

1 **Investigation of protein synthesis in *Drosophila* larvae using puromycin labelling.**

2
3 RUNNING TITLE: protein synthesis in *Drosophila* larvae

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7 Lisa Deliu^{1,2}, Abhishek Ghosh^{1,2}, Savraj S. Grewal^{1*}.

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9 ¹Clark H Smith Brain Tumour Centre, Arnie Charbonneau Cancer Institute, Alberta Children's Hospital
10 Research Institute, and Department of Biochemistry and Molecular Biology Calgary, University of
11 Calgary, Alberta T2N 4N1, Canada.

12
13 ² Equal contribution.

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20 *Author for correspondence (grewalss@ucalgary.ca)

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23 heat-shock.

1 **ABSTRACT**

2
3 **Translational control of gene expression is an important regulator of growth, homeostasis and**
4 **aging in *Drosophila*. The ability to measure changes in protein synthesis in response to genetic**
5 **and environmental cues is therefore important in studying these processes. Here we describe a**
6 **simple and cost effective approach to assay protein synthesis in *Drosophila* larval cells and**
7 **tissues. The method is based on the incorporation of puromycin into nascent peptide chains.**
8 **Using an ex vivo approach, we label newly synthesized peptides in larvae with puromycin and**
9 **then measure levels of new protein synthesis using an anti-puromycin antibody. We show that**
10 **this method can detect changes in protein synthesis in specific cells and tissues in the larvae,**
11 **either by immunostaining or western blotting. We find that the assay reliably detects changes in**
12 **protein synthesis induced by two known stimulators of mRNA translation - the nutrient/TORC1**
13 **kinase pathway and the transcription factor dMyc. We also use the assay to describe how**
14 **protein synthesis changes through larval development and in response to two environmental**
15 **stressors – hypoxia and heat-shock. We propose that this puromycin-labelling assay is a simple**
16 **but robust method to detect protein synthesis changes at the levels of cells, tissues or whole**
17 **body in *Drosophila*.**

1 INTRODUCTION

2
3 *Drosophila* is an excellent genetic model system for studying animal physiology, growth, and
4 development (Grewal, 2009; Partridge et al., 2011; Andersen et al., 2013; Padmanabha and Baker,
5 2014; Parsons and Foley, 2016). Over the last few decades, the versatility of *Drosophila* genetics has
6 led to identification of signalling pathways and gene expression networks important for normal growth,
7 development and aging. Moreover, the amenability of *Drosophila* to biochemical analyses has allowed
8 understanding of how these networks regulate cellular biochemistry and physiology.

9
10 Regulators of protein synthesis contribute to growth, stress responses, immune responses and aging.
11 Developing methods to measure protein synthesis in *Drosophila* is therefore important. Two classic
12 methods to measure translation are polysome profiling and radioactive amino acid labelling of newly
13 synthesized proteins. However, both have their drawbacks for analyzing protein synthesis in *Drosophila*
14 – polysome profiling requires large amounts of material making it difficult to analyze specific larval cells
15 or tissues, while radioactive amino acid labelling requires additional laboratory protocols and
16 procedures to deal with radioactive samples. Moreover, neither approach can be used to analyze
17 protein synthesis in situ in specific cells or tissues.

18
19 Here we present a simple, low cost assay to measure protein synthesis in *Drosophila* larval cells and
20 tissues. This assay is based on a previously described puromycin labelling assay (the SUnSET assay
21 (Schmidt et al., 2009)). Puromycin is an aminoacyl-tRNA analog that, when added to cells at low
22 concentrations, can be incorporated into nascent peptides (Nathans, 1964; Nakano and Hara, 1979;
23 Hansen et al., 1994). By using an anti-puromycin antibody, these newly synthesized puromycin-labelled
24 peptides can be detected by standard immunochemical methods, and the amount of puromycin
25 labelling hence provides a measure of nascent protein synthesis. This approach has been increasingly
26 used to monitor protein synthesis in mammalian cells (e.g. Goodman et al., 2011; Cook et al., 2014;
27 Dalet et al., 2017)). Here we show it can be applied to measure mRNA translational measurements in
28 larval tissues in response to environmental and genetic manipulations.

29 30 RESULTS AND DISCUSSION

31 32 **Measuring protein synthesis during larval development.**

33
34 We began by establishing conditions in which we could obtain reliable labelling of nascent peptides by
35 puromycin. We inverted and then incubated wildtype (w^{1118}) third instar larval carcasses in Schneider's
36 media containing increasing amounts of puromycin for forty minutes. We found that incorporation of

1 puromycin increased progressively with higher concentrations of puromycin (Figure 1A). Importantly,
2 these effects were abolished if we also co-incubated tissues with cycloheximide, indicating that the
3 puromycin incorporation was indeed a measure of protein synthesis.

4
5 We also compared the effects of carrying out the puromycin labelling in media versus PBS. We found
6 that incorporation of puromycin did occur when larval tissues were incubated with PBS, although at a
7 lower level than with incubation in Schneider's media (Figure 1B). This may be because the lack of
8 amino acids may either limit translation or may lead to loss of nutrient-dependent signaling pathways
9 such as the TORC1 kinase pathway. It is worth noting that the levels of amino acids and glucose in
10 Schneider's media are approximately the same as the levels measured in larval hemolymph (Cheng et
11 al., 2011; Pasco and Leopold, 2012). Hence, although this is an ex vivo assay, by using Schneider's
12 media for the labelling period, we are approximating some of the nutrient conditions in vivo.

13
14 In our assays we relied on lysis of whole larvae for our western blots. We therefore next compared
15 puromycin incorporation in different larval tissues. We carried out the puromycin labelling as normal
16 and then isolated specific tissues and carried out western blots. We found robust puromycin
17 incorporation in the three tissues we tested – fat body, gut and muscle – suggesting that the assay
18 conditions probably allow for measurement of protein synthesis in all larval tissues (Figure 1C).

19
20 We next compared protein synthesis levels at different stages of larval development. We found that
21 protein synthesis levels were highest in larvae examined 72 hrs after egg deposition (AED) and then
22 gradually declined throughout the remainder of larval development until wandering stage (Figure 1D).

23
24 Together these data indicate that short-term ex vivo labelling of newly synthesized peptides provides an
25 effective way to measure translation in larval tissues and whole animals during larval development.
26 Another potential approach is to use in vivo labelling of nascent peptides with puromycin to measure
27 new protein synthesis. To try this, we fed larvae food mixed with puromycin and then compared the
28 labelling of peptides by this method with the ex vivo approach described above. We initially found that
29 feeding larvae 5mg/ml of puromycin – the amount used in our ex vivo assays – showed very little
30 labelling, even after 24hrs of feeding (data not shown). We therefore tried a five-times higher
31 concentration of puromycin. In this case, we did see puromycin labelling after both 6hrs and 24hrs of
32 feeding, with the longer feeding showing higher levels of labelling (Figure 1E). However, this labelling
33 was considerably weaker than that seen with the ex vivo method, regardless of whether the ex vivo
34 labeling was carried out in PBS or media (Figure 1E). Hence, although feeding of puromycin provides a
35 method for in vivo assessment of protein synthesis, it does produce much lower levels of labelling than

1 an ex vivo method. This approach will also be subject to the caveat that altered feeding behaviour may
2 influence the amount of puromycin-labelling.

4 **Effects of nutrients/TOR signaling and Myc on protein synthesis**

6 We next examined whether the puromycin-labelling assay was sensitive to detect changes in proteins
7 synthesis mediated by modulation of known regulators of mRNA translation. In developing larvae, the
8 nutrient-dependent TORC1 kinase pathway is a major regulator of protein synthesis and growth
9 (Grewal, 2009). In nutrient-rich conditions, the TORC1 kinase pathway is activated, and promotes
10 mRNA translation and growth. However, upon nutrient deprivation, the TORC1 pathway is rapidly
11 inhibited and protein synthesis is reduced.

13 We first examined the effects of six-hour nutrient deprivation on protein synthesis in third instar
14 compared to fed controls. We carried out the puromycin labelling in Schneider's media as above and
15 we observed that the starved larvae showed a marked decrease on protein synthesis (Figure 2A). We
16 reasoned that incubating the starved larvae in Schneider's media (which contains amino acids and
17 glucose) may potentially acutely reverse some of the physiological effects of dietary starvation. Hence
18 we also performed the puromycin labelling by incubating fed vs. starved larval tissues in PBS plus
19 puromycin. We saw that the overall level of protein synthesis was lower than when the assay was
20 carried out in Schneider's media. However, as before, we found that starvation led to a marked
21 decrease in protein synthesis (Figure 2A).

23 We also looked at pharmacological inhibition of the TORC1 pathway. We carried out the puromycin
24 labelling in third instar larvae and compared the effects of addition or absence of rapamycin – a TOR
25 inhibitor – in the puromycin/media labelling solution. We saw that protein synthesis was markedly
26 reduced when larval tissues were treated with rapamycin (Figure 2C).

28 Another regulator of protein synthesis in larvae is the transcription factor dMyc. Overexpression of
29 dMyc increases expression of rRNA, tRNA, and ribosome biogenesis and translation factors in
30 *Drosophila* (Grewal et al., 2005; Steiger et al., 2008; Marshall et al., 2012). We used the hsflp-out
31 system to ubiquitously overexpress dMyc in third instar larvae. We found that dMyc induced a strong
32 increase in protein synthesis compared to control animals (Figure 3A). We also tested whether the
33 puromycin-labeling could be adapted for immunostaining to measure protein synthesis in individual
34 cells. We used the hsflp-out system to generate GFP-marked cell clones in the larval fat body and then
35 carried out the puromycin-labelling assay but detected puromycin incorporation by immunostaining with
36 the anti-puromycin antibody. We found that dMyc-overexpressing fat body cells showed a marked

1 increase in puromycin labelling compared to surrounding wildtype cells (Figure 3B). Importantly, we
2 found that cells expressing GFP alone did not show any increase in puromycin labelling (Supplemental
3 Fig1), suggesting that the increases in puromycin labelling did not simply reflect high levels of
4 transgene expression.

5
6 Together these data indicate the utility of the puromycin labelling assay to measure protein synthesis in
7 individual cells or tissues in *Drosophila* larvae.

8 9 **Regulation of protein synthesis by hypoxia and heat-shock.**

10
11 Exposure of larvae to environmental stress has been shown to affect many conserved signaling
12 pathways known to regulate mRNA translation in other organisms. We therefore used the puromycin
13 labelling assay to examine how two stressors – hypoxia and heat-shock - affect protein synthesis in
14 larvae. We first exposed third instar larvae to a 5%O₂/95%N mixture for four hours to induce hypoxia.
15 When we performed puromycin labelling, we saw that the hypoxia-treated larvae showed a marked
16 decrease in protein synthesis (Figure 4A). We next examined the effect heat-shock on protein
17 synthesis. Third instar larvae were incubated for one hour at 37°C and then the puromycin labelling was
18 carried out to measure their levels of protein synthesis compared to larvae maintained at 25°C. For the
19 heat-shock conditions, we carried out the 40 min puromycin labelling at both 25 °C and 37°C. In both
20 cases, we saw that a one hour heat-shock led to a marked increase in puromycin incorporation in a
21 large number of peptides (Figure 4B). It is likely that many of these are members of the family of heat-
22 shock proteins that are known to be induced by heat stress.

23 24 **CONCLUSION**

25
26 We describe a simple and relatively low cost *ex vivo* assay for robust measurement of protein synthesis
27 in larval cells and tissues. The assay can detect both increases and decreases in protein synthesis
28 induced by both genetic and environmental cues. Hence, the assay provides a good alternative to
29 classic approaches to measure protein synthesis such as polysome profiling and ³⁵S-methionine
30 labelling. In addition, although Click-IT chemistry has been recently developed with modified analogs of
31 both puromycin and methionine to measure protein synthesis in cells (Liu et al., 2012), these methods
32 are relatively expensive compared to the puromycin labelling approach we describe here. We suggest
33 that the ease of the assay and the ability detect translation in small amounts of tissue, will make it a
34 useful approach to monitor how protein synthesis can be regulated in a variety of different growth,
35 developmental and physiological conditions.

MATERIALS AND METHODS

Fly stocks

Flies were raised on food with the following composition: 150 g agar, 1600 g cornmeal, 770 g Torula yeast, 675 g sucrose, 2340 g D-glucose, 240 ml acid mixture (propionic acid/phosphoric acid per 34 L water). For all experiments larvae were maintained at 25°C, unless otherwise indicated. The following fly stocks were used:

*w*¹¹¹⁸ (used as our wild-type stock)

*ywhsflp*¹²²; *UAS-dMyc* (Grewal et al., 2005)

*ywhsflp*¹²²; +; +

w; +; *act>CD2>GAL4, UAS-GFP*

dMyc overexpression was achieved using the hsflp-out system. Early third instar larvae were heat shocked at 37°C for 2 hrs and then returned to 25°C. Puromycin assays were then carried out 24 hrs later.

Environmental manipulations. For nutrient starvation, third instar larvae were transferred from fly food to wet filter paper and then left for six hours. For hypoxia treatments, third instar larvae were transferred to an airtight chamber perfused with a constant flow of 5% oxygen/95% nitrogen for four hours. During this period, the larvae remained in the food and were eating as normal. For heat-shock experiments, third instar larvae were transferred from 25°C to a 37°C room for one hour.

Puromycin assay. Batches of 5-10 larvae were inverted in Schneider's media and then transferred to Eppendorf tubes containing media plus puromycin (Sigma). The larval samples were then left to incubate in a nutator for 40 mins at room temperature. For the experiments in Fig 1A puromycin was used at the indicated concentrations. For all remaining experiments, puromycin was used at 5µg/ml. For drug treatments, either cycloheximide (100µg/ml) or rapamycin (20nM, Calbiochem) were added to the media/puromycin incubation solution. Following incubation, larval carcasses were snap frozen (for subsequent western blot analyses) or fixed in paraformaldehyde (for immunostaining). For experiments on specific larval tissues, at the end of the puromycin incubation period, larval carcasses were placed in ice-cold PBS and the relevant tissues were isolated and lysed for Western blot analyses.

1 For the puromycin feeding experiments in Figure 1E, third instar larvae were transferred to normal food
2 supplemented with 25 µg/ml of puromycin. Larvae were then left to feed for the indicated times (6 or 24
3 hrs) before being snap frozen for subsequent western blot analysis.

4 5 **Western Blotting**

6 Larval tissues were lysed with a buffer containing 20 mM Tris-HCl (pH 8.0), 137 mM NaCl, 1 mM
7 EDTA, 25 % glycerol, 1% NP-40 and with following inhibitors 50 mM NaF, 1 mM PMSF, 1 mM DTT, 5
8 mM sodium ortho vanadate (Na₃VO₄) and Protease Inhibitor cocktail (Roche Cat. No. 04693124001)
9 and Phosphatase inhibitor (Roche Cat. No. 04906845001), according to the manufacturer's instruction.
10 Protein concentrations were measured using the Bio-Rad Dc Protein Assay kit II (5000112). For each
11 experiment, equal amounts of protein lysates for each sample (usually 15 µg to 40µg) were resolved by
12 SDS-PAGE and electrotransferred to a nitrocellulose membrane. Blots were then briefly stained with
13 Ponceau S to visualize total protein and then subjected to Western blot analysis with specific
14 antibodies. Protein bands were then visualized by chemiluminescence (enhanced ECL solution, Perkin
15 Elmer). Primary antibodies used were anti-puromycin (3RH11] antibody (Kerafast, Catalog No. EQ0001
16 used at 1:1000), anti-alpha-tubulin (alpha-tubulin E7, *Drosophila* Studies Hybridoma Bank), and anti-
17 phospho-S6K (Cell Signalling Technology).

18
19 **Immunostaining.** Following puromycin incubation, *Drosophila* larvae were fixed in 8%
20 paraformaldehyde/PBS at room temperature for 45 mins. After blocking for 2hrs in 1%BSA in
21 PBS/0.1% Triton-X 100, larval carcasses were incubated overnight in anti-puromycin antibody (1:1000).
22 Primary antibody staining was detected using Alexa 488 (Molecular probes) goat-anti rabbit secondary
23 antibodies. Tissues were then dissected out and mounted on coverslips using mounting media
24 (Vectashield).

25 26 **ACKNOWLEDGEMENTS**

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28 study.

29 30 **COMPETING INTERESTS**

31 No competing interests declared.

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13

1 **FIGURE LEGENDS**

3 **Figure 1. Puromycin-labelling to measure protein synthesis during larval development.** (A)

4 Larvae were inverted and whole, intact carcasses were incubated in increasing amounts of puromycin,
5 or puromycin + cycloheximide (CHX- last lane) for 40 mins. Equal amounts of whole larval protein
6 extracts were then analyzed by western blotting. Left, western blot with either anti-puromycin, or anti-
7 tubulin antibodies. Right, Ponceau S staining showing total protein levels. (B) Larvae were inverted and
8 whole, intact carcasses were incubated in either PBS + puromycin or Schneider's media + puromycin
9 for 40 mins. Equal amounts of whole larval protein extracts were then analyzed by western blotting.
10 Left, western blot with either anti-puromycin, or anti-tubulin antibodies. Ponceau S staining showing
11 total protein levels. (C) Larvae were inverted and whole, intact carcasses were incubated in Schneider's
12 media + puromycin for 40 mins. Larval tissues were then isolated and analyzed by western blotting.
13 Left, western blot with either anti-puromycin, or anti-tubulin antibodies. Right, Ponceau S staining
14 showing total protein levels. (D) Larvae at different stages in development (72hrs AED, 96hrs AED,
15 120hrs AED and wandering stage) were inverted and whole, intact carcasses were incubated in
16 Schneider's media + puromycin for 40 mins. Equal amounts of whole larval protein extracts were then
17 analyzed by western blotting. Left, western blot with anti-puromycin. Right, Ponceau S staining showing
18 total protein levels. (E) Comparing ex vivo vs. in vivo feeding for puromycin labelling. For the ex vivo
19 experiments, third instar larvae were inverted and whole, intact carcasses were incubated in either PBS
20 + puromycin or Schneider's media + puromycin for 40 mins. For the feeding experiments, third instar
21 larvae were transferred to either normal food (no puro) or normal food supplemented with 25 µg/ml of
22 puromycin (+ puro) for either 6 or 24 hrs. For both the ex vivo and in vivo samples, equal amounts of
23 whole larval protein extracts were then analyzed by western blotting. Left, western blot with either anti-
24 puromycin, or anti-tubulin antibodies. Right, Ponceau S staining showing total protein levels. Note, the
25 vertical dotted line in the western blots indicate where the blot was spliced to remove an empty lane
26 and the molecular weight ladder lane (see Ponceau S staining).

29 **Figure 2. Regulation of larval protein synthesis by nutrients and TOR signaling.** (A) Fed or six

30 hour starved third instar larvae were inverted and whole, intact carcasses were incubated in either PBS
31 + puromycin or Schneider's media + puromycin for 40 mins. Equal amounts of whole larval protein
32 extracts were then analyzed by western blotting. Left, western blot with either anti-puromycin, or anti-
33 tubulin antibodies. Ponceau S staining showing total protein levels. (B) Larva were inverted and whole,
34 intact carcasses were incubated in Schneider's media + puromycin either with DMSO (control) or
35 Rapamycin, 40 mins. Equal amounts of whole larval protein extracts were then analyzed by western

1 blotting. Left, western blot with either anti-puromycin, or anti-phospho-S6K antibodies. Right, Ponceau
2 S staining showing total protein levels.

3
4 **Figure 3. Regulation of larval protein synthesis by dMyc.** (A) The hsflp-out system was used to
5 induce ubiquitous UAS-dMyc expression in third instar larvae. Control larvae expressed UAS-GFP
6 alone. 24hrs following transgene induction. Larva were inverted and whole, intact carcasses were
7 incubated in Schneider's media + puromycin for 40 mins. Equal amounts of whole larval protein
8 extracts were then analyzed by western blotting. Left, western blot with anti-puromycin antibody. Right,
9 Ponceau S staining showing total protein levels. Genotypes: control = *ywhsflp*^{122/+}; +/+;
10 *act>CD2>GAL4, UAS-GFP/+*, *dMyc = ywhsflp*^{122/+}; *UAS-dMyc/+*; *act>CD2>GAL4, UAS-GFP/+* (B)
11 UAS-dMyc clones were generated in larval fat body cells using the flp-out system. Larvae were inverted
12 and whole, intact carcasses were incubated in Schneider's media + puromycin for 40 mins. Tissues
13 were then immunostained with and anti-puromycin antibody. The nuclear GFP-marked cells
14 overexpressing UAS-dMyc (arrows) show increased puromycin incorporation compared to surrounding
15 non-GFP marked wild-type cells (arrowheads). Genotype: = *ywhsflp*^{122/+}; *UAS-dMyc/+*;
16 *act>CD2>GAL4, UAS-GFP/+*.

17
18 **Figure 4. Regulation of larval protein synthesis by hypoxia and heat stress.** (A) Third instar larvae
19 were either maintained in room air (normoxia) or exposed to 5% O₂ (hypoxia) for four hours. Larvae
20 were then inverted and whole, intact carcasses were incubated in Schneider's media + puromycin for
21 40 mins. Equal amounts of whole larval protein extracts were then analyzed by western blotting. Left,
22 western blot with anti-puromycin antibody. Right, Ponceau S staining showing total protein levels. (B)
23 Third instar were either maintained at 25° C (control) or exposed to a one hour 37°C heat-shock. Larva
24 were then inverted and whole, intact carcasses were incubated in Schneider's media + puromycin for
25 40 mins. For the heat-shock samples the puromycin incubation was carried out either at room
26 temperature (a) or at 37°C (b). Equal amounts of whole larval protein extracts were then analyzed by
27 western blotting Left, western blot with anti-puromycin antibody or anti-tubulin antibody. Right, Ponceau
28 S staining showing total protein levels.

29
30 **Supplemental Figure 1. GFP expression alone does not alter puromycin incorporation.** UAS-GFP
31 clones were generated in larval fat body cells using the flp-out system. Larva were inverted and whole,
32 intact carcasses were incubated in Schneider's media + puromycin for 40 mins. Tissues were then
33 immunostained with and anti-puromycin antibody. The GFP-marked cells overexpressing (arrows)
34 show no change in puromycin incorporation compared to surrounding non-GFP marked wild-type cells
35 (arrowheads). Genotype: *ywhsflp*^{122/+}; +/+; *act>CD2>GAL4, UAS-GFP/+*

Figure 1

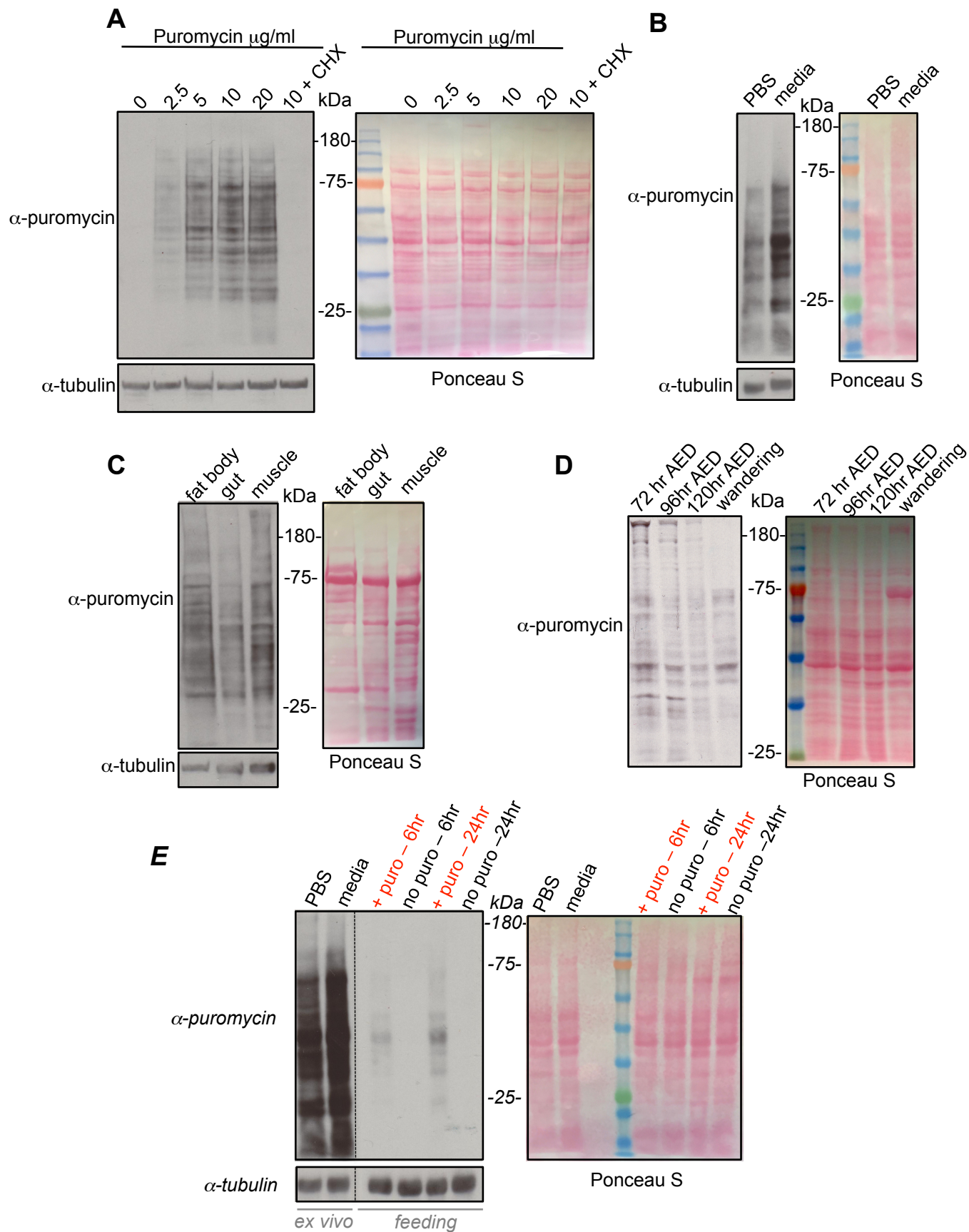


Figure 2

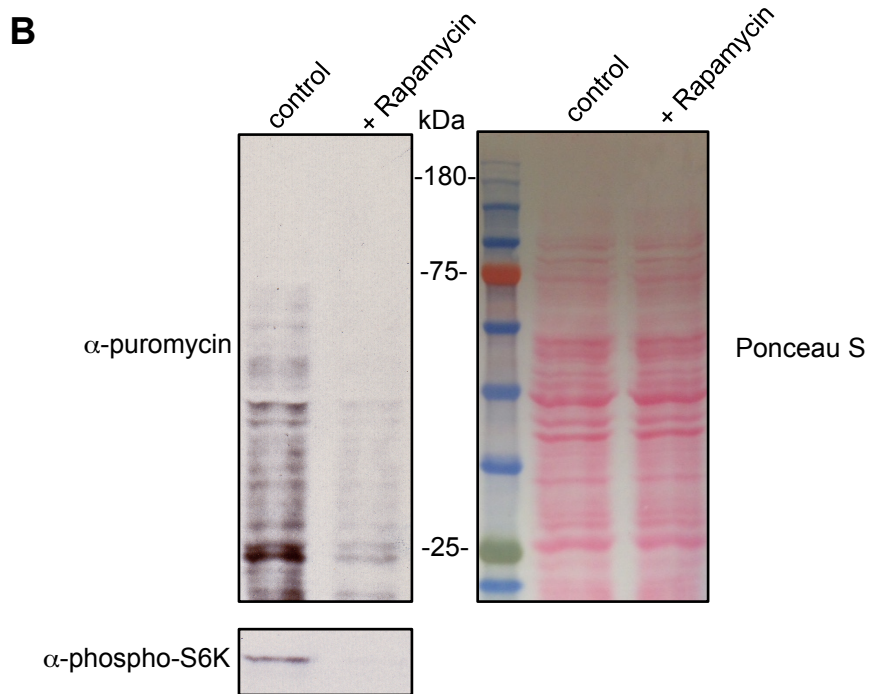
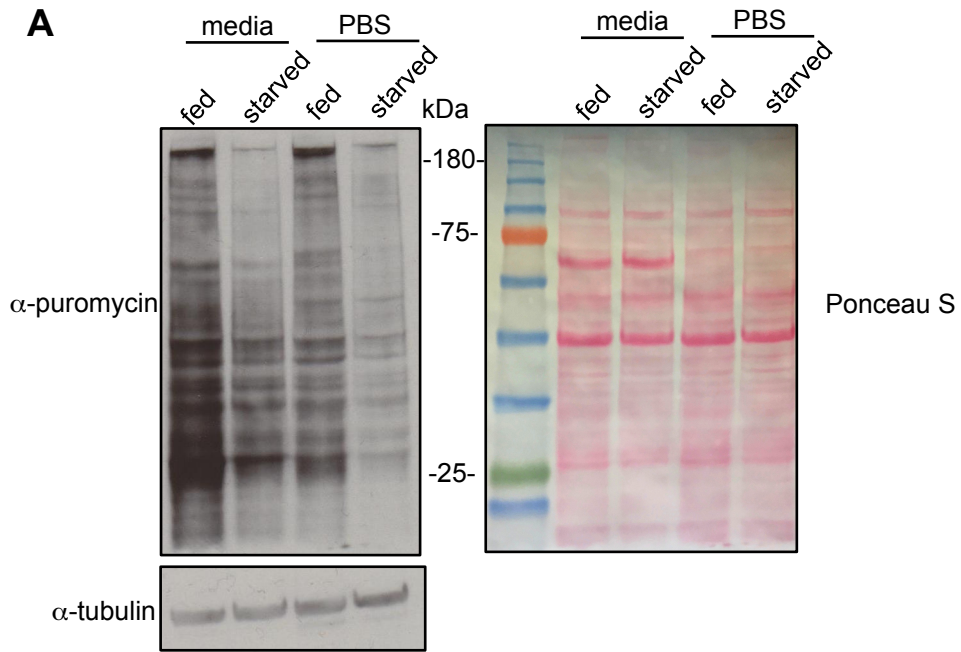
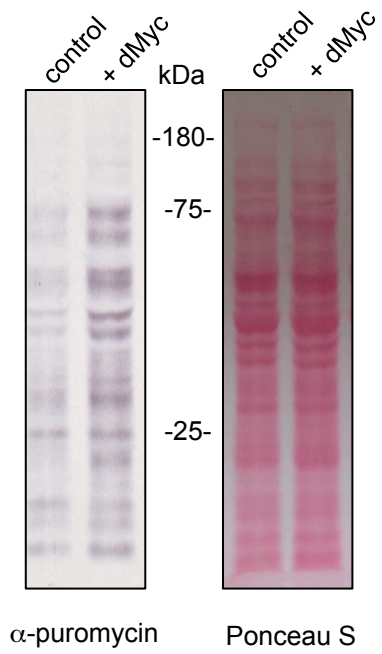


Figure 3

A



B

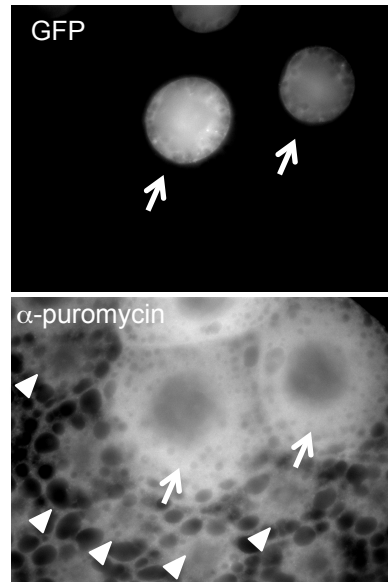
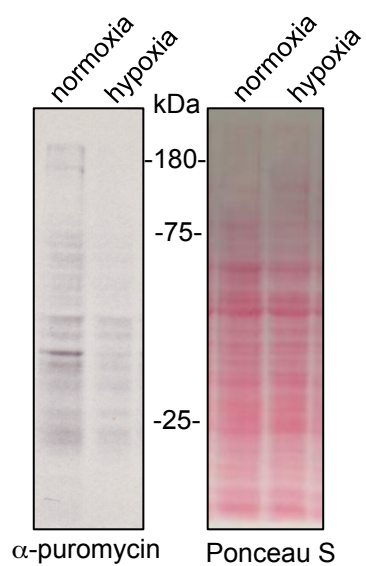
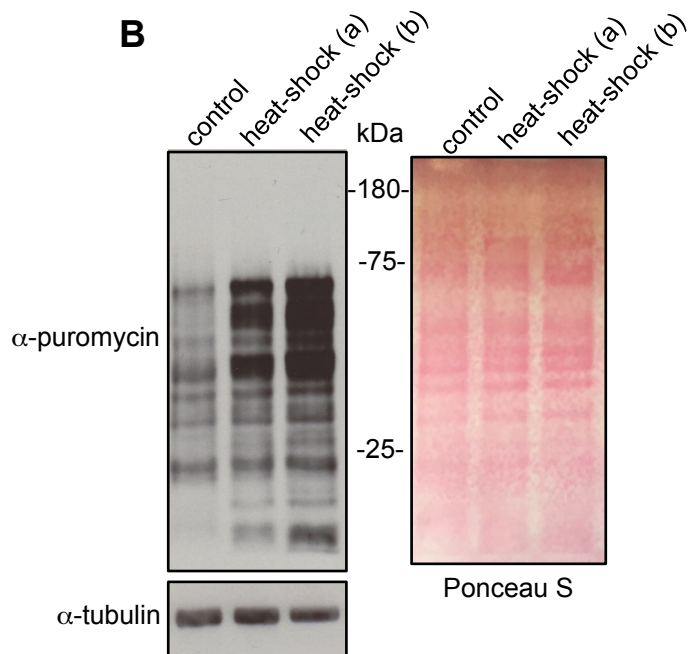


Figure 4

A



B



Suppl Figure 1

