The 5'-3' exoribonuclease Pacman (Xrn1) regulates expression of the heat shock protein Hsp67Bc and the microRNA miR-277–3p in Drosophila wing imaginal discs

Christopher I Jones1, Dominic P Grima1, Joseph A Waldron1, Sue Jones2, Hannah N Parker3, and Sarah F Newbury1,*

1Brighton and Sussex Medical School; Medical Research Building; University of Sussex; Falmer, Brighton, UK; 2Information and Computational Sciences; The James Hutton Institute; Invergowrie, Dundee, UK; 3School of Pharmacy; University of Nottingham; Nottingham, UK

Keywords: Pacman, Xrn1, RNA stability, RNA degradation, Drosophila development, imaginal discs, miRNAs, exoribonuclease, post-transcriptional control

Pacman/Xrn1 is a highly conserved exoribonuclease known to play a critical role in gene regulatory events such as control of mRNA stability, RNA interference, and regulation via miRNAs. Although Pacman has been well studied in Drosophila tissue culture cells, the biologically relevant cellular pathways controlled by Pacman in natural tissues are unknown. This study shows that a hypomorphic mutation in pacman (pcm5) results in smaller wing imaginal discs. These tissues, found in the larva, are known to grow and differentiate to form wing and thorax structures in the adult fly. Using microarray analysis, followed by quantitative RT-PCR, we show that eight mRNAs were increased in level by > 2-fold in the pcm5 mutant wing discs compared with the control. The levels of pre-mRNAs were tested for five of these mRNAs; four did not increase in the pcm5 mutant, showing that they are regulated at the post-transcriptional level and, therefore, could be directly affected by Pacman. These transcripts include one that encodes the heat shock protein Hsp67Bc, which is upregulated 11.9-fold at the post-transcriptional level and 2.3-fold at the protein level. One miRNA, miR-277–3p, is 5.6-fold downregulated at the post-transcriptional level in mutant discs, suggesting that Pacman affects its processing in this tissue. Together, these data show that a relatively small number of mRNAs and miRNAs substantially change in abundance in pacman mutant wing imaginal discs. Since Hsp67Bc is known to regulate autophagy and protein synthesis, it is possible that Pacman may control the growth of wing imaginal discs by regulating these processes.

Introduction

A key aspect in the regulation of eukaryotic gene expression is the cytoplasmic control of mRNA stability. The effect of controlled RNA turnover on gene expression can be extremely significant, for example, some studies have shown that 40–50% of changes in gene expression occur at the level of RNA stability.1 In multicellular organisms, it is increasingly evident that degradation of specific mRNAs is critical for the regulation of many cellular processes, including early development, infection, and inflammation, apoptosis and aging.2,3 For example, in mice deficient for the RNA-binding protein Tristetraprolin, the stability of RNAs such as GM-CSF, TNF-α, and Interleukin-10 increases, resulting in a systemic inflammatory syndrome with autoimmunity and bone marrow overgrowth.4,5 Therefore, transcript degradation can be selective and modulated, suggesting a little studied layer of control of gene expression affecting cellular processes.

This study focuses on Drosophila Xrn1 (Pacman), a 5'-3' cytoplasmic exoribonuclease that is highly conserved, with homologs in humans (XRN1), C. elegans (XRN-1), and S. cerevisiae (Xrn1p).9,11 Pacman/Xrn1 has been shown to processively degrade mRNAs in a 5'-3' direction after they have been decapped.2,12 Pacman is not only involved in the cytoplasmic turnover of RNA but is also required during RNA interference, degradation via miRNAs, and in nonsense-mediated decay.13 Our data, and those of others, show that Pacman is enriched in dynamic cytoplasmic particles termed P-bodies (processing bodies) and is co-localized with many of the other enzymes in the 5'-3' pathway, including the decapping enzyme Dcp2, the decapping activator Dcp1, and the helicase Me31B (Ddh1/p54 in yeast/humans).5,14-16 The crystal structure of the N-terminal region of Pacman has been determined at high resolution.17 This structure reveals that the catalytic domain comprises a pocket of basic residues which interacts with the 5' phosphate of the RNA and positions the first nucleotide for cleavage. The RNA is then pulled through the narrow entrance to the active site by a Brownian ratchet mechanism. The C-terminal domain of the protein (from residues 1140–1612), is less conserved overall

*Correspondence to: Sarah F Newbury; Email: s.newbury@bsms.ac.uk
Submitted: 12/13/2012; Revised: 06/10/2013; Accepted: 06/10/2013
http://dx.doi.org/10.4161/rna.25354
but does include some areas of conservation, termed short linear motifs (SLiMs).

It has recently been shown that a short section of the C-terminal domain of Pacman (residues 1323–1355) interacts directly with the decapping factor Dcp1 and is required for efficient mRNA decapping in Drosophila S2 cells.

Our previous work has shown that mutations in the pacman gene particularly affect growth and differentiation of tissues derived from the wing imaginal discs. Formation of wing imaginal discs begins during embryogenesis and they then grow and differentiate during larval and pupal development to generate specific adult structures such as the thorax, wings, and sensory bristles. Imaginal discs have similarities to adult stem cells in that they have the capacity to differentiate into a number of specific cell types. They therefore provide an excellent system for examining growth, differentiation, and specification of an adult tissue. Hypomorphic mutations in pacman (e.g., pcm5) result in viable adults with a number of defects, including dull wings, ruffling of the posterior wing margin, and bent or multiple sensory bristles.

When the copy number of pcm is reduced from two to one by placing the hypomorphic allele over a deletion (e.g., pcm1/Df(1)Ja27), flies can have a cleft thorax phenotype where the wing imaginal discs have failed to seal together in a process similar to wound healing. These specific phenotypes suggest that Pacman is likely to be degrading particular RNAs within wing imaginal discs.

To determine the mechanisms by which Pacman affects the development and differentiation of wing imaginal discs, it is first necessary to identify the RNAs misexpressed in this tissue in a pcm mutant. In this study, we report that a rather small number of mRNAs and miRNAs are substantially increased or decreased in levels in pcm mutant discs. Of these misexpressed mRNAs, we have identified four that are upregulated at the post-transcriptional level in pcm mutant mutants, suggesting that they could be directly affected by the Pacman exoribonuclease. The upregulated transcripts include those associated with induction of autophagy and inhibition of protein synthesis. One miRNA, miR-277-3p, was post-transcriptionally downregulated, which is consistent with Pacman being specifically involved in the biogenesis of this miRNA. These data therefore suggest that Pacman controls growth of imaginal discs via control of protein synthesis and regulation of autophagy.

Results

The hypomorphic mutation in pacman (pcm5) results in small wings and wing imaginal discs. In order to determine the biological functions of Pacman, we previously generated a number of mutant alleles in the pacman gene, created by excision of a P-element downstream of pacman. The strongest hypomorphic allele generated, pcm1 includes a partial deletion of exons 8 and 9, followed by a frameshift (Fig. 1). This results in a protein that includes the N-terminal catalytic domain (residues 1–674) but is missing residues 1264–1612 of the less structured C-terminal domain (residues 675–1612). Adult flies which are homo- or hemizygous for pcm exhibit a number of phenotypes including dull wings (Fig. 2, panels A and B), duplicated macrochaetae and a cleft thorax, suggesting that pacman affects the development of the wings from the wing imaginal disc. To further investigate the effect of pacman mutations on wing development, we measured the size of male pcm wings and found them to be around 84% the size of wild-type wings (Fig. 2, panel C), while the average size (measured by weight) of wild-type and pcm males did not vary (mean weight of control males = 1.02 mg (SD 0.10 mg, n = 23) and pcm males = 0.98 mg (SD 0.10 mg, n = 23) compared using a t-test, p = 0.2069). To determine whether the decrease in wing size in mutants was due to smaller wing imaginal discs, the wing discs were dissected from wild-type and pcm wandering L3 larvae and compared in size. The pcm wing imaginal discs were found to be 82% the size of wild-type (Fig. 2, panel D). Therefore, this mutation in pacman appears to affect growth of the wing imaginal discs, presumably by affecting the expression of transcripts encoding proteins involved in development of that tissue.

Relatively few transcripts are differentially expressed in pcm wing imaginal discs. In order to identify the mRNAs that change in abundance in the pcm mutant and which therefore may result in reduced growth of the wing imaginal discs, we made use of Affymetrix Drosophila Genome 2.0 mRNA microarrays. A total of 960 wing imaginal discs were dissected from 3rd instar pcm larvae and from wild-type controls and divided into four biological replicates for each genotype. This number of wing discs was sufficient to produce enough mRNA for the microarray
experiment and qRT-PCR validation experiments (≥ 4 μg). RNA extraction, labeling, array hybridization, and initial analyses were performed at the Sir Henry Wellcome Functional Genomics Facility, University of Glasgow. Quality control analysis of the raw data, performed using RMAExpress software, showed that each array was of similar quality, with none falling outside the main intensity grouping. We analyzed the data from the mRNA microarray experiments using three different normalization methods: MASt, RMA, and GCRMA. Lists of differentially expressed genes were created after normalization with each method and then compared to identify genes that appeared consistently in at least two lists. These genes were predicted to be up or downregulated due to a real biological difference, rather than being false positives. Thirty-eight genes were found to be upregulated in pcm5 wing imaginal discs (Fig. 3, panel A) and 34 genes were found to be downregulated (Fig. 3, panel B). We found that rather few mRNAs were expressed at levels greater than 1.5-fold in pcm5 mutants compared with wild-type. Twenty-six mRNAs were upregulated more than 1.5-fold in these mutants, with only nine of these expressed at greater than 2-fold of the levels of controls. Of the 34 downregulated genes, 28 were below 1.5-fold and 16 below 2-fold. The pacman transcript itself was downregulated by 2.6-fold on the arrays, congruent with the 3-fold downregulation of the pacman transcript we have previously observed for pcm5 mutant larvae. Therefore, these data show, for the first time, than the pcm5 mutation results in rather few transcripts which change in abundance at this stage of development in wing imaginal discs.

Verification of microarray results using quantitative RT-PCR. In order to validate the changes in transcript abundance in wing imaginal discs resulting from the pcm5 mutation, TaqMan qRT-PCR was employed to determine the fold changes more precisely for a set of selected up and downregulated mRNAs. Twelve upregulated mRNAs were chosen for verification by qRT-PCR (the top 11 and the transcript encoding the decapping enzyme Dcp2), along with seven downregulated mRNAs (the six most downregulated and pacman). RNA levels were normalized to rp49 (RpL32) mRNA as it did not change in level on the arrays and encodes a ubiquitously expressed ribosomal protein. Expression of each mRNA was tested on at least four biological replicates (up to 11, see Fig. 4 legend). RNA from each biological replicate was converted to cDNA in duplicate and the qRT-PCR performed in duplicate on each cDNA sample (four technical replicates in total per biological replicate). Figure 4 shows that the levels of transcripts, as measured by qRT-PCR, were comparable with the microarray levels in most cases. CG31157 and CG7966 appeared to be downregulated on the arrays, but were not found to differ in expression by qRT-PCR. Two other downregulated mRNAs, CG17669 and Dscam4, were found to be downregulated by a much greater extent by qRT-PCR than they were on the arrays. Additionally, Hsc70-2 appeared to be expressed extremely inconsistently at a very low level by qRT-PCR. Hsc70-2 was not considered further, as the TaqMan assay may have been ineffective at detecting it (not shown). These qRT-PCR experiments showed that eight of the 12 upregulated mRNAs were increased in level by > 2-fold in the pcm5 mutant compared with the control (Hsp67Bc, CG31477, simjang, CG33099, Hsp26, CG5953, CG5326, and CG12842). The pacman, CG32364, CG17669, and Dscam4 transcripts were downregulated by > 2-fold (Fig. 4).

Hsp67Bc, CG31477, simjang and Hsp26 transcripts are post-transcriptionally upregulated in pcm5 mutants. Since mutations in pacman result in specific phenotypes, including reduced size of wing imaginal discs, we wished to concentrate on transcripts that changed significantly in abundance in the pcm5 mutant compared with controls. We reasoned that these are most likely to result in the phenotypic consequences observed. Since Pacman is an exoribonuclease, and is involved in the degradation of RNA, we reasoned that transcripts upregulated at the mRNA level, but unchanged at the transcriptional level (i.e., the pre-mRNA), were most likely to be affected by the Pacman exoribonuclease. In
contrast, mRNAs that increased in abundance at both the transcriptional level and mRNA level are less likely to be directly affected by Pacman. We measured the pre-mRNA levels of the five mRNAs upregulated by > 3-fold in pcm5; Hsp67Bc, CG31477, simjang, CG33099 and Hsp26, to determine whether Pacman was likely to directly affect these transcripts at the post-transcriptional level. Additionally, we quantified the pre-mRNA levels of Dcp2, two mRNAs that did not change level in the pcm5 mutant (CG7699 and CG31157), and the three most downregulated mRNAs (CG32364, CG17669, and Dscam4).

Levels of pre-mRNA vs. mRNA were compared in pcm5 mutants and wild-type L3 wing imaginal discs. TaqMan qRT-PCR assays were designed to specifically amplify the pre-mRNA transcripts using one of two methods. For CG31477, CG33099, simjang, CG7966, CG31157, Dcp2, CG32364, and Dscam4, which contain introns, assays were designed against 100 nt sections located within an intron and at least one exon (Fig. S1, panels A–G). For Hsp67Bc, Hsp26, and CG17669, which are intronless, assays were designed against the last 50 nt of the 3’UTR plus the following 50 nt of the transcribed RNA, over the polyA cleavage site (Fig. S1, panels H–K). The mRNA assays for each gene were the same as those
used previously, with proprietary probe/primer combinations designed across exon-exon boundaries, to ensure specific detection of the mRNA. The TaqMan qRT-PCR assays (mRNA or pre-mRNA) used for genes with more than one mRNA isoform (CG31477, simjang, CG31157, Dcp2, and Dscam4) were chosen/designed to detect all transcript variants from that gene. The different expression profiles between pre-mRNA and corresponding mature mRNA assays (see below) showed that these methods successfully distinguished between pre-mRNA and mature mRNA. Prior to reverse transcription, all samples were treated with DNase I to prevent the pre-mRNA assays detecting genomic DNA. Controls lacking reverse transcriptase showed that genomic DNA was not detected.

Figure 5 shows the pre-mRNA compared with the mature mRNA levels of Hsp67Bc, CG31477, simjang, CG33099, Hsp26, Dcp2, CG7966, CG31157, CG32364, CG17669, and Dscam4 in pcm5 wing imaginal discs. For Hsp67Bc, CG31477, simjang, and Hsp26, the level of pre-mRNA is not significantly different in the mutant compared with wild-type, indicating that the pcm5 mutation does not affect the transcription of these mRNAs. However, the levels of mature mRNA are significantly higher in the mutant than in wild-type, showing that Pacman affects these transcripts post-transcriptionally. In contrast, the levels of CG33099 pre-mRNA and mRNA both increase by approximately the same amount, indicating that the increase in abundance of CG33099 is due to transcriptional rather than post-transcriptional effects.

Each of the downregulated transcripts (CG32364, CG17669, and Dscam4) exhibited substantial reductions of transcription in the pcm5 mutant. CG32364 pre-mRNA and mRNA are both reduced by the same amount (8.1-fold and 8.0-fold, respectively), suggesting control of this gene is entirely transcriptional. The levels of pre-mRNA for CG17669 and Dscam4 are both greatly reduced, but not to such a great extent as for their corresponding mRNAs, which show a remarkable decrease in abundance (62.5-fold and 4020-fold respectively; Fig. 5). This suggests that the downregulation of these mRNAs is not entirely dependent on transcription. However, this is unlikely to be a direct consequence of the pacman mutation as we would expect mRNAs directly affected by Pacman to increase in abundance. The mRNA level for Dcp2 is upregulated 1.3-fold in the pcm5 mutant, while its pre-mRNA is 1.1-fold downregulated. Although these changes are statistically significant, they are very small (<30%) and unlikely to be biologically significant, because a 4-fold increase in Dcp2 protein level (by expression of a transgene) generates no mutant phenotypes when flies are grown under normal conditions. For CG7966 and CG31157, the mRNA levels of which do not change in the pcm5 mutant, the pre-mRNA levels also do not change. Since mRNA decay and transcription are often linked, as has been shown for targets of the deadenylases in mammalian cells, then overall mRNA abundance could remain the same if transcripts are stabilized at the same time as transcription is reduced. However, this does not appear to be the case here, as the pcm5 mutation results in no change in abundance of these transcripts, either transcriptionally or post-transcriptionally.

The heat shock protein Hsp67Bc is upregulated in pcm5 mutant imaginal discs. We have shown that the transcripts Hsp67Bc, CG31477, simjang, and Hsp26 increase post-transcriptionally by at least 3.2-fold in pcm5 imaginal discs compared with controls. To have an effect on imaginal disc development these mRNAs would need to be translated into protein. However, the usual pathway for mRNA degradation is thought to be via deadenylation of the transcript, followed by decaying and then degradation by Xrn1/Pacman. If this is the case, the decayed transcripts, which would not be optimally translated, would be expected to accumulate. To test whether the accumulated transcripts could be translated, we measured Hsp67Bc and Simjang protein levels using western blot analysis (as far as we are aware, antibodies to CG31477 and Drosophila Hsp67Bc are not available). We were unable to obtain a consistent result using the Simjang antibody, but the Hsp67Bc protein did show a significant increase of around 2.3-fold in pcm5 wing imaginal discs (Fig. 5), indicating that a portion of the accumulated transcripts can be

**Figure 5.** Pacman affects some mRNAs at the post-transcriptional level in L3 wing imaginal discs. The pre-mRNA levels were measured for the transcripts upregulated by >3-fold (Hsp67Bc, CG31477, simjang, CG33099 and Hsp26), three downregulated transcripts (CG32364, CG17669 and Dscam4), two unchanged transcripts (CG7966 and CG31157) and Dcp2. Bars show mean and error bars show standard error. One sample t-tests were used to test for significance against an expected mean of 1 for each pre-mRNA/mRNA (**p < 0.0001, ***p < 0.001, **p < 0.01 and *p < 0.05). The pre-mRNA levels for Hsp67Bc (n = 4), CG31477 (n = 6), simjang (n = 6) and Hsp26 (n = 4) do not differ in the pcm5 mutant compared with wild-type, showing that their mRNA levels are affected post-transcriptionally. The level of Hsp67Bc protein (n = 6) increased by 2.3-fold. For CG33099 (n = 3), the pre-mRNA increases by approximately the same amount as the mature mRNA, showing transcriptional upregulation. Similarly, CG32364 (n = 4) pre-mRNA decreases by the same amount as the mRNA, showing transcriptional downregulation. CG17669 (n = 4) and Dscam4 (n = 4) pre-mRNA levels decreased, showing transcriptional downregulation, but by a much smaller amount than the reduction seen for their mRNAs, suggesting a reduction in transcription was part of, but not the entire explanation for, the reduction of these transcripts. The pre-mRNA and mRNA levels of CG7966 (n = 4) and CG31157 (n = 4) were unchanged in the pcm5 mutant. The level of Dcp2 (n = 4) pre-mRNA was significantly reduced, while the mRNA was significantly increased. However, these were very small-scale changes.
arrays, followed by TaqMan qRT-PCR, to compare the levels of mature miRNAs in pcm5 and wild-type L3 wing imaginal discs. For the arrays, 720 wing imaginal discs were dissected from each genotype and divided into two biological replicates. Two dual color arrays were performed (pcm5 vs. wild-type) and each array contained four spots for each miRNA. Only miRNAs with levels above background in > four spots (out of the eight on the two arrays) were accepted as present. Normalization was performed against six spike-in controls (284 spots in total per array). (B) The mean differential expression levels between mutant and wild-type were calculated for each of the detected miRNAs. No miRNA was found to be upregulated by > 2-fold. A single miRNA, miR-277-3p, was found to be downregulated by > 2-fold. Error bars show standard error.

Figure 6. Differential expression of miRNAs in pcm5 L3 wing imaginal discs compared with wild-type. (A) Of 152 miRNAs on the array, 42 were detected above the background level (all were present in both pcm5 and wild-type). The most highly expressed, miR-14-3p, was at level > 100-fold greater than the level of the lowest level miRNA detected, miR-277-3p. Two dual color arrays were performed (pcm5 vs. wild-type) and each array contained four spots for each miRNA. Only miRNAs with levels above background in > four spots (out of the eight on the two arrays) were accepted as present. Normalization was performed against six spike-in controls (284 spots in total per array). (B) The mean differential expression levels between mutant and wild-type were calculated for each of the detected miRNAs. No miRNA was found to be upregulated by > 2-fold. A single miRNA, miR-277-3p, was found to be downregulated by > 2-fold. Error bars show standard error.

The expression levels of the three most downregulated miRNAs, miR-33-5p, miR-34-5p, and miR-277-3p, were verified by Taqman qRT-PCR (n = 4 for each). Two miRNAs that were unchanged on the arrays, miR-14-3p and miR-8-3p, were also verified by qRT-PCR (n = 4 for each) and did not show a difference in level in pcm5 compared with wild-type. miR-33-5p and miR-34-5p were found to be downregulated in the mutant compared with the wild-type. Although these changes were statistically significant, they were < 2-fold. miR-277-3p was downregulated by 5.9-fold in the pcm5 wing discs compared with wild-type discs.
(Fig. 7A). Therefore, Pacman appears to be directly or indirectly involved in expression of this miRNA. To determine whether this effect was at the transcriptional or post-transcriptional level, primers were designed to detect pri/pre-miR-277 (Fig. S1, panel L). mir-R-277-3p and mir-R-277-5p can be processed from pri/pre-miR-277, but mature mir-R-277-3p is the overwhelmingly dominant miRNA produced.35 Comparison of the pri/pre-miRNA-277 levels with mature mir-R-277-3p levels in pcm5 and control wing discs showed that pri/pre-miRNA-277 was found at similar levels in the mutant and wild-type, whereas the mature mir-R-277-3p was reduced 5.9-fold in pcm5 mutant wing imaginal discs (Fig. 7B). These data therefore suggest that Pacman affects the maturation of mir-R-277-3p, although it is also possible that this is an indirect effect.

Discussion

In the present study, we have identified a set of mRNAs and one miRNA that significantly change in abundance upon reduction of expression of the Pacman exonuclease in Drosophila wing imaginal discs (Table 1). Since these RNAs have been identified from wing imaginal discs dissected from developing larvae rather than tissue culture cells, they reflect developmentally important gene expression changes, which occur upon mutation of this exonuclease. Developmentally relevant changes in RNA abundance resulting from a reduction in exonuclease activity have very rarely been identified so this study represents a significant step forward in understanding the function of the conserved exonucleasem in vivo. In particular, analysis of the misregulated transcripts identified may start to explain why pacman can influence growth and differentiation.

Surprisingly, our study found relatively few mRNAs that were significantly up or downregulated in abundance in pcm5 imaginal discs compared with controls. According to our microarray analysis, followed by validation of these misregulated transcripts by TaqMan qRT-PCR, only eight mRNAs were increased in level by > 2-fold in the pcm5 mutant compared with controls (Hsp67Bc, CG31477, simjang, CG33099, Hsp26, CG5953, CG5326, and CG12842; Fig. 4). Of the downregulated transcripts, four (pacman, CG32364, CG17669, and Dscam4) were shown by both microarray and TaqMan RT-PCR to be decreased in abundance by > 2-fold. These results are in line with work on the effects of knockdown of the deadenylase subunits Ccr4a (CNOT6) and Ccr4b (CNOT6L) in MCF7 cells where only 79 genes were found to be upregulated (> 1.5-fold) and only four downregulated.36 Therefore, both studies show that global decay factors affect a surprisingly small number of transcripts.

A possible reason why relatively few transcripts changed in abundance (> 2-fold) in the pcm5 mutant is that stabilization of mRNAs by the pcm5 mutation is accompanied by a compensatory decrease in transcription and consequently no overall change in the abundance of the majority of mRNAs. This compensatory effect has been seen in studies on the effect of PARN knockdown in mouse myoblasts where the majority of transcripts stabilized were reduced in abundance due to transcriptional control.27 Other studies in yeast cells have shown that mRNA synthesis and degradation are coupled and that mRNA decay rates are dependent upon events that occur at the promoter.26,37,38 To determine whether selected transcripts, which did not change in abundance overall, were actually stabilized at the same time as being transcriptionally downregulated, we assessed the levels of pre-mRNA and mRNA of two transcripts, which did not change in overall abundance in the pcm5 mutant compared with controls. We found no evidence for substantial reduction of transcription of those mRNAs suggesting that the pcm5 mutation does not significantly affect transcription of these mRNAs. Another possibility is that the 3’-5’ degradation pathway is upregulated in pcm5 mutants, resulting in no change in abundance of many mRNAs. However, we found no evidence for upregulation of transcripts encoding known 3’-5’ degradation factors. It is also possible that relatively few transcripts were seen to change in abundance as pcm5 is a hypomorphic and not a null mutant. In any case, our experiments aimed to identify the transcripts whose overall expression was substantially perturbed in the pcm5 mutant as these transcripts are most likely to result in the biological phenotypes observed. If there is a mechanism to maintain homeostasis in levels of some transcripts then these transcripts are unlikely to cause the mutant phenotype.

The transcripts that significantly increase in abundance in the pcm5 mutant could either be due to an increase in transcription, a decrease in decay or a combination of both. By using judiciously placed intronic and exonic primers to distinguish between premRNAs and mRNA we were able to determine whether the pcm5 mutation affected these transcripts at the transcriptional and/or post-transcriptional level. As shown in Figure 5, the
levels of Hsp67Bc, CG31477, Hsp26, and simjang pre-mRNAs did not increase in the pcm mutant, but the mature mRNA levels increased significantly. The simplest explanation for this effect is that Pacman normally degrades these mRNAs. However, it is also possible that their increase in abundance is due to an unknown indirect effect. Our results therefore suggest that a limited number of specific transcripts are normally targeted to the 5'-3' degradation machinery for controlled degradation.

Although the above four transcripts are increased in abundance in the pcm mutant, they would need to be translated to have a phenotypic effect on imaginal disc development. Since it is known that decapping precedes degradation of RNAs by Pacman/Xrn1,2,3 it would be expected that the upregulated transcripts in the pcm mutant would be decapped and, therefore, not available for cap-dependent translation. However, our results above show that heat shock protein Hsp67Bc is upregulated 2.3-fold in the pcm mutant suggesting that at least some of the upregulated Hsp67Bc transcripts can be translated. There are at least two possible explanations for this effect. First, it has recently been demonstrated that mRNA decapping is physically coupled to 5'-3' exonucleolytic degradation as Pacman/Xrn1 includes a binding motif for the decapping protein Dcp1 in its C-terminal region (residues 1323–1355 of the 1612aa protein).18 The pcm deletion results in loss or disruption of residues 1264–1612 of Pacman, thus removing the Dcp1-binding site. Since removal of the Dcp1-binding domain in Pacman/Xrn1 severely reduces decapping in S2 cells,19 it is likely that decapping is also inhibited in mutant imaginal disc cells. Second, and additionally, it is possible that the Hsp67Bc transcript includes an Internal Ribosome Entry Site (IRES) similar to that of other Heat shock protein transcripts such as HSP70 in mammalian cells.20 In this case, the decapped transcripts could be translated by a cap-independent process. The exact mechanism of stabilization of the upregulated transcripts in pacman mutants will require further experimentation.

Our experiments also show that the pcm mutation can result in a remarkable downregulation of a small number of transcripts. CG32364, a gene which carries a RNA recognition motif, is downregulated 8-fold at the post-transcriptional level as well as the transcriptional level in pcm discs, suggesting it is indirectly affected by Pacman. CG17669 and Dscam4 are downregulated

### Table 1. Misexpressed RNAs in pcm wing imaginal discs and their associated molecular and biological functions

| Gene name (Human ortholog) | Fold change in pcm mutant | Associated functions (Flybase43) | Refs. |
|---------------------------|---------------------------|----------------------------------|-------|
| **Hsp67Bc** *(HSPB1-3,6,8, CRYAA, CRYAB)* | Pre-mRNA mRNA | | |
| -1.1 | +11.9 ** | Molecular: unknown. Biological: protein lipidaion; response to methotrexate; regulation of translational initiation by elf2α phosphorylation; regulation of autophagy. | 41,42 |
| **CG31477** *(ATPSE)* | +1.7 +6.7 **** | Molecular: hydrogen-exporting ATPase activity; phosphorylative mechanism. Biological: proton transport. | |
| **simjang** *(GATADA2/p66α)* | -1.1 +3.8 **** | Molecular: protein binding. Biological: negative regulation of transcription from RNA polymerase II promoter. | 44,45 |
| **CG33099** | +3.0 +3.8 ** ** | Molecular: gibberellin 20-oxidase activity. Biological: oxidation-reduction process. | |
| **Hsp26** *(HSPB1-3,6,8, CRYAA, CRYAB)* | +1.1 +3.2 *** | Molecular: protein binding. Biological: determination of adult lifespan; cold acclimation. | 46 |
| **CGS953** | - +2.9 ** | Molecular: unknown. Biological: lateral inhibition. | |
| **CGS326** *(ELOVL1,2,4,5,7)* | - +2.7 * | Molecular: unknown. Biological: neurogenesis. | |
| **CG12842** | - +2.4 * | Molecular: unknown. Biological: unknown. | |
| **miR-277-3p** | -1.2 -5.6 *** | Molecular: unknown. Biological: response to rCGG repeats. | 47 |
| **CG32364** | -8.1 -8.0 **** | Molecular: nucleotide binding; nucleic acid binding. Biological: unknown. | |
| **CG17669** *(DNAAF3)* | -2.3 -62.5 ** ** | Molecular: unknown. Biological: unknown. | |
| **Dscam4** *(multiple, inc. DSCAM)* | -328.9 -4019.3 **** | Molecular: identical protein binding. Biological: cell adhesion. | 48 |

Underlined transcripts were upregulated post-transcriptionally. Stars below fold change values represent the P value (** = P < 0.01, *** = P < 0.001, **** = P < 0.0001, * = P < 0.05).
62.5-fold and 4020-fold, respectively, in pcm\(^\text{m} \) discs due to both transcriptional and post-transcriptional effects. The reasons for these decreases are not clear but could be due to Pacman directly or indirectly upregulating a transcriptional repressor. Alternatively, this could be a result of reduction of a specific cell population expressing Dscam4 and/or CG17669.

Our study also shows that the pcm\(^\text{m} \) mutation affects the levels of mature miR-277-3p in wing imaginal discs. The decrease in levels of mature miR-277-3p in imaginal discs of the pcm\(^\text{m} \) mutant is interesting as it is the first time that this 5'-3' exoribonuclease has been shown to specifically affect the expression levels of a miRNA in Drosophila. This mature miRNA was downregulated 5.9-fold in the pcm\(^\text{m} \) mutant while the levels of its pri- and pre-miRNAs were unchanged between mutant and control. Therefore, it appears that Pacman can affect the processing of miR-277-3p, perhaps in a similar manner to that observed for miR-34-5p in Drosophila S2 cells where the 3'-to-5' exoribonuclease Nibbler trims miRNAs bound to Ago1. However, it is also possible that this effect is indirect, in that this miRNA may normally be protected from degradation by binding to its target mRNA (target-mediated miRNA protection). In this case, the downregulation of one or more of the transcripts in the pcm\(^\text{m} \) mutant could result in acceleration of miR-277-3p decay. Although it is presently unclear how Pacman could affect the expression of this miRNA, the processing/degradation of this miRNA must be specific, as it is the only one out of the 42 mature miRNAs detected in wing discs that is regulated in this way.

How could the changes in abundance of these misregulated mRNAs and miRNA in the pcm\(^\text{m} \) mutant affect growth and differentiation of imaginal discs? A summary of the RNAs misregulated in the pcm\(^\text{m} \) mutant are listed in Table 1, together with their proposed functions. A striking function of the most upregulated transcript (Hsp67Bc) is its involvement in autophagy. Hsp67Bc has recently been shown to be the functional ortholog of human HSP8 (Hsp22), which induces autophagy via the eIF2\(\alpha\) pathway. The higher levels of Hsp67Bc protein observed in pcm\(^\text{m} \) mutant wing discs compared with controls could be reducing imaginal disc growth by decreasing protein synthesis and/or inducing autophagy. The significant reduction of expression of miR-277-3p in pcm\(^\text{m} \) mutant discs suggests another way in which Pacman may affect the growth of discs. If miR-277-3p targets mRNAs encoding proteins involved in growth inhibition, then a decrease in this miRNA could lead to a reduction in size of mutant imaginal discs. Although we checked the levels of some of the proteins encoded by putative mRNA targets of miR-277-3p we could not find any evidence for changes in expression. Therefore, the molecular pathways controlled by miR-277-3p in imaginal disc development will require further experimental work. Since Pacman/Xrn1 is highly conserved in all eukaryotes, these investigations are likely to shed light on autophagy and apoptosis control in all multicellular organisms.

Materials and Methods

Fly stocks. Fly stocks were cultivated on standard media at 25 °C in uncrowded conditions. Creation of the pcm\(^\text{m} \) allele was previously described by Grima et al. The wild-type stock used was created by a neutral excision of the P-element used to create pcm\(^\text{m} \) (P[E]/EP1526, stock 11456 from Bloomington Stock Center). A 43 bp “footprint” was left by the P-element in the intron of CG43260.

Measurement of wing and wing disc size. For size measurements, wing imaginal discs were dissected from L3 larvae and an individual image was taken using a dissecting microscope at a constant magnification. The area each disc was then measured in arbitrary units using ImageJ (www.rsbweb.nih.gov/ij/). For images, L3 wing imaginal discs were dissected and mounted in 85% glycerol under a size 1 coverslip, with an additional size one coverslip cut in half and placed at each side of the area containing the imaginal discs to act as spacers. Images were produced using Axiowision 4.7 on an Axioplan microscope (Carl Zeiss). Wings were mounted in DXP medium (Fischer Scientific, Cat. no. 10050080) under a size 0 coverslip (weighted down overnight).

Molecular techniques. RNA extractions were performed using an RNaseasy Mini Kit (Qiagen, Cat. no. 74104) or a miRVana miRNA isolation kit (Life Technologies, Cat. no. AM1560). The miRVana kit was used for total RNA extraction when RNAs < 200 nt (miRNAs etc.) were required. Samples were treated with a DNA-free kit (Life Technologies, Cat. no. AM1906) and their concentrations were measured on a NanoDrop 1000 spectrophotometer (Thermo Scientific). For the Drosophila Genome 2.0 mRNA microarrays (Affymetrix, Cat. no. 900531), wing imaginal disc samples were homogenized in RLT buffer from the RNasey Mini kit with β-mercaptoethanol added before being sent on dry ice to the Sir Henry Wellcome Functional Genomics Facility (University of Glasgow). For the LNA miRNA v11.0 “other species” arrays (Exiqon, Cat. no. 208213-A), the samples were labeled with either Hy5 or Hy3 dyes in the supplied labeling kit (Cat. no. 208032-A). A miRCURY LNA Array Spike-in miRNA kit (Exiqon, Cat. no. 208040) was also used. Hybridization was performed in Microarray Hybridization chambers (Agilent) in a rotary HB-1000 hybridization oven (UVP) at 65 °C. The arrays were scanned using an Axon GenePix 4000B Microarray Scanner (Molecular Devices) and analyzed using GenePix Pro 6.0 (Molecular Devices). Normalization was performed using the spike in miRNAs.

For qRT-PCR, cDNA was prepared from the RNA samples using a High Capacity cDNA Reverse Transcription Kit (Life Technologies, Cat. no. 4368814) for mRNA/pre-mRNA or a TaqMan microRNA Reverse Transcription Kit (Life Technologies, Cat. no. 4366596) for miRNAs. Specific primers (supplied) were used for each mRNA RT reaction, and random primers were used for the mRNA/pre-mRNA RT reactions. qRT-PCR was performed on the cDNA produced from either RT protocol using TaqMan Universal PCR Master Mix, No AmpErase UNG (Life Technologies, Cat. no. 4324018) and an appropriate TaqMan mRNA/miRNA assay (Life Technologies). All mRNA and miRNA TaqMan assays used were pre-designed. For custom pre-mRNA assays, 100 nt of sequence of the desired target area was submitted to Life Technologies’ web-based Custom TaqMan Assay Design Tool (Fig. S1).

Western blotting was performed on samples containing 60 wing imaginal discs. Tubulin was used as an internal control. Mouse
anti-Tubulin primary antibody (Sigma, Cat. no. T9026) was used at a 1:2,000 dilution with an anti-mouse-HRP conjugated secondary antibody (Sigma, Cat. no. A2304) at 1:8000. Hsp67Bc primary antibody was used at a 1:1,000 dilution with an anti-rabbit-HRP conjugated secondary antibody at 1:80000 (Sigma, Cat. no. A0545). Antibody binding was detected using Amersham ECL detection reagents (GE Healthcare, Cat. no. RPN2209). Relative quantification of bands was performed in ImageJ.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

Acknowledgments
The authors would like to thank Clare Rizzo-Singh, Karen Scruby and Ben Towler for technical help. We would also like to thank Julie Aspden and Simon Morley for checking the manuscript and for helpful comments. Rabbit Hsp67Bc primary antibody was kindly provided by Dr Serena Carra (University of Modena and Reggio Emilia). This work was funded by the Biotechnology and Biological Sciences Research Council (grants BB/1021345/1 and BB/G002754/1), an MRC studentship (to JAW) and a Junior Research Associate Summer studentship from the University of Sussex (to HNP).

References
1. Cheddle C, Fan J, Cho-Chung YS, Werner T, Ray J, Do L, et al. Control of gene expression during T cell activation: alternate regulation of mRNA transcription and mRNA stability. BMC Genomics 2005; 6:75; PMID:15907206; http://dx.doi.org/10.1186/1471-2164-6-75
2. Jones CI, Zabotolstaya MV, Newbury SF. The 5'-3' exoribonuclease XRN1/ Pacman and its functions in cellular processes and development. Wiley Interdiscip Rev RNA 2012; 3:455-68; PMID:22383165; http://dx.doi.org/10.1002/wrna.1109
3. Baou M, Jewell A, Murphy JJ. TIS11 family proteins and their roles in posttranscriptional gene regulation. J Biomed Biotechnol 2009; 2009:634520; PMID:19672455; http://dx.doi.org/10.1155/2009/634520
4. Garneau NL, Wilusz J, Wilusz CJ. The highways and byways of mRNA decay. Nat Rev Mol Cell Biol 2007; 8:113-26; PMID:17245413; http://dx.doi.org/10.1038/nrm2104
5. Newbury SF. Control of mRNA stability in eukaryotes. Biochem Soc Trans 2006; 34:30-4; PMID:16246172; http://dx.doi.org/10.1042/BST0340308
6. Ehrlich E, Blackhear PJ. Roles of tumor necrosis factor-alpha receptor subtypes in the pathogenesis of the tristetraprolin-deficiency syndrome. Blood 2001; 98:2389-95; PMID:11588035; http://dx.doi.org/10.1182/blood.v98.8.2389
7. Carballo E, Lai WS, Blackhear PJ. Evidence that tristetraprin is a physiological regulator of granulocyte-macrophage colony-stimulating factor messenger RNA deadenylation and stability. Blood 2000; 95:1891-9; PMID:10768582
8. Stockelkin G, Tennenbaum SA, Mayo T, Chitrat SV, George AD, Baroni TE, et al. Genome-wide analysis identifies interleukin-10 mRNA as target of tristetraprin. J Biol Chem 2008; 283:11689-99; PMID:18256052; http://dx.doi.org/10.1074/jbc.M70957208
9. Newbury SF, Woollard AC. The 5'-3' exoribonuclease Xrn1 is essential for ventral epithelial enclosure during C. elegans embryogenesis. RNA 2004; 10:59-65; PMID:14681585; http://dx.doi.org/10.1261/rna.2139504
10. Parker R, Song H. The enzymes and control of eukaryotic mRNA turnover. Nat Struct Mol Biol 2004; 11:121-7; PMID:14749774; http://dx.doi.org/10.1038/nmb724
11. Till DD, Lint B, Seago JE, Elger SJ, Marujo PE, Elias ML, et al. Identification and developmental expression of a 5'-3' exoribonuclease from Drosophila melanogaster. Mech Dev 1998; 79:51-5; PMID:10349620; http://dx.doi.org/10.1016/S0925-4773(98)00173-7
12. Nagarajan VK, Jones CI, Newbury SF, Green PJ. XRN 5’-3’ exoribonucleases: Structure, mechanisms and functions. Biochem Biophys Acta 2013; 1829:590-603; PMID:23517755; http://dx.doi.org/10.1016/j.bbadis.2013.03.005
13. Orban TJ, Izaurralde E. Decay of mRNAs targeted by RISC requires XRN1, the Ski complex, and the exosome. RNA 2005; 11:459-69; PMID:15703439; http://dx.doi.org/10.1261/rna.2133505
14. Kulkarni M, Osgr S, Stockelkin G. On track with P-bodies. Biochem Soc Trans 2010; 38:242-51; PMID:20074068; http://dx.doi.org/10.1042/BST080242
15. Zabotolstaya MV, Grima DP, Lin MD, Chou TB, Newbury SF. The 5'-3' exoribonuclease Pacman is required for normal male fertility and is dynamically localized in cytoplasmic particles in Drosophila testis cells. Biochem J 2008; 416:327-35; PMID:18652574; http://dx.doi.org/10.1042/BIB20071720
16. Rejins MA, Alexander RD, Spiller MP, Begg JD. A role for Q/N-rich aggregation-prone regions in mRNA stability. RNA 2005; 11:459-69; PMID:15703439; http://dx.doi.org/10.1261/rna.2133505
17. Jinek M, Coyle SM, Doudna JA. Coupled 5' nucleotide recognition and processivity in Xrn1-mediated mRNA decay. Mol Cell 2011; 41:600-8; PMID:21363555; http://dx.doi.org/10.1016/j.molcel.2011.02.004
18. Davey NE, Cowan JL, Shields DC, Gibson TJ, Coldwell MJ, Edwards RJ. SL1MPrints: conservation-based discovery of functional motifs fingerprints in intrinsically disordered protein regions. Nucleic Acids Res 2012; 40:10628-41; PMID:22977176; http://dx.doi.org/10.1093/nar/gks584
19. Braun JE, Truffault V, Boland A, Hunztinger E, Chang CT, Haas G, et al. A direct interaction between DCP1 and XRN1 couples mRNA decapping to 5' exonuclease degradation. Nat Struct Mol Biol 2012; 19:1324-31; PMID:23142987; http://dx.doi.org/10.1038/nbt.2423
20. Grima DP, Sullivan M, Zabotolstaya MV, Browne C, Seago J, Wan KC, et al. The 5'-3' exoribonuclease par- man is required for epithelial sheet sealing in Drosophila and genetically interacts with the phosphatase puck- ered. Biol Cell 2008; 100:687-701; PMID:18547166; http://dx.doi.org/10.1042/BC20080049
21. Bate M, Arias AM. The embryonic origin of imaginal discs in Drosophila. Developmental 1999; 112:755-61; PMID:1935688
22. Irizarry RA, Hobbs B, Collin F, Beazer-Barclay YD, Antonellis KJ, Scherf U, et al. Exploration, normalization, and summaries of high density oligonucleotide array probe level data. Bioinformatics 2003; 19:249-64; PMID:12925520; http://dx.doi.org/10.1093/bioinformatics/4.2.249

Supplemental Materials
Supplemental materials may be found here: www.landesbioscience.com/journals/rnabiology/article/25354
35. Konomara A, Griffiths-Jones S. miRBase: integrating microRNA annotation and deep-sequencing data. Nucleic Acids Res 2011; 39(Database issue):D152-7; PMID:21037258; http://dx.doi.org/10.1093/nar/gkq1027

36. Mittal S, Adam A, Douide R, Medica R, Winlder GS. The Ccr6a (CNOT6) and Ccr6b (CNOT6L) deadenylase subunits of the human Ccr6-Not complex contribute to the prevention of cell death and senescence. Mol Cell 2011; 22:748-58; PMID:21233283; http://dx.doi.org/10.1099/mcb.01011-0898

37. Shalem O, Grosman B, Choody M, Dahan O, Pilpel Y. Transcriptome kinetics is governed by a genome-wide coupling of mRNA production and degradation: a role for RNA Pol II. PLoS Genet 2011; 7:e1002273; PMID:21931566; http://dx.doi.org/10.1371/journal.pgen.1002273

38. Sun M, Schwab B, Schulz D, Pirkl N, Enzold S, Larivière L, et al. Comparative dynamic transcriptome analysis (cDTA) reveals mutual feedback between mRNA synthesis and degradation. Genome Res 2012; 22:1350-9; PMID:22466169; http://dx.doi.org/10.1101/gr.130161.111

39. Rocchi L, Aliferi RR, Petronini PG, Montanaro L, Brigotti M. 5′-Untranslated region of heat shock protein 70 mRNA drives translation under hypertonic conditions. Biochem Biophys Res Commun 2013; 431:321-5; PMID:23291172; http://dx.doi.org/10.1016/j.bbrc.2012.12.100

40. Han BW, Hung JH, Weng Z, Zamoore PD, Ameres SL. The 3′-to-5′ exoribonuclease Nibbler shapes the 3′ ends of microRNAs bound to Drosophila Argonaute1. Curr Biol 2011; 21:1878-87; PMID:22055293; http://dx.doi.org/10.1016/j.cub.2011.09.034

41. Carra S, Boncoraglio A, Kanon B, Brunsting JF, Minhoia M, Rana A, et al. Identification of the Drosophila ortholog of HSPB8: implication of HSPB8 loss of function in protein folding diseases. J Biol Chem 2010; 285:37811-22; PMID:20858900; http://dx.doi.org/10.1074/jbc.M110.127498

42. Carra S, Brunsting JF, Lambert H, Landry J, Kampinga HH. HpB8 participates in protein quality control by a non-chaperone-like mechanism that requires eIF2α phosphorylation. J Biol Chem 2009; 284:5523-32; PMID:19114712; http://dx.doi.org/10.1074/jbc.M807440200

43. McQuilton P, St Pierre SE, Thurmond J. FlyBase Consortium. FlyBase 101--the basics of navigating FlyBase. Nucleic Acids Res 2012; 40(Database issue):D786-14; PMID:22127867; http://dx.doi.org/10.1093/nar/gkr1030

44. Kon C, Cadigan KM, da Silva SL, Nesse R. Developmental roles of the Mi-2/NURD-associated protein p66 in Drosophila. Genetics 2005; 169:2087-100; PMID:15695365; http://dx.doi.org/10.1534/genetics.104.034595

45. Kim YO, Park SJ, Balaban RS, Nirenberg M, Kim Y. A functional genomic screen for cardiogenic genes using RNA interference in developing Drosophila embryos. Proc Natl Acad Sci USA 2004; 101:159-64; PMID:14684833; http://dx.doi.org/10.1073/pnas.0307205101

46. Tower J. Heat shock proteins and Drosophila aging. Exp Gerontol 2011; 46:355-62; PMID:20840862; http://dx.doi.org/10.1016/j.exger.2010.09.002

47. Tan H, Poidevin M, Li H, Chen D, Jin P. MicroRNA-277 modulates the neurodegeneration caused by Fragile X premutation rCGG repeats. PLoS Genet 2012; 8:e1002681; PMID:22570635; http://dx.doi.org/10.1371/journal.pgen.1002681

48. Armitage SAO, Freiburg RY, Kurtz J, Bravo IG. The evolution of Dscam genes across the arthropods. BMC Evol Biol 2012; 12:53; PMID:22500922; http://dx.doi.org/10.1186/1471-2148-12-53