

1 **The heme exporter FLVCR regulates mitochondrial biogenesis and redox
2 balance in the hematophagous insect *Rhodnius prolixus***

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17 *Rhodnius prolixus*.

18

1 **Abstract (250 words)**

2 Heme is a prosthetic group of proteins involved in vital physiological processes
3 in aerobic organisms. It participates in redox reactions crucial for cell
4 metabolism due to the variable oxidation state of its central iron atom. However,
5 excessive heme can be cytotoxic due to its prooxidant properties. Therefore,
6 the control of intracellular heme levels ensures the survival of organisms,
7 especially those that deal with high concentrations of heme during their lives,
8 such as hematophagous insects. The feline leukemia virus C receptor (FLVCR)
9 is a membrane protein responsible for heme transport in mammalian cells. In
10 our study, we found that RpFLVCR serves as a heme exporter in the midgut of
11 the hematophagous insect *Rhodnius prolixus*, a vector for Chagas disease.
12 Silencing RpFLVCR decreased hemolymphatic heme levels and increased the
13 levels of intracellular dicysteinyl-biliverdin, a product of *R. prolixus* heme
14 degradation, indicating heme retention inside midgut cells. FLVCR silencing led
15 to increased expression of heme oxygenase (HO), ferritin, and mitoferrin
16 mRNAs while downregulating the iron importers Malvolio 1 and 2. In contrast,
17 HO gene silencing increased FLVCR and Malvolio expression and
18 downregulated ferritin, revealing crosstalk between heme degradation/export
19 and iron transport/storage pathways. Furthermore, RpFLVCR silencing strongly
20 increased oxidant production and lipid peroxidation, reduced cytochrome c
21 oxidase activity and activated mitochondrial biogenesis, effects not observed in
22 RpHO-silenced insects. These data support FLVCR function as a heme
23 exporter, playing a pivotal role in heme/iron metabolism and maintenance of
24 redox balance, especially in an organism adapted to face extremely high
25 concentrations of heme.

1 **Introduction**

2 Heme, an iron-protoporphyrin IX complex, plays a crucial role in the
3 aerobic metabolism of most organisms. It is a prosthetic group of heme proteins
4 that is involved in a vast array of cellular processes, such as antioxidant
5 protection and xenobiotic detoxification. Due to its ability to bind diatomic gases,
6 heme is involved in oxygen transport and NO- and CO-dependent signaling
7 pathways. Moreover, it is directly involved in most oxidative reactions required
8 for electron transfer and energy transduction in the mitochondria (1–3).

9 To safeguard cellular integrity and its function, it is essential to maintain
10 appropriate levels of intracellular heme, as excess heme can exert cytotoxicity
11 either by directly promoting oxidative damage to biomolecules (4–6) or by
12 altering membrane permeability (7). In most aerobic organisms, heme
13 homeostasis is maintained by orchestrating heme synthesis, degradation, and
14 transport between and within cells, according to the supply and demand of this
15 metallocofactor (8–12).

16 The control of heme homeostasis is particularly critical for
17 hematophagous insects, including vectors of human diseases, which deal with
18 large amounts of this molecule released during the digestion of the host's blood
19 (13). In fact, a variety of mechanisms to counteract the harmful effects of free
20 heme and generated reactive oxygen species (ROS) have evolved in these
21 animals (13). Some of them represent obvious adaptations of organisms that
22 face an overload of heme, such as the formation of insoluble heme aggregates
23 (hemozoin) (14,15), sequestration by heme-binding proteins associated with the
24 extracellular matrix (16) and unique heme enzymatic degradation pathways that
25 result in the production of water-soluble modified biliverdins (17,18). While the
26 biochemical aspects of heme synthesis and degradation have already been
27 described in some of these blood-sucking arthropods (17–20), the precise
28 mechanisms involved in transmembrane heme transport remain largely
29 unexplored. In ticks, an ABCB10 homolog has been implicated in heme
30 transport (21). In contrast, in *Aedes aegypti*, exposing cells and tissues to low or
31 high heme does not result in positive identification of heme transporters (22).

1 In mammals, cellular transmembrane heme export is attributed to feline
2 leukemia virus subgroup C receptor 1 (FLVCR1). FLVCR1 was originally
3 identified as the cell surface receptor for feline leukemia virus subgroup C
4 (23,24), but a role in heme metabolism soon became apparent (25). Flvcr1a is
5 one of the two isoforms codified by the Flvcr1 gene. It is a member of the
6 SLC49 family of the major facilitator superfamily of secondary transporters,
7 capable of transporting small solutes in response to chemiosmotic ion gradients
8 (26,27). Flvcr1a mRNA is widely expressed in various mammalian organs, such
9 as the bone marrow, liver, duodenum, lungs, kidneys, spleen, brain and
10 placenta (28–30). The role of FLVCR1a (herein referred to as FLVCR) as a
11 heme exporter has been described in different cell types, including erythroid
12 cells, macrophages, hepatocytes, enterocytes and endothelial cells (25,28,31–
13 33). Its contribution to the maintenance of heme homeostasis is particularly
14 critical in erythroid cells, where heme is abundantly produced during
15 erythropoiesis (34). In these cells, FLVCR ensures the efficient transport of
16 excess unbound heme molecules, possibly preventing their toxic accumulation
17 (28). However, the role of cellular heme efflux ascribed to FLVCR as an
18 antioxidant mechanism is still controversial (35). The FLVCR1-related protein
19 FLVCR2 has been proposed to be a heme importer in mammals (36) but also
20 seems to be involved in calcium transport (37). Additionally, a member of the
21 FLVCR family has been described in *Leishmania major* (LmFLVCRb) that is
22 capable of taking up porphyrins and heme inclusively from the extracellular
23 medium (38).

24 As previously described, a single FLVCR ortholog has been identified in
25 the genome of *Rhodnius prolixus*, a vector of Chagas disease (39). RpFLVCR
26 has the 12 transmembrane canonical domains that are typical of these proteins.
27 RpFLVCR knockdown impacts the survival of nymphs and adults as well as
28 oogenesis, embryogenesis and molting during their life cycle, indicating that
29 fluctuations in the levels of this protein can be deleterious to insect development
30 (39).

31 In this study, we present evidence that RpFLVCR acts as a heme
32 transporter in *R. prolixus* and that heme efflux from the midgut lumen to the
33 hemolymph is dependent on RpFLVCR. This process is critical for maintaining

1 intestinal homeostasis and redox balance by modulating the expression of
2 genes involved in iron/heme metabolism and antioxidant protection.
3 Furthermore, RpFLVCR knockdown induces mitochondrial biogenesis with
4 altered function, highlighting its paramount role in mitochondrial physiology in *R.*
5 *prolixus*.

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1 **Results and Discussion**

2

3 ***RpFLVCR acts as a heme exporter in Rhodnius prolixus***

4 Heme in cells and extracellular fluids is rarely found as free heme and is
5 more precisely described as “labile heme”. Labile heme is exchangeable
6 between distinct cellular targets, including low-molecular-weight ligands or
7 proteins, nucleic acids or phospholipid membranes (40). In vertebrates, two
8 main mechanisms are known to be involved in the control of intracellular levels
9 of labile heme: enzymatic degradation by heme oxygenase and heme transport
10 provided by membrane transporters (41–43). Although heme degradation
11 pathways have been documented in insects (17,18,44), the proteins responsible
12 for the import and export of heme by cells remain undescribed. Heme
13 molecules provided in the bloodmeal reach the hemolymph by crossing the
14 midgut epithelium of the kissing bug *R. prolixus* (45), thus revealing a
15 mechanism that provides the transfer of heme molecules from the intestinal
16 lumen of blood-sucking insects through enterocytes to the hemolymph.

17 In the genome of *Rhodnius prolixus*, a single FLVCR ortholog has been
18 identified, and gene silencing strongly affects insect reproduction, development
19 and survival after a blood meal (39). Thus, we decided to analyze whether, as in
20 vertebrates, this transporter is involved in the export of intracellular heme in *R.*
21 *prolixus*.

22 Circulating levels of heme in hemolymph were measured in RpFLVCR-
23 silenced females and used as a readout of heme export activity. Figure 1A
24 shows that RpFLVCR-silenced females had lower heme concentrations in their
25 hemolymph than dsMAL-injected controls. If RpFLVCR works as a heme
26 exporter, its knockdown should lead to an increase in intracellular heme
27 followed by heme degradation by heme oxygenase (HO). As observed in the
28 midgut tissue, the levels of Rp-biliverdin, a breakdown product of heme
29 catabolism (17), were higher in RpFLVCR-silenced females than in control
30 females (Figure 1B). These results indicate that FLVCR silencing promotes an
31 increase in the intracellular labile heme pool and support the hypothesis that

1 RpFLVCR acts as a transmembrane exporter of heme from the intestinal
2 epithelium to the hemolymph.

3 ***Knockdown of RpFLVCR modulates the expression of genes involved in***
4 ***heme and iron metabolism***

5 It is well established in the literature that heme is a ubiquitous molecule
6 involved in several cellular processes, including signal transduction and
7 transcriptional modulation (46–54). Thus, possible variations in heme levels
8 caused by RpFLVCR KD could impact the transcription of other genes involved
9 in iron and heme metabolism. Thus, we sought to observe phenotypes that
10 could be associated with variations in intracellular heme levels. We analyzed
11 the mRNA levels of genes encoding key proteins such as HO (heme
12 degradation), Malvolium 1 and 2 (NRAMP orthologs from mammals involved in
13 iron import), mitoferrin (Mfrn, a mitochondrial iron importer) and ferritin (Fer, an
14 intracellular iron-storage protein). RpFLVCR knockdown promoted increases in
15 the expression of HO, Mfrn, and Fer and decreases in the expression of the iron
16 importers MVL1 and MVL2 (Figure 2). These results suggest that the increase
17 in HO expression may have been a compensatory mechanism to control
18 intracellular heme levels that were not exported due to RpFLVCR silencing.
19 Increased expression of intracellular iron-binding proteins, such as ferritin (Fer)
20 and mitoferrin (Mfrn), was required to prevent oxidative damage caused by iron
21 from heme porphyrin ring breakage. On the other hand, with the increased
22 availability of intracellular iron, import by MLV proteins became unnecessary,
23 explaining the decrease in MLV expression (Figure 2B). Interestingly, HO KD
24 caused an opposite effect on gene expression in comparison to that of
25 RpFLVCR silencing, leading to increased expression of the RpFLVCR, MVL1
26 and MVL2 genes and decreased mRNA levels of ferritin (Figure 2C and 2D).
27 These results suggested that the reduction in HO expression increased
28 intracellular heme but decreased labile iron levels. These results are consistent
29 with increased RpFLVCR transcription working to remove excess heme. A
30 decrease in free iron availability would promote MVL importer expression and,
31 conversely, lead to reductions in the expression of iron-chelating genes, such as
32 ferritin and mitoferrin.

1 **RpFLVCR depletion caused redox imbalance**

2 Heme is known to be a pro-oxidant molecule due to its ability to promote
3 the formation of radical species (ROS). It can promptly react with organic
4 hydroperoxides, producing alkoxy or peroxy lipid radicals, thus increasing lipid
5 peroxidation (6). Indeed, the midguts of RpFLVCR-silenced insects showed
6 increased fluorescence of the redox-sensitive probe DHE (Figure 3A),
7 suggesting redox imbalance. This conclusion was further supported by TBARS
8 assay analysis of lipid peroxidation levels in the midgut, which showed
9 increased lipid peroxidation in dsRpFLVCR-injected females (Figure 3C). The
10 impact on the midgut redox balance was also monitored by quantification of
11 mRNA levels of antioxidant genes whose expression is usually induced in
12 response to high levels of ROS, such as catalase (CAT), glutathione peroxidase
13 (PHGPx), thioredoxin reductase (TrxR) and peroxiredoxins (Prx). Corroborating
14 the DHE fluorescence and TBARS data, females with RpFLVCR gene silencing
15 showed higher antioxidant enzyme mRNA levels than control insects (Figure
16 3D). Surprisingly, HO KD had no effect on the cellular redox status (Figure 3B,
17 C and D). This result could be explained by one of two mechanisms: i) Rp
18 FLVCR mediated export of the remaining labile heme left undegraded upon HO
19 KD or ii) the oxidative insult to the intestinal cells upon RpFLVCR KD was
20 derived more from iron produced via heme cleavage by HO than from an
21 increase in the level of labile heme itself. In fact, it has already been shown that
22 knockdown of ferritin, the main intracellular iron chelator, causes a dramatic
23 increase in oxidant production in the *R. prolixus* midgut (39). Choosing between
24 these alternative hypotheses is a central point for future research on redox
25 metabolism in blood-sucking insects.

26 **RpFLVCR silencing induces mitochondrial biogenesis with altered
27 function**

28 Heme proteins represent a significant fraction of the electron transport
29 system (ETS) components, implying that mitochondria are the main sites of iron
30 and heme storage in eukaryotic cells (55). Therefore, changes in heme levels in
31 animals with RpFLVCR silencing should interfere with energy metabolism and
32 mitochondrial function. To test this hypothesis, we first determined
33 mitochondrial content in the intestinal cells of the silenced animals through

1 MitoTracker Green fluorescence microscopy, as this probe accumulates
2 preferably in mitochondria. We observed that 5 days after blood feeding, the
3 females with silencing of the RpFLVCR gene showed a higher fluorescence
4 than the control insects or insects with silencing of HO, suggesting an increase
5 in the mitochondrial content (Figure 4A and 4B). This result was corroborated
6 by the increased activity of citrate synthase, an important tricarboxylic acid cycle
7 enzyme classically used as an index of mitochondrial content (56), in the
8 midguts of RpFLVCR-silenced insects (Figure 4C). Surprisingly, cytochrome c
9 oxidase activity was strongly reduced specifically in RpFLVCR-silenced insects,
10 suggesting that *de novo* mitochondrial biogenesis generates organelles with
11 lower electron flux and respiratory rates (Figure 4D). To gain further insights into
12 the mechanisms underlying FLVCR KD-induced mitochondrial expansion, we
13 measured the expression of genes that have a central role in mitochondrial
14 biogenesis. Mitochondrial transcription factor A (TFAM) is a nuclear DNA-
15 encoded protein responsible for the transcription and translation of
16 mitochondrial DNA (mtDNA) (57,58). Delg (CG6338; *Drosophila* Ets-like gene)
17 is a close homolog of mammalian NRF-2 α that is critical for adjusting
18 mitochondrial abundance (59), and its expression is frequently associated with
19 mitochondrial biogenesis. The quantification of *R. prolixus* orthologs of these
20 genes revealed that RpFLVCR KD promoted increases in the mRNA levels of
21 both genes, whereas HO KD did not (Figure 4 E and F), suggesting that
22 RpFLVCR silencing increases mitochondrial mass in the midgut in association
23 with increased TFAM and DELG expression.

24 Consistent with the finding that RpFLVCR KD promotes mitochondrial
25 biogenesis and the knowledge that mitochondria are sources of ROS in
26 eukaryotic cells (60–62), we noticed that the RpFLVCR KD-induced increase in
27 DHE fluorescence upon RpFLVCR KD was strongly reduced by MitoTempo
28 (Figure 5A). Conceivably, increased cellular oxidant production upon RpFLVCR
29 silencing results from reduced cytochrome c oxidase activity, facilitating
30 mitochondrial electron leakage and superoxide production. In this sense,
31 mitochondria represent the main sites of cellular oxidant production (63), and
32 altered mitochondrial electron flux promoted by RpFLVCR silencing (Figures 4
33 and 5) might contribute to superoxide production. Altogether, these results

1 indicate that the redox imbalance observed in RpFLVCR-silenced insects is
2 derived from mitochondrial oxidant production. However, the mechanism by
3 which RpFLVCR KD modulates mitochondrial biogenesis and the relationship of
4 this phenomenon with the increase in cellular oxidant levels still need to be
5 clarified.

6 Recently, it was shown in two elegant reports that the mammalian
7 FLVCR works as a choline transporter instead of a heme transporter (64,65).
8 Evidence excluding a role for this membrane protein in heme transport came
9 from experiments showing that FLVCR KO in cells does not impact the
10 expression of HO or other heme- and iron-related genes (64). The same report
11 also observed alterations in mitochondria comparable to those found here but
12 instead attributed this phenotype to deficient phospholipid biosynthesis. Here,
13 we did not address a role of RpFLVCR in choline transport, an interesting
14 possibility that could well explain part of the deleterious effects of RpFLVCR on
15 insect oogenesis and embryo and nymph development (39), all biological
16 phenomena that need large amounts of phosphatidylcholine. However, the
17 results presented here reveal a robust impact of FLVCR on heme and iron cell
18 biology that is unlikely to be explained by choline deficiency alone. Therefore, it
19 is possible that FLVCR is a moonlighting transporter, with choline transport
20 being the function for most cell types that live in the presence of heme
21 concentrations in the low micromolar range (used in the experiments of Kenny
22 et al. (64)), while cells that physiologically face higher heme concentrations may
23 use FLVCR as a low-affinity but functional transporter. Vertebrate blood has
24 approximately 150 mg/ml hemoglobin, which, upon complete digestion, should
25 result in ~5 mM heme. This considerable number suggests that RpFLVCR may
26 well be such a moonlighting heme transporter. As hematophagy has arisen
27 independently multiple times during the evolution of insects (66), further
28 investigation with other hematophagous insect species is needed to determine
29 how frequently the recruitment of FLVCR homologs has been a key player in
30 the adaptation of the insect to hematophagy, as seems to be the case for
31 *Rhodnius prolixus* intestinal epithelia.

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3 **Experimental procedures**

4 ***Experimental Insects***

5 Insects were taken from a colony of *R. prolixus* maintained at 28 °C and 70–
6 90% relative humidity under a photoperiod of 12 h of light/12 h of dark. All
7 animals used in this work were mated females fed on rabbit blood at 3-week
8 intervals. *R. prolixus* females injected with dsRNA were kept in individual vials
9 maintained under the same conditions.

10 ***Ethics Statement***

11 All animal care and experimental protocols were conducted following the
12 guidelines of the institutional care and use committee (Committee for Evaluation
13 of Animal Use for Research from the Federal University of Rio de Janeiro,
14 CAUAP-UFRJ), which are based on the National Institutes of Health Guide for
15 the Care and Use of Laboratory Animals (ISBN 0-309-05377-3). The protocols
16 were approved by the Committee for Evaluation of Animal Use for Research
17 from the Federal University of Rio de Janeiro under registry number
18 IBQM0123/22. Dedicated technicians in the animal facility at the Instituto de
19 Bioquímica Médica Leopoldo de Meis (UFRJ) carried out all protocols related to
20 rabbit husbandry under strict guidelines to ensure careful and consistent animal
21 handling.

22 ***Tissue Isolation and RNA Extraction***

23 Posterior midguts from blood-fed females were dissected on different days after
24 a blood meal. Total RNA was extracted from individual tissues or pools of 3–5
25 midguts using TRIzol reagent (Invitrogen, Carlsbad, CA, United States)
26 according to the manufacturer's instructions. Complementary DNA was
27 synthesized using a High-Capacity cDNA Reverse Transcription Kit (Applied
28 Biosystems, Foster City, CA, United States).

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3 **dsRNA Synthesis and Gene Silencing Assays**

4 Fragments of 320–400 bp were amplified by PCR using cDNA from midgut
5 epithelia from blood-fed females (48 h after feeding) produced as described
6 above. The following conditions were used for amplification: one cycle for 5 min
7 at 95 °C followed by 40 cycles of 30 s at 95 °C, 30 s at 63 °C, and 1 min at 72
8 °C, with a final step of 10 min at 72 °C. The oligonucleotides used for
9 amplification of templates for dsRNA synthesis are listed in Supporting Table
10 S1. Amplified cDNAs were used as a template for dsRNA synthesis using a
11 MEGAScript RNAi Kit (Ambion Inc., Austin, TX, United States) according to the
12 manufacturer's instructions. The maltose-binding protein (MAL) gene
13 from *Escherichia coli* (gene identifier 7129408) in a pBlueScript KS (Stratagene)
14 was amplified by PCR using T7 minimal promoter primers under the following
15 conditions: one cycle for 10 min at 95 °C followed by 40 cycles of 15 s at 95 °C,
16 15 s at 45 °C, and 45 s at 72 °C, with a final step of 10 min at 72 °C. The PCR
17 product produced was used as a template for MAL dsRNA synthesis and as a
18 control in the gene silencing assays. Following *in vitro* synthesis, all dsRNAs
19 were purified according to the manufacturer's instructions. For gene silencing, 1
20 µg of dsRNA specific for RpFLVCR (dsRpFLVCR), heme oxygenase (dsHO) or
21 MAL (dsMAL) was injected into the starved insect hemocoel. Insects were fed
22 on rabbit blood 48 h after injection. At different times after feeding, midguts were
23 dissected, total RNA was extracted as described above, and gene silencing
24 efficiency was evaluated by quantitative RT–PCR. The efficiency of RpFLVCR
25 and RpHO silencing is shown in Supporting Figure S1.

26 **Quantitative RT–PCR Analysis**

27 Quantitative gene amplification (qPCR) was performed with a StepOnePlus
28 real-time PCR system (Applied Biosystems, Foster City, CA, United States)
29 using Power SYBR Green PCR Master Mix (Applied Biosystems, Foster City,
30 CA, United States) under the following conditions: one cycle for 10 min at 95 °C
31 followed by forty cycles of 15 s at 95 °C and 45 s at 60 °C. PCR amplification
32 was performed using the oligonucleotides specified in Supporting Table S2. *R.*

1 *prolixus* elongation factor 1 gene (RPRC007684) expression was used as an
2 internal control for normalization (67). The relative expression values based on
3 $2^{-\Delta\Delta CT}$ were used in silencing gene analyses (68). Differences were
4 considered significant when $p < 0.05$. The relative expression values based on
5 the $2^{-\Delta CT}$ method were used only for figure construction.

6 ***Quantification of heme content in the hemolymph***

7 Hemolymph was collected 3 days after blood feeding from previously silenced
8 females in tubes containing a few crystals of phenylthiourea by cutting a leg and
9 applying gentle pressure to the insect abdomen. Qualitative analyses of heme
10 levels were performed by diluting a hemolymph aliquot of 10 μL in 490 μL of
11 PBS pH 7.4, and the light absorption spectra were analyzed between 300 nm
12 and 800 nm in a Shimadzu UV-2550 spectrophotometer. Absolute quantification
13 of total heme was determined by the alkaline pyridine-hemochrome method
14 using the reduced minus oxidized spectra as described elsewhere (69).

15 ***Quantification of biliverdin in the midgut***

16 Two days prior to the blood meal, adult females were injected with 1 μL of
17 dsRNA (1 $\mu\text{g}/\mu\text{L}$) into the thoracic cavity. Five individual midguts were dissected
18 3 days after feeding; individually homogenized with 200 μL of 5% acetonitrile
19 and 0.05% TFA, pH 2.0, (used as solvent for the HPLC column); and
20 centrifuged for 15 min at 12,000 $\times g$. The supernatant was applied onto a
21 Shimadzu CLC-ODS C18 column (15 mm \times 22 cm) equilibrated with the same
22 solvent using a flow rate of 0.4 mL/min using an LC-10AT device (Shimadzu,
23 Tokyo, Japan) equipped with a diode array detector (SPDM10A). After 10 min,
24 an acetonitrile linear gradient (5–80%) was applied for 10 min followed by 20
25 min of 80% acetonitrile with 0.05% TFA, pH 2.0. The biliverdin peak was
26 identified and quantified as previously described (17).

27 ***Analysis of oxidant status in different tissues***

28 Lipid peroxidation levels in the hemolymph of silenced females were assessed
29 3 days after a blood meal by quantifying the levels of thiobarbituric acid reactive
30 substances (TBARS) at 532 nm in a Molecular Devices Spectra Max M5
31 spectrophotometer as described elsewhere (70). Additionally, to evaluate

1 oxidant levels in the midgut, starved females were injected with 1 μ g of
2 RpFLVCR dsRNA, HO dsRNA or MAL dsRNA (control). Two days after
3 injection, insects were fed with rabbit blood, and their wings, legs and dorsal
4 cuticle were removed by dissection. The insect hemocoel was filled with 50 μ M
5 of the oxidant-sensitive fluorophore dihydroethidium (hydroethidine; DHE;
6 Invitrogen, Carlsbad, CA, United States) diluted in Leibovitz-15 medium
7 containing 5% fetal bovine serum or with DHE and 5 μ M MitoTEMPO (Santa
8 Cruz, Dallas, TX, United States). The midguts were incubated in the dark at 28
9 $^{\circ}$ C for 20 min, washed with 0.15 M NaCl, and immediately transferred to a glass
10 slide for fluorescence microscopy analysis, as previously described (71).
11 Quantitative evaluation of fluorescence levels was performed by acquiring
12 images under identical conditions using an objective of 20X and 90 ms
13 exposure time in each experiment. The images were acquired in a Zeiss
14 Observer. Z1 with a Zeiss Axio Cam MrM Zeiss, and the data were analyzed
15 using AxioVision version 4.8 software. The filter set (excitation BP 546/12 nm;
16 beam splitter FT 580 nm; emission LP 590 nm) was used for DHE labeling.

17 ***Analysis of mitochondrial content***

18 Mitochondrial content was determined by measuring the activity of citrate
19 synthase (CS) and by MitoTracker Green fluorescence. CS activity was
20 assayed according to the method described by Hansen and Sidell (1983)(72),
21 with modifications. Pools of two midguts were homogenized in 200 μ L of saline
22 solution. After 2 min of decantation, 40 μ L of supernatant was incubated with
23 7.5 mM Tris buffer (pH 8.0) containing 50 μ M DTNB (5,5'-dithiobis-(2-
24 nitrobenzoic acid)) (Sigma-Aldrich, MI, United States), 300 μ M acetyl-CoA and
25 1 mM oxaloacetate. Immediately, DTNB reduction was measured for 10 min at
26 412 nm. The specific activity was calculated using the reduced DTNB molar
27 extinction coefficient ($\epsilon = 13.6 \text{ mM}^{-1} \cdot \text{cm}^{-1}$). MitoTracker Green is a mitochondrial
28 selective probe that binds covalently to mitochondrial proteins by reacting with
29 cysteine residues and accumulates in the mitochondrial matrix (73–75). This
30 reaction is independent of mitochondrial membrane potential and is widely used
31 in the literature to represent mitochondrial mass (56,76). Starved adult females
32 were injected with 1 μ L of dsRpFLVCR, dsHO or dsMAL into the thoracic cavity.
33 Two days after injection, the insects were fed on blood. Mitochondria were

1 stained with 100 μ M MitoTracker Green FM (Invitrogen, Carlsbad, CA, United
2 States) diluted in Lebovitz-15 medium containing 5% fetal bovine serum for 30
3 minutes and with DAPI (0.1 mg/mL) for 10 minutes at 28 °C in the dark 5 days
4 after feeding. Afterward, the midguts were washed with 0.15 M NaCl and
5 immediately transferred to a glass slide for fluorescence microscopy analysis.
6 Images were acquired in an Olympus IX81 microscope and a CellR MT20E
7 Imaging Station equipped with an IX2-UCB controller and an
8 ORCAR2 C10600 CCD camera (Hammamatsu). Image processing was
9 performed with Xcellence RT version 1.2 Software.

10 ***Cytochrome c Oxidase Activity***

11 The activity of cytochrome *c* oxidase was measured in a total reaction volume of
12 1 mL using a Shimadzu UV-visible 2450 spectrophotometer (Shimadzu
13 Scientific Instruments, Tokyo, Japan). Enzyme activity was measured by
14 following the decrease in absorbance caused by the oxidation of
15 ferrocytochrome *c* ($\epsilon = 18.5 \text{ mM}^{-1} \text{ cm}^{-1}$) (77) modified according to Gaviragh
16 (78). The reaction mixture consisted of 100 mM potassium phosphate (pH 7.4)
17 and 50 mM reduced cytochrome *c*. The reaction was initiated by the addition of
18 freeze-thawed mitochondria (80 μ g of protein), and the reduction in absorbance
19 at 550 nm was monitored. KCN (1 mM) was added to inhibit
20 cytochrome *c* oxidase activity, and the resulting rate was considered the
21 cyanide-sensitive rate of cytochrome *c* oxidation. The data are expressed as
22 nmol of reduced cytochrome *c*/min/mg protein of isolated mitochondria.

23

24 ***Statistical analysis***

25 All analyses were performed with the GraphPad Prism statistical software
26 package (Prism version 6.0, GraphPad Software, Inc., La Jolla, CA). Significant
27 differences are indicated by asterisks (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; ns,
28 not significant), and the type of test used in each analysis is described in its
29 respective figure legend.

30

31 *Supporting information* - This article contains supporting information.

1 *Author contributions* - ABWN, MFO and GOPS conceived and designed the
2 experiments; ABWN, MTA and MPO performed the experiments; ABW-N, MFO,
3 PLO and GOPS analyzed the data; ABWN wrote the original draft; all authors
4 reviewed and edited the manuscript; and GOPS supervised the study.

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15

1 **References**

2 1. PONKA P. Cell Biology of Heme. *Am J Med Sci.* 1999 Oct;318(4):241.

3 2. Kim HJ, Khalimonchuk O, Smith PM, Winge DR. Structure, function, and
4 assembly of heme centers in mitochondrial respiratory complexes. Vol.
5 1823, *Biochimica et Biophysica Acta - Molecular Cell Research.* 2012. p.
6 1604–16.

7 3. Shimizu T, Huang D, Yan F, Stranava M, Bartosova M, Fojtíková V, et al.
8 Gaseous O₂, NO, and CO in Signal Transduction: Structure and Function
9 Relationships of Heme-Based Gas Sensors and Heme-Redox Sensors.
10 Vol. 115, *Chemical Reviews.* American Chemical Society; 2015. p. 6491–
11 533.

12 4. TAPPEL AL. Unsaturated lipide oxidation catalyzed by hematin
13 compounds. *J Biol Chem.* 1955 Dec 1;217(2):721–33.

14 5. Gutteridge JMC, Smith A. Antioxidant protection by haemopexin of haem-
15 stimulated lipid peroxidation. Vol. 256, *Biochem. J.* 1988.

16 6. Ryter SW, Tyrrell RM. Hypothesis Paper THE HEME SYNTHESIS AND
17 DEGRADATION PATHWAYS: ROLE IN OXIDANT SENSITIVITY Heme
18 Oxygenase has Both Pro-and Antioxidant Properties. 2000.

19 7. Schmitt TH, Frezzatti WA, Schreier S. Hemin-Induced Lipid Membrane
20 Disorder and Increased Permeability: A Molecular Model for the
21 Mechanism of Cell Lysis. *Arch Biochem Biophys.* 1993 Nov;307(1):96–
22 103.

23 8. Rajagopal A, Rao AU, Amigo J, Tian M, Upadhyay SK, Hall C, et al. Haem
24 homeostasis is regulated by the conserved and concerted functions of
25 HRG-1 proteins. *Nature.* 2008 Jun 19;453(7198):1127–31.

26 9. Chen C, Samuel TK, Krause M, Dailey HA, Hamza I. Heme utilization in
27 the *Caenorhabditis elegans* hypodermal cells is facilitated by heme-
28 responsive gene-2. *Journal of Biological Chemistry.* 2012 Mar
29 16;287(12):9601–12.

1 10. White C, Yuan X, Schmidt PJ, Bresciani E, Samuel TK, Campagna D, et
2 al. HRG1 is essential for heme transport from the phagolysosome of
3 macrophages during erythrophagocytosis. *Cell Metab.* 2013;17(2).

4 11. Chiabrand D, Vinchi F, Fiorito V, Mercurio S, Tolosano E. Heme in
5 pathophysiology: A matter of scavenging, metabolism and trafficking
6 across cell membranes. *Front Pharmacol.* 2014;5:1–24.

7 12. Donegan RK, Moore CM, Hanna DA, Reddi AR. Handling heme: The
8 mechanisms underlying the movement of heme within and between cells.
9 Vol. 133, *Free Radical Biology and Medicine*. Elsevier Inc.; 2019. p. 88–
10 100.

11 13. Graça-Souza A V., Maya-Monteiro C, Paiva-Silva GO, Braz GRC, Paes
12 MC, Sorgine MHF, et al. Adaptations against heme toxicity in blood-
13 feeding arthropods. Vol. 36, *Insect Biochemistry and Molecular Biology*.
14 Elsevier Ltd; 2006. p. 322–35.

15 14. Oliveira MF, Kycia SW, Gomez A, Kosar AJ, Bohle DS, Hempelmann E, et
16 al. Structural and morphological characterization of hemozoin produced
17 by *Schistosoma mansoni* and *Rhodnius prolixus*. *FEBS Lett.* 2005 Nov
18 7;579(27):6010–6.

19 15. Stiebler R, Timm BL, Oliveira PL, Hearne GR, Egan TJ, Oliveira MF. On
20 the physico-chemical and physiological requirements of hemozoin
21 formation promoted by perimicrovillar membranes in *Rhodnius prolixus*
22 midgut. *Insect Biochem Mol Biol.* 2010 Mar;40(3):284–92.

23 16. Davenport M, Alvarenga PH, Shao L, Fujioka H, Bianconi ML, Oliveira PL,
24 et al. Identification of the *Aedes aegypti* peritrophic matrix protein
25 AelMUCI as a heme-binding protein. *Biochemistry.* 2006 Aug
26 8;45(31):9540–9.

27 17. Paiva-Silva GO, Cruz-Oliveira C, Nakayasu ES, Maya-Monteiro CM,
28 Dunkov BC, Masuda H, et al. A heme-degradation pathway in a blood-
29 sucking insect [Internet]. 2006. Available from:
30 www.pnas.org/cgi/doi/10.1073/pnas.0602224103

1 18. Pereira LOR, Oliveira PL, Almeida IC, Paiva-Silva GO. Biglutaminyl-
2 biliverdin IX alpha as a heme degradation product in the dengue fever
3 insect-vector *Aedes aegypti*. *Biochemistry*. 2007 Jun 12;46(23):6822–9.

4 19. Braz GRC, Coelho HSL, Masuda H, Oliveira PL. A missing metabolic
5 pathway in the cattle tick *Boophilus microplus*. 1999; Available from:
6 <http://biomednet.com/elecref/0960982200900703>

7 20. Braz GRC, Moreira MF, Masuda H, Oliveira PL. Rhodnius heme-binding
8 protein (RHBP) is a heme source for embryonic development in the
9 blood-sucking bug *Rhodnius prolixus* (hemiptera, reduviidae). *Insect
10 Biochem Mol Biol*. 2002;32(4).

11 21. Lara FA, Pohl PC, Gandara AC, Ferreira JDS, Nascimento-Silva MC,
12 Bechara GH, et al. ATP binding cassette transporter mediates both heme
13 and pesticide detoxification in tick midgut cells. *PLoS One*. 2015 Aug
14 10;10(8).

15 22. Eggleston H, Adelman ZN. Transcriptomic analyses of *Aedes aegypti*
16 cultured cells and ex vivo midguts in response to an excess or deficiency
17 of heme: A quest for transcriptionally-regulated heme transporters. *BMC
18 Genomics*. 2020 Aug 31;21(1).

19 23. Tailor CS, Willett BJ, Kabat D. A Putative Cell Surface Receptor for
20 Anemia-Inducing Feline Leukemia Virus Subgroup C Is a Member of a
21 Transporter Superfamily. Vol. 73, *JOURNAL OF VIROLOGY*. 1999.

22 24. Quigley JG, Burns CC, Anderson MM, Lynch ED, Sabo KM, Overbaugh J,
23 et al. Cloning of the cellular receptor for feline leukemia virus subgroup C
24 (FeLV-C), a retrovirus that induces red cell aplasia. *Blood*. 2000;95(3).

25 25. Quigley JG, Yang Z, Worthington MT, Phillips JD, Sabo KM, Sabath DE,
26 et al. Identification of a Human Heme Exporter that Is Essential for
27 Erythropoiesis through a balance among heme biosynthesis, utilization for
28 hemoproteins, and catabolism by the microsomal enzyme, heme
29 oxygenase (HO) (Ponka, 1997), to generate carbon monoxide, iron, and
30 biliverdin [Internet]. Vol. 118, *Cell*. 2004. Available from:
31 <http://source.stanford.edu>

- 1 26. Pao SS, Paulsen IT, Saier MH. Major Facilitator Superfamily. Vol. 62,
2 MICROBIOLOGY AND MOLECULAR BIOLOGY REVIEWS. 1998.
- 3 27. Chiabrand D, Marro S, Mercurio S, Giorgi C, Petrillo S, Vinchi F, et al.
4 The mitochondrial heme exporter FLVCR1b mediates erythroid
5 differentiation. *J Clin Invest* [Internet]. 2012;122:4569. Available from:
6 <http://www.jci.org>
- 7 28. Keel SB, Doty RT, Yang Z, Quigley JG, Chen J, Knoblaugh S, et al. A
8 heme export protein is required for red blood cell differentiation and iron
9 homeostasis. *Science* (1979). 2008;319(5864).
- 10 29. Khan AA, Quigley JG. Control of intracellular heme levels: Heme
11 transporters and heme oxygenases. Vol. 1813, *Biochimica et Biophysica
12 Acta - Molecular Cell Research*. 2011.
- 13 30. Khan AA, Quigley JG. Heme and FLVCR-related transporter families
14 SLC48 and SLC49. Vol. 34, *Molecular Aspects of Medicine*. 2013.
- 15 31. Vinchi F, Ingoglia G, Chiabrand D, Mercurio S, Turco E, Silengo L, et al.
16 Heme exporter FLVCR1a regulates heme synthesis and degradation and
17 controls activity of cytochromes P450. *Gastroenterology*. 2014;146(5).
- 18 32. Fiorito V, Forni M, Silengo L, Altruda F, Tolosano E. Crucial role of
19 FLVCR1a in the maintenance of intestinal heme homeostasis. *Antioxid
20 Redox Signal*. 2015 Dec 20;23(18):1410–23.
- 21 33. Petrillo S, Chiabrand D, Genova T, Fiorito V, Ingoglia G, Vinchi F, et al.
22 Heme accumulation in endothelial cells impairs angiogenesis by triggering
23 paraptosis. *Cell Death Differ*. 2018 Mar 1;25(3):573–88.
- 24 34. Mercurio S, Petrillo S, Chiabrand D, Bassi ZI, Gays D, Camporeale A, et
25 al. The heme exporter Flvcr1 regulates expansion and differentiation of
26 committed erythroid progenitors by controlling intracellular heme
27 accumulation. *Haematologica*. 2015;100(6):720–9.
- 28 35. Ponka P, Sheftel AD, English AM, Scott Bohle D, Garcia-Santos D. Do
29 Mammalian Cells Really Need to Export and Import Heme? Vol. 42,
30 Trends in Biochemical Sciences. Elsevier Ltd; 2017. p. 395–406.

1 36. Duffy SP, Shing J, Saraon P, Berger LC, Eiden M V., Wilde A, et al. The
2 Fowler Syndrome-Associated Protein FLVCR2 Is an Importer of Heme.
3 Mol Cell Biol. 2010 Nov 1;30(22):5318–24.

4 37. Brasier G, Tikellis C, Xuereb L, Craigie J, Casley D, Kovacs CS, et al.
5 Novel hexad repeats conserved in a putative transporter with restricted
6 expression in cell types associated with growth, calcium exchange and
7 homeostasis. Exp Cell Res. 2004 Feb 1;293(1):31–42.

8 38. Cabello-Donayre M, Orrego LM, Herráez E, Vargas P, Martínez-García M,
9 Campos-Salinas J, et al. Leishmania heme uptake involves LmFLVCRb, a
10 novel porphyrin transporter essential for the parasite. Cellular and
11 Molecular Life Sciences. 2020;77(9).

12 39. Walter-Nuno AB, Taracena ML, Mesquita RD, Oliveira PL, Paiva-Silva
13 GO. Silencing of iron and heme-related genes revealed a paramount role
14 of iron in the physiology of the hematophagous vector *Rhodnius prolixus*.
15 Front Genet. 2018;9(FEB).

16 40. Gouveia Z, Carlos AR, Yuan X, Aires-da-Silva F, Stocker R, Maghzal GJ,
17 et al. Characterization of plasma labile heme in hemolytic conditions.
18 FEBS Journal. 2017 Oct 1;284(19):3278–301.

19 41. Hamza I, Dailey HA. One ring to rule them all: Trafficking of heme and
20 heme synthesis intermediates in the metazoans. Vol. 1823, Biochimica et
21 Biophysica Acta - Molecular Cell Research. 2012.

22 42. Chambers IG, Willoughby MM, Hamza I, Reddi AR. One ring to bring
23 them all and in the darkness bind them: The trafficking of heme without
24 deliverers. Vol. 1868, Biochimica et Biophysica Acta - Molecular Cell
25 Research. 2021.

26 43. Korolnek T, Hamza I. Like iron in the blood of the people: The requirement
27 for heme trafficking in iron metabolism. Vol. 5 JUN, Frontiers in
28 Pharmacology. 2014.

29 44. Caiaffa CD, Stiebler R, Oliveira MF, Lara FA, Paiva-Silva GO, Oliveira PL.
30 Sn-protoporphyrin inhibits both heme degradation and hemozoin

1 formation in *Rhodnius prolixus* midgut. *Insect Biochem Mol Biol.* 2010
2 Dec;40(12):855–60.

3 45. Dansa-Petretski M, Ribeiro JMC, Atella GC, Masuda H, Oliveira PL.
4 Antioxidant role of *Rhodnius prolixus* heme-binding protein. *Protection*
5 *against heme-induced lipid peroxidation*. *Journal of Biological Chemistry.*
6 1995;270(18).

7 46. Zhang L. *Heme Biology: The secret life of heme in regulating diverse*
8 *biological processes*. First Edition. Singapore: World Scientific; 2011.
9 139–196 p.

10 47. Shimizu T, Lengalova A, Martínek V, Martínková M. *Heme: Emergent*
11 *roles of heme in signal transduction, functional regulation and as catalytic*
12 *centres*. *Chem Soc Rev.* 2019 Dec 21;48(24):5624–57.

13 48. Bottino-Rojas V, Talyuli OAC, Jupatanakul N, Sim S, Dimopoulos G,
14 Venancio TM, et al. *Heme signaling impacts global gene expression,*
15 *immunity and dengue virus infectivity in Aedes aegypti*. *PLoS One.* 2015
16 Aug 14;10(8).

17 49. Woldt E, Sebti Y, Solt LA, Duhem C, Lancel S, Eeckhoute J, et al. *Rev-*
18 *erb-α modulates skeletal muscle oxidative capacity by regulating*
19 *mitochondrial biogenesis and autophagy*. *Nat Med.* 2013 Aug;19(8):1039–
20 46.

21 50. Mense SM, Zhang L. *Heme: a versatile signaling molecule controlling the*
22 *activities of diverse regulators ranging from transcription factors to MAP*
23 *kinases*. *Cell Res.* 2006 Aug 8;16(8):681–92.

24 51. Suzuki H, Tashiro S, Hira S, Sun J, Yamazaki C, Zenke Y, et al. *Heme*
25 *regulates gene expression by triggering Crm1-dependent nuclear export*
26 *of Bach1*. *EMBO Journal.* 2004 Jul 7;23(13):2544–53.

27 52. Ogawa. *Heme mediates de-repression of Maf recognition element*
28 *through direct binding to transcription repressor Bach1*. 2001;

29 53. Zhang L, Guarente L. *Heme binds to a short sequence that serves a*
30 *regulatory function in diverse proteins*. Vol. 14, *The EMBO Journal.* 1995.

1 54. Zhang L. *Heme Biology: Heme acts as a versatile signalling molecule*
2 regulating diverse biological processes. Second Edition. Zhang L, editor.
3 Dallas : World Scientific ; 2020.

4 55. Jhurry ND, Chakrabarti M, McCormick SP, Holmes-Hampton GP, Lindahl
5 PA. Biophysical investigation of the ironome of human Jurkat cells and
6 mitochondria. *Biochemistry*. 2012 Jul 3;51(26):5276–84.

7 56. Larsen S, Nielsen J, Hansen CN, Nielsen LB, Wibrand F, Stride N, et al.
8 Biomarkers of mitochondrial content in skeletal muscle of healthy young
9 human subjects. *Journal of Physiology*. 2012 Jul;590(14):3349–60.

10 57. Picca A, Lezza AMS. Regulation of mitochondrial biogenesis through
11 TFAM-mitochondrial DNA interactions. Useful insights from aging and
12 calorie restriction studies. Vol. 25, *Mitochondrion*. Elsevier; 2015. p. 67–
13 75.

14 58. Cardanho-Ramos C, Morais VA. Mitochondrial biogenesis in neurons:
15 How and where. Vol. 22, *International Journal of Molecular Sciences*.
16 MDPI; 2021.

17 59. Baltzer C, Tiefenböck SK, Marti M, Frei C. Nutrition controls mitochondrial
18 biogenesis in the Drosophila adipose tissue through Delg and cyclin
19 D/Cdk4. *PLoS One*. 2009 Sep 9;4(9).

20 60. Nickel A, Kohlhaas M, Maack C. Mitochondrial reactive oxygen species
21 production and elimination. Vol. 73, *Journal of Molecular and Cellular*
22 *Cardiology*. Academic Press; 2014. p. 26–33.

23 61. Starkov AA. The role of mitochondria in reactive oxygen species
24 metabolism and signaling. In: *Annals of the New York Academy of*
25 *Sciences*. Blackwell Publishing Inc.; 2008. p. 37–52.

26 62. Murphy MP. How mitochondria produce reactive oxygen species. Vol.
27 417, *Biochemical Journal*. 2009. p. 1–13.

28 63. Boveris A, Oshino N, Chance B. The Cellular Production of Hydrogen
29 Peroxide. Vol. 128, *Biochem. J.* 1972.

1 64. Kenny TC, Khan A, Son Y, Yue L, Heissel S, Sharma A, et al. Integrative
2 genetic analysis identifies FLVCR1 as a plasma-membrane choline
3 transporter in mammals. *Cell Metab.* 2023 Jun 6;35(6):1057-1071.e12.

4 65. Tsuchiya M, Tachibana N, Nagao K, Tamura T, Hamachi I. Organelle-
5 selective click labeling coupled with flow cytometry allows pooled CRISPR
6 screening of genes involved in phosphatidylcholine metabolism. *Cell
7 Metab.* 2023 Jun;35(6):1072-1083.e9.

8 66. Marquardt WC, Kondratieff BC. *Biology of Disease Vectors*. Second
9 Edition. Burlington: Elsevier Academic Press; 2005.

10 67. Majerowicz D, Alves-Bezerra M, Logullo R, Fonseca-De-Souza AL,
11 Meyer-Fernandes JR, Braz GRC, et al. Looking for reference genes for
12 real-time quantitative PCR experiments in *Rhodnius prolixus* (Hemiptera:
13 Reduviidae). *Insect Mol Biol.* 2011 Dec;20(6):713–22.

14 68. Livak KJ, Schmittgen TD. Analysis of relative gene expression data using
15 real-time quantitative PCR and the 2- $\Delta\Delta CT$ method. *Methods.*
16 2001;25(4):402–8.

17 69. Falk JE. *Porphyrin and metalloporphyrins: their general, physical and
18 coordination chemistry, and laboratory methods*. Elsevier Publishing
19 Company; 1964.

20 70. Liedtke AJ, Mahar CQ, Ytrehus K, Mjcs OD. Estimates of free-radical
21 production in rat and swine hearts: method and application of measuring
22 malondialdehyde levels in fresh and frozen myocardium. Vol. 179, *Basic
23 Res.* 1984.

24 71. Walter-Nuno AB, Oliveira MP, Oliveira MF, Gonçalves RL, Ramos IB,
25 Koerich LB, et al. Silencing of maternal heme-binding protein causes
26 embryonic mitochondrial dysfunction and impairs embryogenesis in the
27 blood sucking insect *rhodnius prolixus*. *Journal of Biological Chemistry.*
28 2013;288(41).

29 72. Hansen CA, Sidell BD. Atlantic hagfish cardiac muscle: metabolic basis of
30 tolerance to anoxia [Internet]. 1983. Available from:
31 www.physiology.org/journal/ajpregu

1 73. Presley AD, Fuller KM, Arriaga EA. MitoTracker Green labeling of
2 mitochondrial proteins and their subsequent analysis by capillary
3 electrophoresis with laser-induced fluorescence detection. *Journal of*
4 *Chromatography B*. 2003 Aug;793(1):141–50.

5 74. Poot M, Zhang YZ, Krämer JA, Wells KS, Jones LJ, Hanzel DK, et al.
6 Analysis of mitochondrial morphology and function with novel fixable
7 fluorescent stains. *Journal of Histochemistry & Cytochemistry*. 1996 Dec
8 25;44(12):1363–72.

9 75. Soultanakis RP, Melamede RJ, Bespalov IA, Wallace SS, Beckman KB,
10 Ames BN, et al. Fluorescence detection of 8-oxoguanine in nuclear and
11 mitochondrial DNA of cultured cells using a recombinant Fab and confocal
12 scanning laser microscopy. *Free Radic Biol Med*. 2000 Mar;28(6):987–98.

13 76. Agnello M, Morici G, Rinaldi AM. A method for measuring mitochondrial
14 mass and activity. *Cytotechnology*. 2008 Mar;56(3):145–9.

15 77. Kirby DM, Thorburn DR, Turnbull DM, Taylor RW. Biochemical Assays of
16 Respiratory Chain Complex Activity. Vol. 80, *Methods in Cell Biology*.
17 2007. p. 93–119.

18 78. Gaviragli A, Correa Soares JBR, Mignaco JA, Fontes CFL, Oliveira MF.
19 Mitochondrial glycerol phosphate oxidation is modulated by adenylates
20 through allosteric regulation of cytochrome c oxidase activity in mosquito
21 flight muscle. *Insect Biochem Mol Biol*. 2019 Nov 1;114.

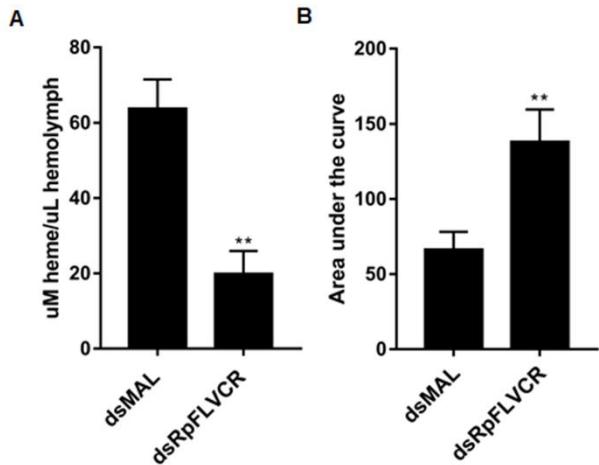
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2 **Figure Legends**

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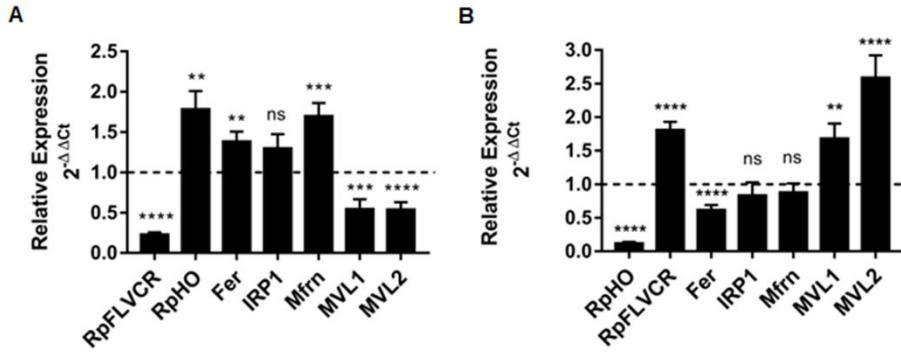
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6 **Figure 1: FLVCR acts as a heme exporter in *R. prolixus*.** Adult females were
7 injected with dsRpFLVCR or dsMAL (control group) and fed on blood as
8 described. (A) Quantification of heme present in the hemolymph of females
9 injected with dsRpFLVCR and dsMAL. The amount of heme present in
10 hemolymph was determined by the alkaline pyridine method. The data are
11 presented as the mean \pm SE for 10 individual determinations per experiment of
12 four independent experiments. Statistical analysis between the two groups was
13 performed using Student's *t* test. (B) Quantification of biliverdin present in the
14 midgut of RpFLVCR-silenced insects. The amount of biliverdin was measured
15 as described in Section 2 by HPLC. The data are presented as the mean \pm SE
16 for n=5 of three independent experiments. Statistical analysis between the two
17 groups was performed using Student's *t* test. ** $p < 0.01$

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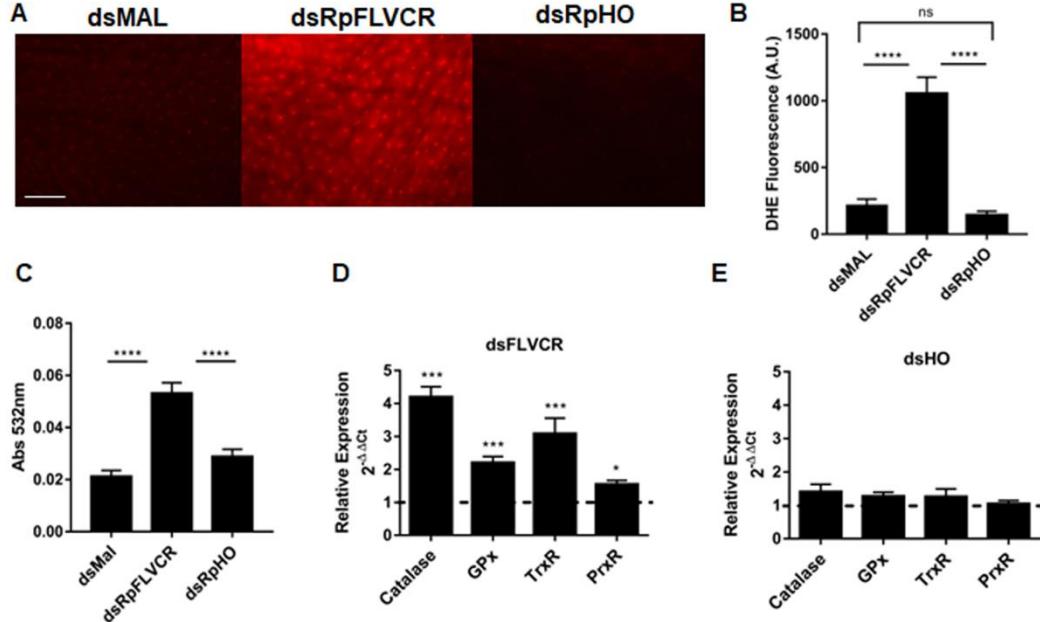


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2 **Figure 2: FLVCR silencing is able to modulate genes from heme and iron**
3 **metabolism.** Starved adult females were injected with dsRpRFLVCR (A) or
4 dsRpHO (B). Insects were fed on blood 48 h after injection. Total RNA was
5 extracted from the foregut and hindgut, and the mRNA levels of genes involved
6 in iron and heme metabolism were analyzed by quantitative RT-PCR. The EF-1
7 gene was used as an endogenous control. The result was normalized to
8 animals injected with dsMAL (dashed line). The data are presented as the mean
9 ± SE (n= 14-15) of three independent experiments. Statistical analyses were
10 performed using Student's t test (experimental versus their respective controls,
11 dsMal). *p<0.05; ** p<0.01; *** p<0.001; ****p<0.0001. RpFLVCR, feline
12 leukemia virus C receptor FLVCR; RpHO, heme oxygenase; Fer, ferritin; IRP1,
13 iron regulatory protein 1; Mfrn, mitoferrin; MVL1, Malvolio 1; MVL2, Malvolio 2

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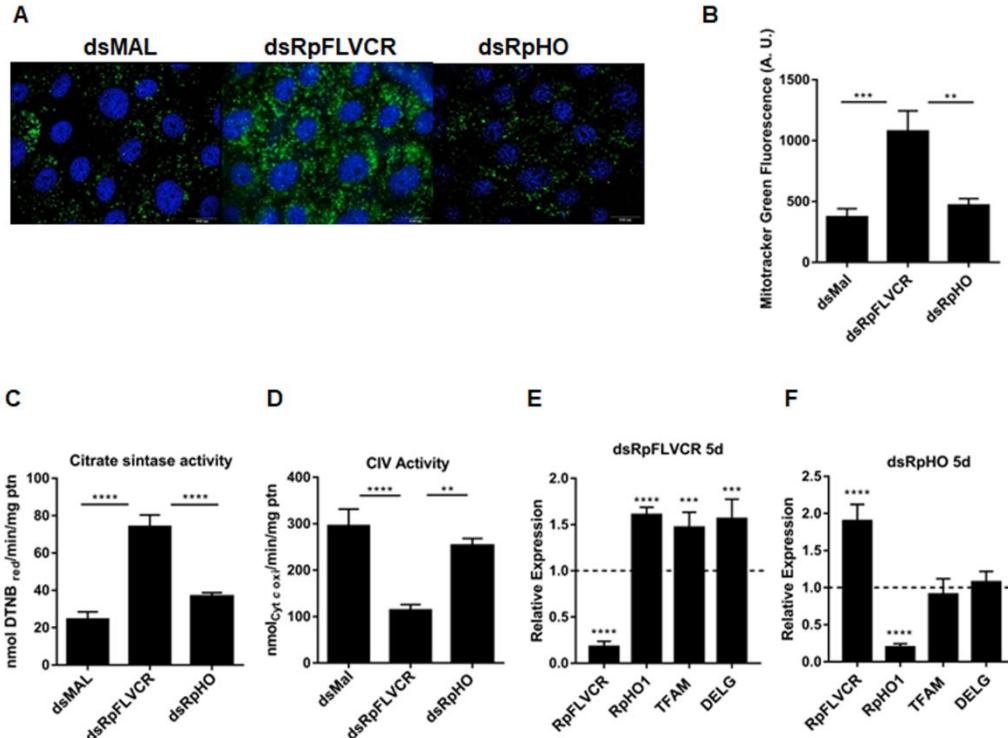


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4 **Figure 3. FLVCR silencing increases ROS levels in midgut cells.** (A) ROS
5 levels were evaluated from oxidized DHE fluorescence in cells from blood-fed
6 females previously injected with dsRpFLVCR, dsRpHO or dsMal (control).
7 Representative images of insects for each experimental condition are shown,
8 scale bar 2 μ m. Quantitative analysis of DHE fluorescence in 10 individual
9 intestines from three independent experiments. The data shown are the mean \pm
10 SE, **** p<0.0001 for one-way ANOVA with Tukey's posttest. (B) Lipid
11 peroxidation of hemolymph was quantified by the TBARS assay as described.
12 The data shown are the mean \pm SE (n= 4) from three independent experiments.
13 **** p<0.0001 for one-way ANOVA with Tukey's posttest. (C-D). The expression
14 of selected antioxidant genes was evaluated by quantitative RT-PCR in insects
15 with silenced RpFLVCR (C) or RpHO (D). The result was normalized to that of
16 animals injected with dsMAL (dashed line). Statistical analyses were performed
17 using Student's t test (experimental versus their respective controls, dsMal).
18 The data shown are the mean \pm SE, *p<0.05; *** p<0.001 (n=12-14).

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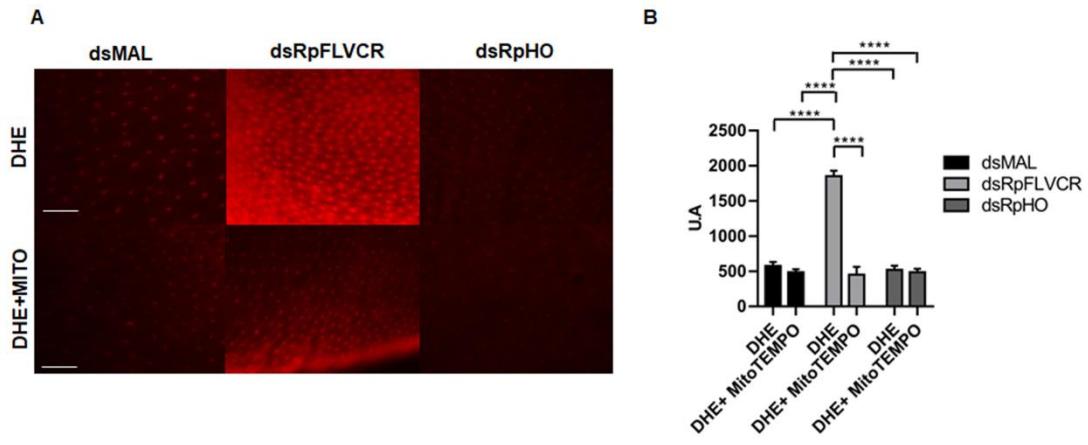
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Figure 4: Knockdown of FLVCR increases mitochondrial biogenesis in the midgut. (A) Unfed *R. prolixus* females were injected with dsMal, dsRpFLVCR or dsRpHO; 3 days after injection, they were fed on blood. Five days after a blood meal, the insects were incubated with MitoTracker Green and DAPI as described in the Experimental section. The scale represents 20 μ m. All pictures were taken with an exposure time of 260 ms. The images are representative of a total of 18 intestines analyzed. (B) Quantification of MitoGreen fluorescence using Olympus quantification software. **P \leq 0.01; *** P \leq 0.001 one-way ANOVA with Tukey's posttest. (C) The mitochondrial content of the midgut was also determined by measuring the activity of citrate synthase in silenced females as described in the methods section. The data shown are the mean \pm SE. ****P <0.0001 . One-way ANOVA with Tukey's posttest (n=7). (D) The activity of cytochrome c oxidase was measured using a Shimadzu spectrophotometer UV-visible 2450. The data shown are the mean \pm SE. ** P \leq 0.01; ****P \leq 0.0001, one-way ANOVA with Tukey's posttest (n=8). (E) dsRpFLVCR- and (F)

1 dsRpHO-injected females had their midgut dissected 5 days after feeding. The
2 transcript levels of genes that control mitochondrial mass were measured by
3 quantitative RT-PCR. The result was normalized to that of animals injected with
4 dsMAL (dashed line). Statistical analyses were performed using Student's t test
5 (experimental versus their respective controls, dsMal). The data shown are the
6 mean \pm SE. *** $P \leq 0,001$; **** $P \leq 0.0001$. (n= 8-11) TFAM; mitochondrial
7 transcription factor A; DELG; CG6338/Drosophila Ets-like gene.

8

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3 **Figure 5: Knockdown of FLVCR promotes an imbalance in the**
4 **mitochondrial redox state.** (A) Anterior midguts (AMs) from FLVCR and HO-
5 silenced females were incubated with a 50 μ M solution of oxidant-sensitive
6 fluorophore DHE or the tissues were preincubated with 50 μ M MitoTEMPO, a
7 selective mitochondrial antioxidant, prior to DHE incubation. dsMal-injected
8 females were used as controls. DHE oxidation in the AMs was analyzed by
9 fluorescence microscopy (Zeiss Axio Observer Microscope) using a 20 \times lens
10 with an 80 ms exposure time for all conditions. The images are representative
11 of a total of 10 midguts analyzed. Scale bar 2 μ m. (B) Graph represents the
12 quantification of fluorescence using Zeiss Axio Observer Quantification
13 software. The data shown are the mean \pm SE. ****P \leq 0.0001 (one-way ANOVA
14 followed by Tukey's test).

15

16