, and evidence of autoimmunity. Molecular markers of
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14 78 aging, including inflammatory cytokines, telomere-associated DNA damage, and markers of
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16 79 senescence in various tissues were also elevated in our autophagy inhibited mice. Together, the
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18 80 study provides evidence that loss of autophagy systemically induces molecular, cellular, and
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20 81 organismal phenotypes that are strongly associated with increasing age. Whilst we were unable
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22 82 to determine a singular cause of death to contributed to mortality in our Atg5i mice (as the
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24 83 cause of death appears to be non-uniform), we view this as a positive outcome for the model.
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26 84 Aging is a complex and multifaceted process that is associated with some degree of
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28 85 stochasticity, this process at least appears to be recapitulated in our Atg5i mice. Note similar
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30 86 aging phenotypes were observed in Atg5i-2 (median survival 240 days), suggesting that a
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32 87 modest decrease in autophagy reduction is sufficient for age acceleration.
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43 89 Using the Atg5i mice, we next approached our second question and inhibited autophagy in
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45 90 mice for four months, wherein Atg5i mice would universally display aging phenotypes and an
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47 91 increase in frailty. At this timepoint, we removed doxycycline from the diet and restored
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49 92 autophagy levels. Strikingly, mice showed a gross recovery in frailty and a dramatic recovery
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51 93 in their health- and life-span. However, we also noted that kyphosis and greying phenotypes
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53 94 were largely, if not completely, irreversible, whilst the molecular damage that had accumulated
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55 95 (such as telomere-associated DNA damage) was also irremediable. Thus, although
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57 96 encouraging from a translatable aspect, it is important to note that not all damage induced by
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59 97 autophagy loss was reversible in this model. Furthermore, we noted that this temporal period
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98 of reduced autophagy was associated with an increased incidence of spontaneous tumor
99 formation, suggesting that this irreversible damage can be tumorigenic in nature. We speculate
100 that preventing damage through the promotion of autophagy would be more beneficial than
101 late-stage restoration.

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103 Overall our study provides missing data further linking autophagy and mammalian aging,
104 whilst at the same time exploring the timing and efficacy of autophagy restoration therapies on
105 aging pathologies. Importantly our work also provides supportive evidence for a biphasic role
106 of autophagy in cancer development (Fig. 1). Wherein a reduction in autophagy is associated
107 with the accumulation of pro-tumorigenic damage and possibly the establishment of
108 premalignant disease without further progression, at least in the liver as previously reported.¹⁰
109 Once the irreversible damage has accumulated, a tumorous cell that has re-established
110 autophagic flux would undoubtedly have a fitness advantage, as autophagy is important for
111 basic cellular homeostasis. Although it should be noted that our work does not conclusively
112 prove this and further studies would be required. These results also raise the specter of long-
113 term cancer risk in the setting of early life autophagy inhibition, such as childhood obesity.
114 Further studies, both in mice and epidemiologically in humans, would add welcome real-world
115 data to support or refute these possibilities.

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118 No potential conflicts of interest were disclosed.

119
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148 Figure 1. Potential impact of autophagy modulation on aging and tumorigenesis

149 (1) Autophagy is required to maintain normal tissue and organismal homeostasis. (2) Loss of
150 autophagy induces premature aging phenotypes, which is associated with cellular dysfunction.

151 (3) The restoration of autophagy leads to the gross recovery of cellular and organismal
152 homeostasis. However, some effects are irreversible, such as genomic damage. We speculate
153 that the accumulation of this irreversible damage may accelerate the development of
154 spontaneous tumor formation in the presence of the intact autophagy flux.

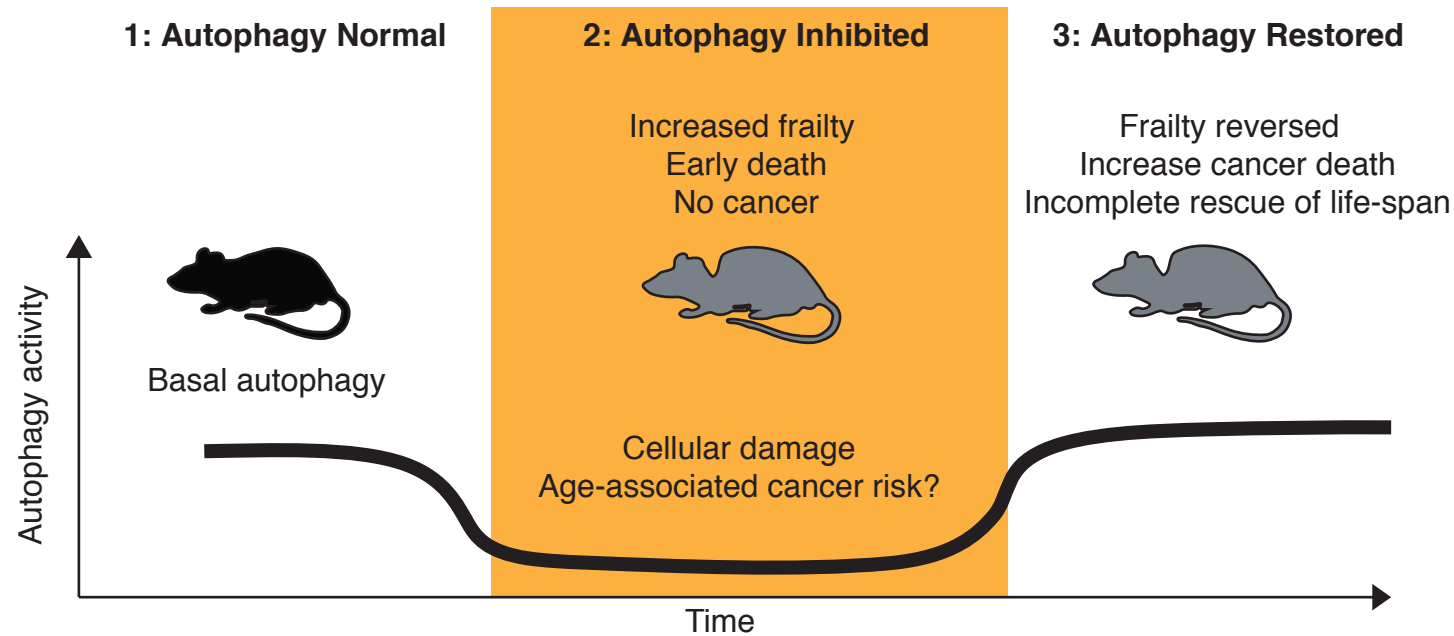


Figure 1. Potential impact of autophagy modulation on aging and tumorigenesis

(1) Autophagy is required to maintain normal tissue and organismal homeostasis. (2) Loss of autophagy induces premature aging phenotypes, which is associated with cellular dysfunction. (3) The restoration of autophagy leads to the gross recovery of cellular and organismal homeostasis. However, some effects are irreversible, such as genomic damage. We speculate that the accumulation of this irreversible damage may accelerate the development of spontaneous tumor formation in the presence of the intact autophagy flux.