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RESEARCH ARTICLE

Acute and long-term outcomes in a Drosophila melanogaster model of classic galactosemia occur independently of galactose-1-phosphate accumulation

Jennifer M. I. Daenzer, Patricia P. Jumbo-Lucioni*, Marquise L. Hopson*, Kerry R. Garza†, Emily L. Ryan† and Judith L. Fridovich-Keil**

ABSTRACT

Classic galactosemia (CG) is a potentially lethal inborn error of metabolism that results from the profound loss of galactose-1-phosphate uridylyltransferase (GALT), the second enzyme in the Leloir pathway of galactose metabolism. Neonatal detection and dietary restriction of galactose minimizes or resolves the acute sequelae of CG, but fails to prevent the long-term complications experienced by a majority of patients. One of the substrates of GALT, galactose-1-phosphate (Gal-1P), accumulates to high levels in affected infants, especially following milk exposure, and has been proposed as the key mediator of acute and long-term pathophysiology in CG. However, studies of treated patients demonstrate no association between red blood cell Gal-1P level and long-term outcome severity. Here, we used genetic, epigenetic and environmental manipulations of a Drosophila melanogaster model of CG to test the role of Gal-1P as a candidate mediator of outcome in GALT deficiency. Specifically, we both deleted and knocked down the gene encoding galactokinase (GALK) in control and GALT-null Drosophila, and assessed the acute and long-term outcomes of the resulting animals in the presence and absence of dietary galactose. GALK is the first enzyme in the Leloir pathway of galactose metabolism and is responsible for generating Gal-1P in humans and Drosophila. Our data confirmed that, as expected, loss of GALK lowered or eliminated Gal-1P accumulation in GALT-null animals. However, we saw no concomitant rescue of larval survival or adult climbing or fecundity phenotypes. Instead, we saw that loss of GALK itself was not benign and in some cases phenocopied or exacerbated the outcome seen in GALT-null animals. These findings strongly contradict the long-standing hypothesis that Gal-1P alone underlies pathophysiology of acute and long-term outcomes in GALT-null Drosophila and suggests that other metabolite(s) of galactose, and/or other pathogenic factors, might be involved.

INTRODUCTION

Galactosemia is one of the most common metabolic diseases identified by newborn screening (NBS) in the United States (CDC, 2012). Classic galactosemia (CG) results from profound loss of galactose-1-P uridylyltransferase (GALT, EC 2.7.7.12) (Isselbacher et al., 1956), the second enzyme in the highly conserved Leloir Pathway of galactose metabolism (Fig. 1). Affected infants can appear normal at birth, but following exposure to high levels of galactose from lactose in breast milk or milk-based formula experience a rapid and devastating decline that can progress in days from vomiting, diarrhea and jaundice to hepaticomegaly, failure to thrive, E. coli sepsis and neonatal death (Berry, 2014).

The early detection and rapid restriction of dietary galactose enabled by NBS for galactosemia prevents or resolves the acute and potentially lethal symptoms of CG. However, by school age most patients experience one or more of a constellation of long-term complications that include: speech, cognitive and behavioral difficulties in at least half of all patients; tremor and/or other movement problems in close to 40% of patients; growth delay in many children; low bone mineral density in many children and adults; and primary or premature ovarian insufficiency in >80% of girls and young women (Bosch, 2006; Schweitzer et al., 1993; Spencer et al., 2013; Waggoner et al., 1990; Waisbren et al., 2012). Life-long dietary restriction of galactose remains the only accepted treatment for patients with CG (Berry, 2014). However, a literature trail extending back more than 30 years documents that this treatment fails to prevent the long-term complications experienced by most patients (Gitzelmann and Steinmann, 1984; Hughes et al., 2009; Jumbo-Lucioni et al., 2012; Schweitzer et al., 1993; Segal, 1995). The mechanisms underlying acute and long-term outcomes in CG remain unclear, limiting prognosis and hampering efforts at improved intervention.

A number of intriguing hypotheses have been proposed to explain the acute and long-term pathophysiology of classic galactosemia. Many have focused on Gal-1P (e.g. Bosch, 2006; Gitzelmann and Steinmann, 1984; Tang et al., 2012), a substrate of GALT that accumulates to high levels in the red blood cells (RBCs) and tissues of affected infants, especially following milk exposure. However, repeated studies asking whether either acute neonatal or chronic childhood RBC Gal-1P levels are associated with more severe long-term outcomes among patients have failed to demonstrate a correlation (Ficiocioglu et al., 2008; Hughes et al., 2009; Leslie, 2003; Schweitzer et al., 1993; Waggoner et al., 1990; Walter et al., 1999).

Studies from yeast, mice, and flies have also directly or indirectly addressed the role of Gal-1P as a candidate mediator of outcomes in GALT deficiency, and with the exception of yeast,
Galactose, galactitol, and galactonate also accumulate in patients with GALK deficiency, an extremely rare condition in many populations that was long considered benign except for galactose-dependent cataracts (reviewed in Fridovich-Keil and Walter, 2008). However, until recently these other metabolites were generally discounted because they also accumulate in patients with GALK deficiency, an extremely rare condition in many populations that was long considered benign except for galactose-dependent cataracts (reviewed in Bosch et al., 2002). In 2011, that assumption was upended, however, by a report describing the outcomes of 18 C5068 (EY03791). This deletion removed almost the entire GALK coding sequence and also part of the neighboring gene, C5068 (Fig. S1). Maintained under normal conditions (25°C) on molasses food, flies homozygous for dGALKcex9 remained both viable and fertile, although fecundity, as judged by the production of viable offspring, was reduced.

As expected, flies homozygous for dGALKcex9 exhibited no detectable GALK enzyme activity but normal levels of both GALT and UDP-galactose 4′-epimerase (GALE; Table 1). Also as expected, GALK-null animals lacking GALK demonstrated essentially normalized levels of Gal-1P despite dietary exposure to galactose (Table 2), confirming that, as in humans, GALK in flies is the enzyme principally responsible for the generation of Gal-1P.

In separate animals, we drove a UAS-GALKRNAi allele by a broadly expressed GAL4 driver to effectively knockdown GALK ubiquitously. Biochemical assays of lysates from these flies demonstrated that GALK activity was diminished to less than 4% of wild-type levels (Table 1). Metabolite studies further demonstrated that Gal-1P levels were diminished to less than 35% of the levels seen in GALT-null, GALK+ animals following galactose exposure (Table 2).

Loss of GALK fails to rescue larval sensitivity to galactose, adult climbing and fecundity defects in GALT-null Drosophila

To test the role of Gal-1P as a candidate mediator of outcomes in GALT deficiency, we created a genetic deletion of GALK in Drosophila and crossed this allele into both GALT+ and GALT-null backgrounds. As described in Materials and Methods, we created the GALK deletion, dGALKcex9, by imprecise excision of a P-element in a neighboring gene, C5068 (EY03791). This deletion removed almost the entire GALK coding sequence and also part of the neighboring gene, C5068 (Fig. S1). Maintained under normal conditions (25°C) on molasses food, flies homozygous for dGALKcex9 remained both viable and fertile, although fecundity, as judged by the production of viable offspring, was reduced.

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each of these phenotypes, and in some cases GALK loss itself appeared deleterious to outcome.

Specifically, whereas loss of GALT clearly compromised survival rates of larvae in the presence of 200 mM galactose, loss of GALK alone had only a small impact. Loss of GALT slightly lowered survival rates of GALT+ animals in both the absence (P<0.0172) and presence (P<0.0001) of 200 mM galactose (Fig. 2A). Small decreases in survival of GALT-null, GALK-null animals were also evident in both the absence and presence of galactose, but these differences were not significant (P>0.05 in both comparisons; Fig. 2A).

Loss of GALK had a larger negative impact on the ability of young adult male flies, raised at 28°C in the absence of dietary galactose, to climb above a set mark in 10 s (Fig. 2B). This was true for both GALT+ (P<0.0001) and GALK-null (P=0.0006) flies (Fig. 2B, upper graph). Finally, the compromised ability of GALT-null females to produce viable offspring when paired with wild-type males and reared at 28°C in the absence of dietary galactose was diminished by more than 50-fold rather than mitigated by loss of GALK (Fig. 2C, upper graph). Notably, deletion of GALK alone also caused a striking decline of more than 14-fold in the number of viable progeny produced by GALT+ females paired with wild-type males at 28°C (P<0.0001, Fig. 2C, upper graph). In all cases, animals lacking GALT accumulated Gal-1P unless GALK was also missing, in which case Gal-1P did not accumulate to substantial levels (Table 2).

As a further test of the roles of GALK and Gal-1P in modifying adult climbing and female fecundity outcomes, we combined a GALKRNAi allele called GALKRNAi(40A1), created previously in our laboratory, with a broadly expressed GAL4 driver to knockdown expression of GALK in GALT+ and GALT-null Drosophila. Biochemical assays performed in adult animals demonstrated that the knockdown was effective; animals expressing the GALKRNAi(40A1) allele with either of the two GAL4 drivers used in this study (Act5C-GAL4 and ubi-GAL4) demonstrated less than 4% of the wild-type levels of GALK (Table 1). Of note, whereas this substantial loss of GALK did lessen the accumulation of Gal-1P in GALT-null animals exposed to 200 mM galactose, the decrease was not proportional.

Specifically, despite a greater than 25-fold decrease in GALK activity, Gal-1P accumulation decreased by only around three-fold (from 17,763.23±3426.60 to 6485.71±753.52, Act5C driver, or 5735.47±190.50, ubi driver, Table 2). We also noted an increase in Gal-1P accumulation in animals that were either GALT+ (1889.11±92.29) or heterozygous for GALT-deletion (3064.93±394.54) upon knockdown of GALK and exposure to 200 mM galactose; by comparison, the level of Gal-1P seen in GALT+ GALK+ animals exposed to 200 mM galactose was only 210.72±36.08 (Table 2). The meaning of this apparent Gal-1P increase despite a >25-fold knockdown of GALK remains unclear.

As illustrated in Fig. 2B, lower graph, knockdown of GALK compromised the climbing ability of both GALT+ and GALT-null flies, though by only about a factor of two rather than the factors of eight and ten, respectively, seen with GALK deletion. Control (GALT+) animals in these experiments carried either the UAS-GALRKRNAi allele in the absence of driver, or the Act5C-GAL4 driver alone, confirming that both were required together to see the effect.

Table 1. Leloir enzyme activities in Drosophila stocks used in this study

<table>
<thead>
<tr>
<th>Genotype</th>
<th>GALK activity pmol/μg/min</th>
<th>GALT activity pmol/μg/min</th>
<th>GALE activity pmol/μg/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>dGALTΔC(GALT+, GALK+; wild-type control)</td>
<td>54.9±12.22 (n=7)</td>
<td>19.34±5.53 (n=6)</td>
<td>47.54±10.10 (n=6)</td>
</tr>
<tr>
<td>dGALTΔAP2 (GALT-null, GALK+)</td>
<td>47.53±17.11 (n=7)</td>
<td>0.02±0.03 (n=8)</td>
<td>58.67±10.00 (n=6)</td>
</tr>
<tr>
<td>dGALTΔC; dGALKRNAi(70A1)+ (GALT+, GALT-null)</td>
<td>0.40±0.08 (n=4)</td>
<td>0.00±0.03 (n=3)</td>
<td>Not tested</td>
</tr>
<tr>
<td>dGALTΔC; dGALKRNAi(40A1)+ (GALT-null, GALK knockdown)</td>
<td>0.40±0.08 (n=4)</td>
<td>0.00±0.03 (n=3)</td>
<td>Not tested</td>
</tr>
<tr>
<td>dGALTΔAP2, ubi-GAL4+; dGALKRNAi(40A1)+ (GALT+ (heterozygous), GALK knockdown)</td>
<td>0.64±0.11 (n=5)</td>
<td>15.62±0.63 (n=3)</td>
<td>Not tested</td>
</tr>
<tr>
<td>dGALTΔAP2, ubi-GAL4+; dGALKRNAi(40A1)+ (GALT-null, GALK knockdown)</td>
<td>1.89; 2.25 (n=2)</td>
<td>0.04 (n=1)</td>
<td>Not tested</td>
</tr>
</tbody>
</table>

Enzyme activities were measured in lysates prepared from cohorts of ten adult male flies collected at 1 to 3 days post eclosion. All flies developed on standard molasses food. Values presented are mean±s.e.m.

Table 2. Accumulation of Gal-1P in Drosophila exposed to galactose

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Gal-1P (pmol/mg protein) in lysates of animals raised on food containing 555 mM galactose</th>
</tr>
</thead>
<tbody>
<tr>
<td>dGALTΔC(GALT+, GALK+; wild-type control)</td>
<td>555 mM galactose/no gal</td>
</tr>
<tr>
<td>dGALTΔAP2 (GALT-null, GALK+)</td>
<td>82.0±21.03 (n=12)</td>
</tr>
<tr>
<td>dGALTΔC; dGALKRNAi(70A1)+ (GALT+, GALT-null)</td>
<td>320.6±66.13 (n=15)</td>
</tr>
<tr>
<td>dGALTΔAP2; dGALKRNAi(40A1)+ (GALT-null, GALK knockdown)</td>
<td>0.57±0.27 (n=5)</td>
</tr>
<tr>
<td>Act5C-GAL4+; dGALKRNAi(40A1)+ (GALT+, GALK knockdown)</td>
<td>0.40±0.08 (n=4)</td>
</tr>
<tr>
<td>dGALTΔAP2; Act5C-GAL4/dGALTΔAP2; dGALKRNAi(40A1)+ (GALT-null, GALK knockdown)</td>
<td>0.64±0.11 (n=5)</td>
</tr>
<tr>
<td>dGALTΔAP2; ubi-GAL4+; dGALKRNAi(40A1)+ (GALT+ (heterozygous), GALK knockdown)</td>
<td>1.89; 2.25 (n=2)</td>
</tr>
<tr>
<td>dGALTΔAP2; ubi-GAL4+ dGALKRNAi(40A1)+ (GALT-null, GALK knockdown)</td>
<td>17.27±9.85 (n=3)</td>
</tr>
</tbody>
</table>

gal, galactose; glc, glucose. Levels of Gal-1P were measured in lysates prepared from cohorts of ten third-instar larvae (L3) raised on food containing only 555 mM glucose, 555 mM galactose plus 50 mM galactose, or 555 mM glucose plus 200 mM galactose. Values presented are mean±s.e.m.
As illustrated in Fig. 2C, bottom graph, unlike genetic depletion, knockdown of GALK had no significant effect on the female fecundity of either GALT+ (P>0.05) or GALT-null (P>0.05) flies. Again, control (GALK+) animals in these experiments carried either the UAS-GALK\text{ exc9} allele in the absence of driver, or driver (Ubi-GAL4) alone.

**Exposure of GALT-null Drosophila to a low level of galactose causes accumulation of Gal-1P, but has little impact on larval galactose sensitivity or adult phenotypes**

As an alternative approach to testing the potential relationship between Gal-1P accumulation and outcomes in GALT-null Drosophila, we exposed both GALT-null and control animals to food containing 50 mM glucose with or without 200 mM galactose (gal). Loss of GALK diminished survival rates of both control and GALT-null animals in both the presence and absence of galactose. For GALT+ animals these differences were significant: P=0.0172 in the absence of galactose and P=0.0001 in the presence of 200 mM galactose, but for GALT-null animals these differences were not significant (P>0.05 in both comparisons). (B) Climbing ability of male flies reared at 28°C in the absence of dietary galactose. Deletion of GALK (upper graph) not only failed to rescue this phenotype but had a significant negative impact on climbing ability for both GALT+ (P=0.0001) and GALT-null (P=0.0006) flies. Knockdown (KD) of GALK (lower graph) also failed to rescue the climbing phenotype of GALT-null flies and further demonstrated a negative impact on this outcome that was independent of GALT. (C) Fecundity of female flies reared at 28°C in the absence of dietary galactose. Genetic deletion of GALK (upper graph) caused a striking decline in numbers of viable progeny from GALT+ crosses (P=0.0001) and also exacerbated the diminished number of viable offspring resulting from crosses of GALT-null flies (P=0.0001). Knockdown of GALK (lower graph) also failed to rescue the fecundity defect of GALT-null females but did not otherwise appear to impact this outcome. Values plotted represent means ± s.e.m.; the number of cohorts tested for each genotype (n) is indicated on the figure. P-values were calculated using an effects model, as described in Materials and Methods, and a t-test for pair-wise comparisons.

**Maternal loading of GALK**

Finally, to address the timing of larval sensitivity to loss of GALK, we repeated the experiments presented in Fig. 2A, but set up the crosses so that resulting embryos either did or did not receive maternal loading of GALK (see Materials and Methods). Specifically, eggs produced by mothers heterozygous for dGALK\text{ exc9} would be expected to include trace maternally loaded GALK whereas eggs produced by GALK-null mothers would not. This experimental design therefore tested the role of GALK in early embryogenesis.

As illustrated in Fig. 4, loss of maternally loaded GALK compromised survival of GALT+ GALK-null larvae by about two-fold in both the absence and presence of dietary galactose (P<0.0001 for both comparisons). The effect was accentuated in genetically GALT-nullGALT-null larvae, so that loss of maternally loaded GALK compromised survival of GALT-null GALT-null larvae by close to three-fold in the absence of galactose (P<0.0001) and by close to ten-fold in the presence of galactose (P=0.0005). This result demonstrated an important role for GALK at the earliest stages of Drosophila development in the presence of GALT, and an apparent synergism with loss of GALT.

**DISCUSSION**

Newborn screening for galactosemia coupled with rapid dietary restriction of galactose has saved the lives of thousands of infants born with CG in the United States in the past 50 years (Pyhtila et al., 2015). However, the long-term outcomes of those infants with CG who do survive remain challenging and uncertain, in large part because we still do not fully understand the pathophysiology of this
Fig. 3. Impact of low-level galactose exposure on acute and long-term outcomes in GALT-null Drosophila. (A) Survival of GALT-null and control (GALT+) larvae to adulthood when raised on food containing 555 mM glucose with or without 50 mM galactose (gal). These differences were not significant (P>0.05; both comparisons). (B) Climbing ability of adult flies reared at 28°C in the presence versus absence of 50 mM dietary galactose. This low level of dietary galactose exposure had no apparent impact on climbing ability of GALT+ flies and slightly improved climbing ability of the GALT-null flies (P=0.048). (C) Fecundity of female flies reared and tested at 28°C in the presence versus absence of 50 mM dietary galactose. We saw no significant impact of low-level galactose exposure on female fecundity of control animals (P>0.05) or GALT-null animals (P>0.05). Values plotted represent means±s.e.m.; the number of cohorts tested for each genotype (n) is indicated on the figure. P-values were calculated using an effects model, as described in Materials and Methods, and a t-test for pair-wise comparisons.

Fig. 4. Impact of maternal loading for GALK on survival of larvae to adulthood in the presence versus absence of 200 mM dietary galactose. As indicated, GALT+, GALK-null larvae that received maternally loaded GALK survived to a greater extent in both the absence and presence of dietary galactose (gal) than did their counterparts that did not receive GALK maternal loading (P<0.0001 for both comparisons). In contrast, loss of maternally loaded GALK compromised survival of GALT-null GALK-null larvae by close to three-fold in the absence of galactose (P<0.0001) and by close to 10-fold in the presence of galactose (P=0.0005). NA, not applicable. Values plotted represent means±s.e.m.; the number of cohorts tested for each genotype (n) is indicated on the figure. P-values were calculated using an effects model, as described in Materials and Methods, and a t-test for pair-wise comparisons.
dGALT\textsuperscript{ΔAP2} and the dGALK\textsuperscript{Δc/c9} alleles provided by our laboratory to test the role of GALK loss on synapse morphology and a larval movement phenotype in GALT-deficient Drosophila (Jumbo-Lucioni et al., 2014a). Their report stated that homozygosity for the dGALK\textsuperscript{Δc/c9} allele relieved many of the phenotypes they measured. However, the larval outcomes described by Jumbo-Lucioni et al. were different from the phenotypes measured here. Of note, some of the larval phenotypes assessed by Jumbo-Lucioni and colleagues (Jumbo-Lucioni et al., 2014a) were also apparently phenocopied in control (GALT\textsuperscript{+}) animals exposed to galactose, which is contrary to the larval and adult phenotypes we have observed previously and describe here (Kushner et al., 2010; Ryan et al., 2012). To be clear, even exposure of wild-type Drosophila to high (200 mM) levels of galactose does not mimic the larval death and adult climbing and female fecundity outcomes described here (Fig. 2A, and data not shown) and previously by our group (e.g. Kushner et al., 2010; Ryan et al., 2012). Given that normal human breast milk contains approximately 170 mM galactose (in the form of lactose) (Lubetzky et al., 2015), phenocopying of patient outcomes in controls exposed to galactose is also clearly at odds with the experience in humans.

One potential caveat to the experiments described here is that in addition to deleting dGALK this excision also removes part of a neighboring gene, CG5068. Little is known about the function of CG5068, but from homology studies it is predicted to encode a carboxylic ester hydrolase ostensibly responsible for the cataract formation observed in those animals. That both deletion and knockdown of GALK failed to mitigate most of the phenotypes studied here, and in fact phenocopied or exacerbated some of them, suggests that galactose, galactitol, or other galactose metabolites – or a combination of metabolites and other factors such as oxidative stress (Jumbo-Lucioni et al., 2013) or perturbed glycosylation resulting from altered levels or ratios of UDP-sugars (reviewed in Fridovich-Keil and Walter, 2008) – might underlie the pathophysiology of acute and long-term outcomes in GALT deficiency.

**MATERIALS AND METHODS**

**Fly stocks and maintenance**

Unless otherwise noted, stocks were maintained at 25°C with 60–70% humidity on a molasses-based food containing 43.5 g/l cornmeal, 17.5 g/l yeast extract, 8.75 g/l agar, 54.7 ml/l molasses, 10 ml proionic acid and 14.4 ml/l tegosept mold inhibitor (10% w/v in ethanol). For most experiments in which the levels and types of sugar were to be varied we used a glucose-based food [5.5 g/l agar, 40 g/l yeast, 90 g/l cornmeal, 100 g/l glucose, 10 ml proionic acid and 14.4 ml/l tegosept mold inhibitor (10% w/v in ethanol)] (Honjo and Furukubo-Tokunaga, 2005) supplemented with galactose, as indicated. For female fecundity experiments, we either did or did not add galactose to molasses food. All fly stocks were obtained from the Bloomington Drosophila Stock Center at Indiana University unless otherwise noted.

**Creation of a dGALK\textsuperscript{Δc/c9} deletion allele by imprecise P-element excision**

We created the dGALK\textsuperscript{Δc/c9} deletion allele by imprecise excision of an existing P-element insertion, EY03791, located less than 1 kb upstream of the dGALK start site and within a neighboring gene, CG5068. The P-element was mobilized by transient expression of the \textsc{Δ2} transposable enzyme in the male germ line, according to standard methods (Ryder and Russell, 2003). Flies carrying excision alleles were identified by loss of the associated mini-w\textsuperscript{+} marker (white eyes) and were screened biochemically by performing a GALK enzyme assay in lysates. One imprecise excision, designated as dGALK\textsuperscript{Δc/c9}, demonstrated complete loss of detectable GALK activity. The breakpoints of the 2990 bp deletion were determined by PCR amplification with primers 5′-TAATGGCCTCCTAGGCCTGTC-3′ and 5′-GTCACACGAAATCGCAGATGC-3′ followed by sequencing of the junction fragment.

**Generation of animals experiencing GALK knockdown**

\textsc{UAS-GALK\textsuperscript{RNAi}} lines were created in our laboratory by cloning a GALK\textsc{RNAi} fragment made by PCR amplification of wild-type Drosophila genomic DNA (using primers 5′-CCGCGAATTCGAGCTTCCAAAGAGTGG-3′ and 5′-CCGCGAATTCGACGTTGACGCGCTTGAC-3′) into the expression vector pSYMP using EcoRI sites. Transgenic lines were created by injecting this plasmid together with P/TS129A.Act5C (Beall et al., 2002). Injections were performed at BestGene Inc. (https://www.thebestgene.com/) and resulting transformants were identified by the presence of red eye color. The genomic insertions were mapped by standard methods. The allele used here was designated GALK\textsc{RNAi}(40A1).

Knockdown of GALK was achieved by crossing flies carrying GALK\textsc{ΔAP2} to flies carrying an appropriate GAL4 driver. For climbing experiments, the driver used was \textsc{P}/\textsc{Act5C-GAL4}\textsc{Δ25FO1}; for fecundity experiments the driver used was \textsc{P}/\textsc{Ubi-GALA}\textsc{ΔU}2. Both drivers were recombined with GALT\textsc{ΔAP2} to test GALK knockdown in GALT\textsc{-null} flies. For fecundity experiments involving GALK knockdown, flies denoted ‘GALT\textsuperscript{+}’ were actually heterozygotes with one wild-type chromosome 2 and one chromosome 2 that carried the GALT\textsc{ΔAP2} deletion allele. Specifically, GALK knockdown flies carried a recombinant chromosome 2 with both GALT\textsuperscript{ΔAP2} and Ubi-GALA, whereas ‘control’ flies lacking driver carried a chromosome 2 with GALT\textsc{ΔAP2}. In all cases, these flies had maternal loading of GALT. To ensure homozygosity for the GALT\textsc{ΔAP2} deletion did not impact fecundity, we quantified the numbers of viable...
offspring produced by GALT+/+ versus GALT+/GALTPAAP2 females in parallel crosses; there was no significant difference (data not shown).

**Quantifying enzymes and metabolites**

GALK, GALT and GALE enzyme activity assays were performed on adult male flies as described previously (Sanders et al., 2010). Drosophila larvae intended for analysis of galactose metabolites were raised on food containing either 555 mM glucose as the sole sugar or 555 mM glucose plus the indicated level of galactose (e.g. 50 mM or 200 mM). Drosophila adults intended for analysis of galactose metabolites were raised on standard molasses food. The newly eclosed adults were placed on food containing either 555 mM glucose as the sole sugar or 555 mM glucose plus 200 mM galactose and harvested after 48 h. Cohorts of third-instar larvae or adults were harvested and metabolites extracted as described previously (Sanders et al., 2010); metabolites were separated and quantified using a Dionex HPLC, essentially as described previously (Ross et al., 2004) with the following changes: measurement of galactose was performed using an MA1 column (ThermoFisher) with buffers A (1 M sodium hydroxide) and B (15 mM sodium hydroxide). Galactose was separated using an isocratic procedure with a flow rate of 0.4 ml/min and buffer concentrations of 50% buffer A and 50% buffer B for 30 min. For all samples, 20 µl was injected into a 25 µl injection loop.

**Quantifying survival of Drosophila larvae to adulthood on different foods**

We measured the impact of dietary galactose exposure on survival of developing Drosophila as described previously (Jumbo-Lucioni et al., 2013). Briefly, parents of the desired genotypes were allowed to mate and deposit eggs on grape juice and agar medium for 24 h. After an additional 24 h, cohorts of 20 first-instar larvae were collected under a dissecting microscope with a small spatula and transferred to 0.5 ml microfuge tubes pre-loaded with the desired food. Once loaded with larvae, each microfuge tube was positioned into the bottom of a 12×55 mm clear polystyrene vial. Vials were then plugged with cotton and maintained at 25°C with 60-70% humidity, and inspected daily. The number of surviving adult flies in each vial was recorded for 9 days beyond appearance of the first adult.

**Quantifying climbing ability of adult Drosophila**

Newly eclosed male flies, which developed at 28°C, were collected and maintained in cohorts of 9–11 animals per vial on standard molasses food. After 48 h, each cohort was tapped into a tall glass test tube marked with a blue line at either 3 cm or 8 cm above the base and plugged with cotton. Because we found that, as a group, flies carrying the mini-white marker climbed better than wild-type flies, we required them to climb the greater distance (8 cm). Only flies matched in terms of presence or absence of mini-white were compared. Specifically, genetic mutants and controls, all of which were wild-type, were required to climb 3 cm (Fig. 2B, top panel, and Fig. 3B), whereas flies used to test the effects of feeding GALT+ and GALT-null flies a diet containing 200 mM galactose (Kushner et al., 2010), unless otherwise noted, here we only made statistical comparisons between groups of flies where the GALT genotype and diet were held constant, so the sole difference was presence or absence of GALT. The criterion for statistical significance was P<0.05, and P-values were adjusted for multiple comparisons using a simple Bonferroni correction. All data are presented as mean±s.e.m.

**Statistical analyses**

Statistical analyses were performed using JMP-SAS software. Survival, climbing and fecundity data were analyzed using linear regression models that included both genotype and diet (when diet was varied) as independent variables and also included the genotype by diet interaction. Post-hoc comparisons were performed on the least-square means to determine significant differences between groups. Because we have previously established the effects of feeding GALT+ and GALT-null flies a diet containing 200 mM galactose (Kushner et al., 2010), unless otherwise noted, here we only made statistical comparisons between groups of flies where the GALT genotype and diet were held constant, so the sole difference was presence or absence of GALT. The criterion for statistical significance was P<0.05, and P-values were adjusted for multiple comparisons using a simple Bonferroni correction. All data are presented as mean±s.e.m.

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**Competing interests**

The authors declare no competing or financial interests.

**Author contributions**

J.M.I.D. conducted most of the experiments presented and participated in writing and editing the manuscript; P.P.J.-L. contributed to this project in its early stages and also participated in editing the manuscript; M.L.H. contributed to this project in its early stages and also participated in editing the manuscript; K.R.G. created both the GALKcano and GALTcano alleles and participated in editing the manuscript; E.L.R. contributed to this project in its early stages and also participated in editing the manuscript; J.L.F.-K. conceived of this project, coordinated the activities of the other authors, finalized the figures and wrote most of the manuscript.

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**Supplementary information**

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