General, negative feedback mechanism for regulation of Trithorax-like gene expression in vivo: new roles for GAGA factor in flies

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ABSTRACT

Expression of every gene is first regulated at the transcriptional level. While some genes show acute and discrete periods of expression others show a rather steady expression level throughout development. An example of the latter is Trithorax-like (Trl) a member of the Trithorax group that encodes GAGA factor in Drosophila. Among other functions, GAGA factor has been described to stimulate transcription of several genes, including some homeotic genes. Here we show that GAGA factor is continuously down-regulating the expression of its own promoter using a negative feedback mechanism in vivo. Like its expression, repression by GAGA factor is ubiquitous, prevents its accumulation, and takes place throughout development. Experimental alteration of GAGA factor dosage results in several unexpected phenotypes, not related to alteration of homeotic gene expression, but rather to functions that take place later during development and affect different morphogenetic processes. The results suggest that GAGA factor is essential during development, even after homeotic gene expression is established, and indicate the existence of an upper limit for GAGA factor dosage that should not be exceeded.

INTRODUCTION

Drosophila GAGA factor is encoded in the single copy gene Trithorax-like (Trl) and is present in two isoforms, GAGA519 and GAGA581 generated by alternative splicing that only differ at the C-terminus (1,2). They share a POZ/BTB domain, responsible for the formation of homo- and hetero-oligomers (3–5), a DNA-binding domain (DBD) containing a single zinc finger flanked by three basic regions that confer specificity for binding GA-rich sequences (6,7), and a domain (X) of largely unknown structure and function(s) between the former two that interacts with some nuclear factors, NURF301 and FACT, and directs GAGA to the nucleus [8,9] Regué, L. and J.B., unpublished data, for a review see (10). At the C-terminal part the two isoforms present a glutamine-rich domain (Q-domain) that, although different in sequence and in length, is similar in amino acid composition. Both Q-domains have the ability to stimulate transcription of several reporter genes in transiently transfected cells. Both isoforms are modified post-translationally, and recently phosphorylation at the DBD has been reported (11). GAGA factor is present in all cell types of the fly and it is strictly nuclear [(2); our unpublished data].

GAGA factor belongs to the Trithorax group of genes and is involved in maintaining large regions of chromatin in an open state, in particular those regions of certain homeotic genes. Trl mutants behave as enhancers of position effect variegation (1). Recently, GAGA factor has been shown to prevent heterochromatin spreading by directing histone H3.3 replacement in association with FACT (12). GAGA factor collaborates with NURF in chromatin remodeling in vitro and also stimulates transcription of many genes both in vitro and in vivo [(13–19), for a review see (20)]. GAGA factor presents maternal effect, and null mutants are embryonic lethal. Although a few adult flies can develop with low levels of GAGA factor, homozygous hypomorphic Trl13C embryos present major defects in nuclear divisions at early stages of embryonic development and strong embryonic lethality. Severe defects in expression of en and ftz genes were also reported (18). Homozygous Trl885 null mutant embryos (from heterozygous females) showed reduced levels of some homeotic genes (Ubx and en), but not of others (Scr, Antp, Abd-A and Abd-B) indicating that adequate regulation of some homeotic genes can still be observed in developing embryos despite

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a lack in the maternal contribution. During larval development, loss of function clones also suggest that Trl function is not required for homeotic gene expression (21).

In transient transfection experiments, GAGA was found to down-regulate its own expression by binding to the Trl promoter in S2 cells. This repression was very efficient, dose-dependent, and did not require either the Q-domain or the POZ/BTB domain but was strictly dependent on the integrity of the DBD (22). Here we show in vivo that Trl gene is self-regulated by its own product GAGA factor in a negative way. This repression appears to be general during development and is dose-dependent. Alteration of local levels of GAGA factor protein, by forced expression and depletion by RNAi, resulted in a variety of new phenotypic defects that appeared after homeotic gene expression is already established.

MATERIALS AND METHODS

Transgenic flies

Transgenic fly lines were generated by microinjection of a P-element based vector construct bearing a white marker (pCasper or pUAST) along with a construct source of transposase in 0–45 min Drosophila embryos (w or w+) (23). UAS-GAGA line was kindly supplied by Ma Lluïsa Espina ´s, IBMB). RNAi GAGA lines contain two copies of a fragment of GAGA coding sequence (from +263 to +927), coding for a C-ter region of the POZ domain and the entire X domain, inserted in pWIZ in inverted orientations at AvrII and NheI sites (construct kindly provided by Mª Lluisa Espinãs, IBMB). To generate Trl-GFP fly lines a GFP-pCasper4 vector was prepared by inserting a GFP coding sequence at NotI/BamHI blunt-ended with T4 DNA polymerase and inserted at the StuI in the polylinker of the GFP-pCasper4 vector. +927), coding for a C-ter region of the POZ domain and the entire X domain, inserted in pWIZ in inverted orientations at AvrII and NheI sites (construct kindly provided by Mª Lluisa Espinãs, IBMB). To generate Trl-GFP fly lines a GFP-pCasper4 vector was prepared by inserting a GFP coding sequence at NotI/BamHI sites in the pCasper4 polylinker. Then a long Trl promoter fragment (NheI/PstI from previous constructs) was inserted between XbaI and PstI sites in the polylinker (23). Dark-field pictures were taken on a Nikon E-1000 microscope equipped with a DCM 1200F camera.

Immunostaining and microscopy

Embryos were collected and dechorionated in sodium hypochlorite for 2.5 min, exhaustively washed with 0.1% Triton X-100 and fixed by the slow formaldehyde fix procedure (23). Imaginal disks were dissected from 3rd instar larvae in ice-cold PBS and immediately fixed in 4% p-formaldehyde in PBS for 20 min at room temperature, followed by extensive washing with PBS–0.3% Triton X-100. Disks were either directly used or stored in this buffer at 4°C until use. For immunostaining, all washes and incubations were in PBS–0.3% Triton X-100–2% BSA. Embryos or imaginal disks were incubated overnight at 4°C with primary antibodies with agitation. Embryos and disks were then extensively washed and secondary antibodies labeled with fluorophores were added and incubated in the dark for 2 h with agitation at room temperature. Samples were then extensively washed and DNA stained with 20 ng/ml DAPI in PBS for 5 min. After extensive washing with PBS–0.3% Triton-X-100, the tissues were mounted in Mowiol. Primary antibodies were used as follows: rat x-GAL4 (1:100), rabbit x-GFP (1:1000) (Moebular Proteomes), rabbit x-GAL4 (1:600) (Santa Cruz). Secondary antibodies were always used at 1:600 and were x-rabbit IgG-Cy2 and x-rabbit IgG-Cy3 and x-rat IgG-Cy3. Images were recorded on a Leica confocal microscope.

RESULTS

GAGA represses expression of its own promoter in vivo

In a previous study, GAGA was found to down-regulate its own expression by binding to the Trl promoter in Drosophila cells (22). To study this negative regulation and its consequences in vivo, transgenic flies carrying different versions of the Trl promoter fused to green fluorescent protein (GFP) coding sequences as a reporter were generated. Three constructs containing 3.47 kb, 345 bp and 49 bp long sequences corresponding to the longest, minimal and null promoter described previously, plus 737 bp of 5’ UTR region, were selected (Figure 1A). Several independent transgenic lines were obtained for each construct. None of them showed any visible defect and stocks grew normally. Characterization of these transgenic lines indicated that the long and the minimal Trl promoter constructs expressed GFP indistinguishable to endogenous GAGA expression, and defined a compact Trl promoter that, to the extent analyzed, did not show tissue-specific or development-specific regulation. The null Trl promoter construct did not express GFP at all, as expected (data not shown).

To manipulate the levels of the GAGA factor, and to direct specific GAGA factor over-expression or depletion via RNAi, the GAL4-UAS system was used.
Over-expression of GAGA\textsubscript{519}, from a UAS-GAGA\textsubscript{519} construct, was tested by crossing with several GAL4 drivers and expression was checked by antibody staining (data not shown). We next proceeded to study the effect of GAGA\textsubscript{519} over-expression on the activity of the \textit{Trl}-GFP. Because flies carrying long and minimal \textit{Trl} promoter constructs produced identical results, only results obtained with the long construct are presented.

GAGA\textsubscript{519} over-expression experiments showed high lethality with all GAL4 drivers (even at 18°C, see below and Table 1). Among them prdGAL4 (at 18°C) was selected because it allowed the study of effects in the embryos (that further develop to reach larval stage) and also because GAL4 protein was expressed in alternating stripes thus providing convenient internal negative controls. Over-expression of GAGA\textsubscript{519} resulted in a pattern of seven bands of high expression of GAGA\textsubscript{519} alternating with bands of background GAGA expression from the endogenous \textit{Trl} gene (Figure 1B, a). In segments where GAGA\textsubscript{519} over-expression took place (in red) a reduction in GFP signal (in green) was observed. The intensity of this reduction was variable among embryos while no reduction was observed in control stripes adjacent to the GAGA\textsubscript{519} over-expression domain. GAL4 expression on its own had no effect on GFP levels (Figure 1B, b). GAGA\textsubscript{519} over-expression had no effect on flies carrying a null promoter \textit{Trl}–GFP construct and no GFP signal appeared, as expected (data not shown).

Table 1. Lethality observed in GAGA over-expression experiments. Unless specified lethality was 100%

<table>
<thead>
<tr>
<th>Condition</th>
<th>Lethality</th>
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<tr>
<td>ptcGAL4/UASGAGA\textsubscript{519}</td>
<td>Larval (at 18°C)</td>
</tr>
<tr>
<td>prdGAL4/UASGAGA\textsubscript{519}</td>
<td>Larval (at 18°C)</td>
</tr>
<tr>
<td>dppGAL4/UASGAGA\textsubscript{519}</td>
<td>Just before hatching, some escapers (at 18 and 25°C)</td>
</tr>
<tr>
<td>MS1096GAL4/UASGAGA\textsubscript{519}</td>
<td>Pupal/some escapers (at 18°C)</td>
</tr>
<tr>
<td>ApGAL4/UASGAGA\textsubscript{519}ΔQ</td>
<td>Larval/pupal (at 18°C)</td>
</tr>
<tr>
<td>ptcGAL4/UASGAGA\textsubscript{519}ΔQ</td>
<td>Larval (at 18°C)</td>
</tr>
<tr>
<td>prdGAL4/UASGAGA\textsubscript{519}ΔQ</td>
<td>No lethality (at 25°C)</td>
</tr>
<tr>
<td>MS1096GAL4/UASGAGA\textsubscript{519}ΔQ</td>
<td>Larval/pupal (at 18°C)</td>
</tr>
<tr>
<td>ptcGAL4/UASGAGA\textsubscript{519}DBDKO</td>
<td>No lethality (at 25°C)</td>
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<tr>
<td>prdGAL4/UASGAGA\textsubscript{519}DBDKO</td>
<td>No lethality (at 25°C)</td>
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<tr>
<td>MS1096GAL4/UASGAGA\textsubscript{519}DBDKO</td>
<td>No lethality (at 25°C)</td>
</tr>
<tr>
<td>dppGAL4/UASGAGA\textsubscript{519}DBDKO</td>
<td>No lethality (at 25°C)</td>
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Embryos shown in Figure 1 corresponded to stages 13–14. Although expression of GAL4 protein from the paired promoter could be detected earlier (and GAGA\textsubscript{519} over-expression was easily detected in embryos from stages 9–11) no effect on GFP expression could be observed at these earlier stages (data not shown). Perhaps, the short time elapsed between forced GAGA expression and assay (a few hours before collection) combined with the long GFP half-life in flies (>24 h)
makes it technically impossible to detect changes in GFP protein content at these early stages. This may also explain why GFP reduction was less pronounced in embryos when compared to imaginal disks (see below and compare Figures 1 and 2).

GAGA factor repression of Trl was further studied in 3rd instar larval imaginal disks. Flies carrying several GAL4 drivers for expression in wing and haltere imaginal disks were crossed to longTrl-GFP/UASGAGA519 transgenic lines. GAGA519 over-expression under MS1096GAL4 (Figure 2A and B in red) resulted in a clear reduction of GFP expression (in green) in the area of GAGA519 over-expression both in wing and haltere imaginal disks. Without GAGA519 over-expression GFP expression was not affected (Figure 2C). When dppGAL4 was used equivalent results were obtained. In this case, equally efficient repression of the Trl-GFP reporter was also observed in leg disks where dppGAL4 could also direct UASGAGA519 expression (data not shown).

With the different GAL4 drivers used, repression of Trl-GFP was variable in intensity (depending on the GAL4 driver) but never complete, suggesting a dose dependence. Figure 2D shows that repression can also take place when a C-terminal deletion encompassing the Q domain (the transactivation domain) is expressed. However, repression is fully abolished when a GAGA factor is expressed carrying a single point mutation at the DB domain that disrupts the zinc finger (Figure 2E and F). Additionally, with this point mutant there is no lethality at all and drivers like ptcGAL4 can be used to reveal expression of this GAGA mutant throughout development (an example is its expression in the wing disk, Figure 2E).

We conclude that GAGA519 repression of Trl expression is a general mechanism apparently operating throughout fly development—likely at all cell types—that takes place through interaction with DNA sequences.

Depletion of GAGA factor stimulates Trl transcription

A logical consequence of the negative feedback model is that depletion of GAGA factor should result in stimulation of Trl transcription. To test this hypothesis, a complementary set of experiments was carried out to deplete GAGA factor. Two transgenic lines carrying a UASRNAiGAGA construct were obtained (4-2 and 7-2 on chromosomes II and III, respectively) and conditions to obtain substantial depletion of GAGA factor with several GAL4 expressing lines were determined. Depletion was always more efficient with UASRNAiGAGA4-2 although results were equivalent at 29°C (results with line 7-2 are not shown). In general, GAL4-driven expression of RNAi constructs showed no lethality. In embryos only moderate depletion, not sufficient for our purposes, was obtained (even at 29°C, data not shown). In wing imaginal disks (and also haltere, data not shown) of 3rd instar larvae expression of RNAiGAGA under ptcGAL4 control resulted in a clear GAGA depletion in a central stripe defining the anterior–posterior axis (Figure 3A, in red) that corresponded to ptcGAL4 expression domain. On its own ptcGAL4 expression did not affect GAGA expression (data not shown). GAGA depletion resulted in enhanced expression of Trl-GFP reporter constructs (Figure 3A, in green) exactly in the area of GAGA depletion. In the absence of RNAiGAGA expression, neither GAGA nor GFP expression were altered (Figure 3B, in red and green, respectively). GAGA depletion was higher at 29°C than at 25°C and Trl-GFP expression was also more intense at 29°C than at 25°C (data not shown). Note that in these experiments, RNAiGAGA knocked down both GAGA isoforms (see Materials and Methods section). These results show that Trl-GFP expression in vivo is stimulated by GAGA depletion in a dose-dependent manner and, therefore, that GAGA factor is keeping Trl promoter partially repressed in vivo.

Phenotypic consequences of altering GAGA factor dosage

Analysis of the high lethality observed in GAGA519 over-expression experiments (Table 1) revealed a remarkable amount of morphological defects, usually local even though GAGA519 was over-expressed in a larger area. These defects affected different body parts and were observed independently of the presence of the GFP reporters.

When MS1096GAL4 was used to over-express GAGA519 only a few escapers hatched and reached adult stage at 18°C (none at 25°C). These flies showed a severe wing phenotype with only some remnants of the wing vein pattern apparent, complete loss of the wing border identity and a clear separation of the two dorsal/ventral cell layers. The rest of the body looked normal in these flies (Figure 4A). When ApGAL4 was used, lethality was absolute and earlier (larval, data not shown). GAGA519 over-expression under ptcGAL4 control resulted in a major abnormality in the T1–T3 segments affecting the larval cephalopharyngeal skeleton at 18°C (Figure 4B, red circle). While GAGA519 is similarly over-expressed in the other segments in the embryo (data not shown), no other morphological defects could be observed. These animals died before reaching 3rd instar larvae. When dppGAL4 was used, a large majority of the animals completed metamorphosis at 25°C without hatching. The few that hatched showed all their legs reduced to two apparently normal segments (femur and tibia) whereas the five tarsal segments and tips were reduced to a stump (Figure 4C, central panels). In males, some remnants of the sex combs could still be appreciated abnormally developing on the stump (arrow in Figure 4C). In more severe cases, legs were further reduced and could be completely absent and these animals could not hatch (see the lower three panels on the right column in Figure 4C showing increasing phenotype indicated with an arrow from – to + ). This same phenotype could also be observed at 18°C although in the less severe forms.

Over-expression of GAGAΔQ resulted in a variation of all the phenotypes that depended on the driver used. Thus, when it was over-expressed with MS1096 no animals hatched from pupae at 18°C. However, GAGAΔQ over-expression with pApGAL4 did not result in any lethality. Importantly, over-expression of GAGA519DBDKO did
Figure 2. GAGA519 can strongly repress Trl transcription in imaginal disks. Confocal microscopy images of Drosophila imaginal disks from 3rd instar larvae stained with α-GAGA (in red) and α-GFP (in green) antibodies. Central panels show merge images. (A and B) Wing and haltere imaginal disks carrying a long Trl promoter–GFP reporter and over-expressing GAGA519 under MS1096 control, respectively; (C) control imaginal disks carrying a long Trl promoter–GFP reporter but not over-expressing GAGA519; (D) wing imaginal disk carrying a long Trl promoter–GFP reporter and over-expressing GAGAΔQ under MS1096 control. Samples were obtained at 18°C. (E and F) Wing and haltere imaginal disks carrying a long Trl promoter–GFP reporter and over-expressing GAGAΔQDBDKO under ptc and MS1096 control, respectively. Samples were obtained at 25°C. (W: wing, H: haltere, L: leg).
not result in any lethality nor did we detect any phenotypic defects with this mutant (Table 1 and data not shown).

Flies expressing RNAi_GAGA also showed some abnormal phenotypes with the use of some GAL4 drivers. Defects were absent in embryos and larvae, probably because RNAi-based depletion likely generates a hypomorphic situation (see the previous section). Hypomorphic GAGA mutants are known to show a wt phenotype even in homozygosis, and the sole defect observed is that females are sterile and can only lay a few eggs (18).

GAGA depletion with ptcGAL4 resulted in a reduction of the L3–L4 intervein territory in wings of adult flies (Figure 5, compare wt and GAGA depleted, A and B, respectively). This phenotype was of high penetrance (~90%) at 25°C (100% at 29°C, data not shown) and frequently (≥50%) included a loss of the anterior cross-vein (acv). GAGA depletion with MS1096GAL4 resulted in a frequent appearance of deltas (denoted by asterisks in Figure 5) at the tip of veins L3, L4 and L5 and even some branching (Figure 5, black arrowhead) and a complete or partial loss of acv (with a lower incidence than above). To a lower extent, these abnormalities were also seen in MS1096GAL4 control flies as a result of the insertion of the GAL4 sequence itself as already described (Figure 5, compare black arrowhead in D with gray arrowhead in C) (24). In addition, ectopic veins were frequently observed (Figure 5D, arrow). In this case, no reduction of the L3–L4 intervein territory was observed (Figure 5A, C and D). When ApGAL4 directed depletion of GAGA factor adult wings displayed a curled phenotype, the distal parts of veins L2 to L5 frequently showed deltas (completely absent at L2 with MS1096) and also acv was often split although complete loss was rare. Neither L3–L4 intervein territory was reduced, nor ectopic veins were observed (Figure 5E and F). All depletion defects were enhanced at 29°C and were independent of the presence of Trl-GFP reporters (data not shown). Although the drivers used also direct expression in the halteres, our experiments never resulted in any haltere phenotype, in agreement with similar results obtained by other techniques (1,21). In principle, Ubx is described to be under GAGA control in halteres because of an observed low frequency of enhancement (0.27–6%, depending on experimental conditions) of the Ubx haplo-insufficient phenotype in Trl1055 (or Trl13C)/Ubx130 flies (1,21). However, regulation of Ubx by GAGA has not been demonstrated by other means.

DISCUSSION

Transcriptional regulation is the first point of control of gene expression and often plays a key role among other
Figure 4. Phenotypes associated to GAGA\textsubscript{519} over-expression. (A) GAGA\textsubscript{519} over-expression under MS1096 control. Left panel: adult displaying strong abnormalities in wings while the rest of the body looks normal. Right panel: wing from the adult in left panel at higher magnification. Scale bar is 100\,\mu m. (B) Wild type (left panels) and over-expressing GAGA\textsubscript{519} under ptcGAL4 control larvae (right panels) observed at 18°C. Magnification of the anterior region is shown below each, respectively (defects are indicated by a red circle). (C) GAGA\textsubscript{519} over-expression under dppGAL4 control. Left panels: legs from wt flies. Central panels: legs from flies over-expressing GAGA\textsubscript{519} under dppGAL4 control. Arrow points
Here we show that this mechanism is operative in vivo and generally used throughout development. Thus, Trl expression is actively balanced and kept between certain limits by a negative action of GAGA factor. Remarkably, a reduction in GAGA factor is much better tolerated than an increase in general terms, suggesting the existence of a critical upper threshold that must not be exceeded.

GAGA_{519} over-expression experiments revealed that negative autoregulation of Trl could be observed during embryogenesis and more clearly at larval stages. In all cases, reduction in GFP signal strictly co-localized with GAGA_{519} over-expression indicating a direct cause–effect. Although GAGA_{581} was not over-expressed in these experiments, we speculate that these results can be extended to this isoform, because the GAGA domain(s) involved in down-regulation of Trl expression are shared by the two isoforms (22). RNAi depletion experiments affected both isoforms and gave exactly the complementary result, i.e. an increased expression of Trl–GFP in the regions where GAGA protein factors were depleted. In combination with the results obtained with GAGAΔQ over-expression and the results obtained in S2 cells (22) they provide additional evidence in favor of a similar repressive activity of Trl promoter by GAGA_{581} isofrom. Taking into account that largely overlapping functions have been reported for the two isoforms in flies this is not surprising (25). In any case, GAGA_{581} over-expression experiments are in progress to confirm this point.

In the course of over-expression experiments, a high lethality was observed (even at 18°C) essentially with all GAL4 drivers tested. Some phenotypes have been described here and include morphological defects occurring at different developmental stages that frequently are local, despite the fact that GAGA_{519} over-expression takes place in a larger area. For example, even though GAGA_{519} was expressed in all along embryonic segments using ptcGAL4, morphological defects are only seen in T1–T3 thoracic segments. Similarly, GAGA_{519} over-expression directed by dppGAL4 resulted in important defects only in legs. While this phenotype affected the most distal parts of the legs, expression of distal-less (dll) gene was not affected at all (data not shown). At present these results could be explained in different ways and may involve cell growth, cell proliferation, cell migration and/or apoptosis. Over-expression of GAGA_{519} using MS1096GAL4 resulted in major and rather general wing disorders in the few flies that could still hatch at 18°C. MS1096 is a rather late driver, expressing GAL4 in the whole dorsal wing blade and part of the ventral wing blade. On the other hand, despite the fact that ApGAL4 is expressed much in the same area (except for the ventral wing blade) when it was used to drive over-expression of GAGA_{519}, lethality was absolute and earlier (larval) at 18°C. The differences observed between ApGAL4 and MS1096 may be due to the earlier expression of the first

To sex combs abnormally developing on a stump of the tarsal segments. Scale bar is 100 μm. Right panels: general view of GAGA_{519} over-expressing flies that hatched spontaneously (upper one) or dissected pupae (lower three) showing increasing degrees of severity (indicated – to +, respectively). Samples were obtained at 25°C.
in tissues other than wing [e.g. in central nervous system where Ap is known to be active (26)].

Some results suggest that the high lethality are related to the activation/repression activities of GAGA, because while over-expression of GAGA319 directed by prdGAL4 is 100% lethal, over-expression of GAGAΔQ (a mutant unable to transactivate) with the same driver is not. Interestingly, over-expression of this mutant with MS1096GAL4 is still highly lethal suggesting that in some contexts GAGA wt and GAGAΔQ behave similarly (Table 1). These results suggest that GAGA factor might be able to act both as an activator and as a repressor in vivo. In any case, interaction with DNA is absolutely required, as demonstrated by the lack of any effect from over-expression of GAGA519DBDKO (a GAGA mutant unable to interact with DNA).

While GAGA over-expression resulted in strong phenotypes, GAGA depletion using RNAi was difficult to study because only moderate reduction of GAGA protein levels were often achieved. This resulted in the lack of effects on Trl-GFP expression in imaginal disks when certain GAL4 drivers were used (e.g. dppGAL4, ApGAL4). On the other hand, GAGA depletion was efficient with the use of ptcGAL4 and with other drivers showing high GAL4 expression at later stages in wing development, like MS1096GAL4 (data not shown). A possible explanation takes into account a considerably long half-life for GAGA factor protein. In this respect, we have estimated a GAGA half-life of ~3 days from inducible expression experiments of stably transfected S2 cells (data not shown). In addition, because of the negative feedback mechanism described above, removal of GAGA factor protein would increase Trl-GAGA mRNA production, thus making it even more difficult to deplete GAGA factor protein. In any case, ptcGAL4 allowed us to observe GAGA depletion in imaginal disks, likely because it is highly expressed since embryonic stages. Phenotypes from the other GAL4 drivers could appear later in the adults because GAGA depletion continued beyond 3rd instar. Results obtained with ptcGAL4, MS1096GAL4 and ApGAL4 drivers show a variety of defects in venation that suggest that GAGA factor is involved in establishing the correct wing vein pattern, likely by regulating the expression of different genes. While MS1096 and ApGAL4 expression largely overlaps on the dorsal part of the wing disk, ectopic veins appeared with MS1096 but never with ApGAL4. This result may be explained by the different expression timing of these two drivers and/or because of the ventral wing expression of MS1096. In addition, the intensification of the phenotype that MS1096 produces on its own suggests that GAGA depletion is interacting with MS1096 and enhancing its effects. The curling of the wings observed with ApGAL4 together with the reduction of the L3–L4 intervein territory observed with ptcGAL4 driver may indicate a growth defect. In this sense, we have noted a moderate reduction in wing size (6.2–8.4% with ApGAL4 and MS1096) and a remarkable reduction of the L3–L4 intervein territory with ptcGAL4 (~25%) that correlates with a reduction in the cell number (data not shown). These results are consistent with some previous studies indicating that GAGA depletion in cultured cells affects cell growth and/or viability, that imaginal disks are consistently smaller in larvae trans-heterozygous for hypomorphic and null alleles (TrlR85TrlR85), and that severe GAGA loss of function results in many nuclear cleavage cycle defects in embryos (18,21,27).

Our results suggest that GAGA factor may be regulating the expression of genes other than homeotics, either by activation or repression, during larval to adult development. In fact, GAGA is likely controlling some essential function(s) in the larva, because general depletion of GAGA factor using actinGAL4 or armadilloGAL4 is absolutely lethal (data not shown). We suggest the phenotypes observed are likely due to effects on different genes rather than effects on a common gene or on an essential cellular function. In fact, a genome-wide analysis of GAGA factor target genes in Drosophila Kc cells has shown that the number of genes under GAGA factor regulation can be remarkably high (at least 250) and that GAGA factor can affect many cellular pathways (28).

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Conflict of interest statement. None declared.

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Drosophila GAGA factor and ISWI activates fushi tarazu gene


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