The role of the *Enhancer of split* complex during cell fate determination in *Drosophila*

Fred Tata and David A. Hartley
Department of Biochemistry, Imperial College of Science, Technology and Medicine, London SW7 2AZ, UK

**SUMMARY**

Molecular and genetic data predict that the *Enhancer of split* locus functions at the end of a pathway dictating appropriate cell fate determination in a number of developmental contexts. We have sought to dissect the role individual member genes of the complex play through a molecular analysis. Of the two principle class of genes, the first, members of the basic helix-loop-helix (bHLH) class of proteins are expressed in specific regions of the embryo in subtle, overlapping patterns in cells that will differentiate as epidermis. The second, *groucho*, a member of the WD40 class of proteins, is expressed more generally. Immunoprecipitation experiments do not implicate *groucho* in G protein mediated signal transduction, a known function of many WD40 type proteins. Instead, the nuclear localisation of the protein suggests a relationship to the bHLH members of the complex. Differences in expression of the bHLH genes between neurogenic mutants implies two pathways to their activation during epidermal determination.

Key words: *Drosophila*, cell fate determination,

---

**INTRODUCTION**

During development, cells rely upon extrinsic cues to adopt fates suitable to their surroundings. A group of genes in *Drosophila* appear to be called upon at many times and in many places to facilitate such decisions (Artavanis-Tsakonas and Simpson, 1991; Campos-Ortega and Knust, 1991; Hartley, 1990). They are called the neurogenic genes, since the primary defect in embryos lacking any of them is an inability to distinguish epidermal from neural precursor during neurogenesis (Lehmann et al., 1983; Poulsen, 1937). Mutants of any of the neurogenic genes die as embryos, lack large regions of the epidermis, and have a concomitant enlarged nervous system. In addition to their role in neurogenesis, these genes appear to function in an analogous fashion in many other developing organs (Cagan and Ready, 1989; Hartenstein and Posakony, 1990; Ruohola et al., 1991; Corbin et al., 1991; Xu et al., 1992; Hartenstein et al., 1992). They are not a curiosity to *Drosophila* - for example, at least some of the genes appear to have been conserved between vertebrates and invertebrates (Coffman et al., 1990; Ellisen et al., 1991; Weinmaster et al., 1991; Del Amo et al., 1992; Stifani et al., 1992). However, it is in *Drosophila* that their function is best understood. From the ongoing molecular and genetic analysis of their function, it seems that these two of the neurogenic genes, *Notch* and *Delta*, interact at the cell surface to provide necessary cues for cell fate determination, probably in the form of "lateral inhibition" of one cell type by another (Artavanis-Tsakonas and Simpson, 1991). Although it remains unproven, the data are consistent with a model whereby the *Delta* gene product acts as a ligand for a *Notch* gene product receptor (Heitzler and Simpson, 1991; Febron et al., 1990). From standard epistasis tests using duplications and deficiencies, the *Enhancer of split* complex behaves as if it were downstream of *Notch* and *Delta* (de la Concha et al., 1988). The role of the remaining neurogenic genes, *mastermind*, *big brain* and *neuralized* remains relatively obscure when compared to the others. However, it has been proposed, at least in the case of determination of the adult sensilla, that the pathway mediated by the neurogenic genes serves to repress the expression of neural determinants (provided by the *Achaete-scute* complex of genes) in all cells of a "proneural cluster" with the exception of the single sensory mother cell (Artavanis-Tsakonas and Simpson, 1991). This acts to restrict fate to a single cell from within a field of equivalent pluripotential cells, thus allowing the remaining cells to adopt a different fate (Simpson, 1990). The molecular analysis of members of this pathway should test the merit of this model.

The *Enhancer of split* (*E(spl)*) locus consists of a number of genes some or all of which may have a function in cell fate determination. On the basis of mutant phenotype, two classes of genes are definitely implicated (Delidakis et al., 1991; Schrons et al., 1992). The first, and only gene that mutates to give a neurogenic phenotype, is allelic to a previously described gene *groucho* (Preiss et al., 1988). The *groucho* gene has been cloned and sequenced and the gene product has homology to a class of proteins defined by the presence of an approximately 40 amino acid repeat with characteristicly located tryptophan and asparagine residues - the so called WD40 repeat (Hartley et al., 1988). Closely related genes in humans and mice have been identified
The related amino acid sequences of *groucho* in flies, humans, rats and mice. A multiple alignment using ClustalV was made of the ten related sequences found in the GenBank non-redundant database. Amino acids are coloured using the SeqApp program where blue codes for basic residues, red for acidic, cyan for hydroxyl, green for amide, yellow for sulphur containing, black for hydrophobic residues, orange for aromatic, purple for proline and grey for glycine. Note as well as the full-length orthologues in humans (TLE 1,2 and 3) mice (Mouse ESG) and rats (Rat esp2), there are proteins highly related to just the N-terminal domain of groucho (Mouse AES 1 and 2; Human AES1) whilst the other sequences are homologous over the entire length of groucho. The source references are for Human TLEs (Stifani et al., 1992), Rat esp2 (Schmidt, C.J. and Sladek, T.E. (1993), unpublished), Mouse grg (Mallo, M., Franco del Amo, F. and Gridley, T. (1993), unpublished), Human and mouse AES sequences (Miyasaka, H., Choudhury, B.K., Hou, E.W. and Li, S.S.I. (1993), unpublished).
(Stifani et al., 1992). Amongst the members of this class of proteins are the β subunits of guanine nucleotide regulatory proteins (G proteins). A prominent function for G proteins is in the transduction of cell surface receptor mediated signals (Bourne et al., 1991). It was therefore an attractive possibility to postulate the role of the groucho gene in signal transduction, particularly since point mutations of groucho interact genetically with specific point mutations of Notch, potentially the receptor in a lateral inhibition pathway (Xu et al., 1990). The second class of Enhancer of split genes number seven homologous members (Knust et al., 1992; Delidakis et al., 1992). This family is related to basic helix-loop-helix proteins which are known in many instances to be DNA sequence specific transcription factors (e.g. Pabo and Sauer, 1992). The relationship between groucho and the bHLH members of the E(spl) complex is implied from genetic interaction. Transformed groucho genes are able to improve the phenotype of deficiencies of the complex as long as at least one bHLH gene is present in the genome (Delidakis et al., 1991; Schrons et al., 1992). Thus, genetically, groucho acts as an activator of E(spl) bHLH function. We have been investigating the function of the genes of E(spl) in Drosophila development with a view to revealing the molecular mechanism of their action. Our data do not conform to a role for groucho in G protein mediated signal transduction. Instead, the localisation of the gene product points to a requirement in the nucleus. Thus, the interaction between groucho and E(spl) bHLH members suggested genetically, may be direct.

The expression of Enhancer of split bHLH genes is temporally and spatially complex (Godt et al., 1991; Knust et al., 1992). From various work, a part of this expression appears to be immediately succeeding or coincident with the separation of neural from epidermal precursor cells, specifically in the epidermal precursors. This expression is superficially normal in Notch mutants, but abnormal in neutralized mutants. This hints at two requirements for normal Enhancer of split function in dictating cell fates during embryogenesis.

MATERIALS AND METHODS

Antibody staining
Affinity purified-antibodies raised to pATH or pGEX fusions of groucho or Notch cDNA have been previously described (Fehon et al., 1990; Delidakis et al., 1991). Third instar larval discs and brains were fixed in 4% formaldehyde in PBS and stained with antibody overnight at 4°C in PBS/0.2% saponin/5% normal goat serum. Anti-IgG secondaries labelled with fluorescein were used to visualise staining. Preparations were imaged using the MRC 500 laser scanning confocal microscope.

Immunoprecipitation
Embryonic protein extracts were prepared from dechorionated embryos by homogenising in 300 mM NaCl, 50 mM Tris-HCl, 0.5% NP-40, 0.5% deoxycholate in the presence of proteinase inhibitors and immunoprecipitations performed as described in Fehon et al. (1990).

G protein experiments
Embryonic or Drosophila Kc cell protein extracts were prepared in 20 mM Tris-HCl, pH 8.0, 100 mM NaCl, and either 1 mM EDTA, 0.1 mM GDP or 10 mM MgCl2, 0.3 mM GTP or 10 mM MgCl2, 0.3 mM GTP·S. Extracts were incubated for 40 minutes at 30°C with 2 μg activated pertussis toxin in the presence of phosphatidyl choline and [32P]NAD. The reactions were chased for 10 minutes with 14 mM NAD and immunoprecipitated as above with anti-groucho antibodies. In a parallel set of experiments, the same types of protein extract were incubated with 32P-labelled 8-azido-GTP and irradiated with UV for 30 seconds. Then the different extracts were immunoprecipitated with anti-groucho antibodies.

In situ hybridization
In situ hybridization to whole embryos was performed essentially as described in Tautz and Pfeifle (1989). Anti-sense RNA probes were labelled with digoxigenin as described by the manufacturer (Boehringer Mannheim). After staining, embryos were dehydrated through an ethanol series and mounted in methacrylate.

RESULTS

The members of the Enhancer of split complex
Genetic and molecular genetic criteria have been used to define members of the Enhancer of split complex (Delidakis et al., 1991; Schrons et al., 1992; Knust et al., 1992). In terms of sequence homology, two types of gene product have been implicated with respect to cell fate determination. Seven members of the complex (called m3, m5, m7, m8, mα, mβ and mγ) are related to the basic helix loop helix class of trans regulators (Delidakis and Artavanis-Tsakonas, 1992; Knust et al., 1992). Another member, variously called m9/10 or groucho, is a member of the WD40 class of proteins, whose largest individual members are the β subunits of signal transducing guanine nucleotide binding proteins. However, since the sequence of groucho was determined, a number of extremely homologous vertebrate sequences have been identified (Stifani et al., 1992; Schmidt and Sladek, unpublished; Mallo et al., unpublished; Miyasaka et al., unpublished). Fig. 1 shows the current members of this orthologous gene family, a subset of the WD40 domain proteins, found in flies, mice, rats and humans. The sequences are conserved essentially throughout the length of the proteins, but virtually identical in two areas, firstly within the N-terminal region and secondly the C-terminal halves of the proteins, which consist of the WD40 domain. The striking degree of homology within this family of related sequences implies functional conservation, although of these members, only groucho has a known function. The N-terminal sequence domain has no significant homology to any other protein sequences in the databases but the WD40 domain has a number of relatives. Fig. 2 shows some of these relatives with the salient residues of the primary sequence based on the BLOCKS v6.0/Prosite v10.0 database definition of consensus sequence for the WD40 repeat. These classes of proteins exhibit diverse functions and intracellular locations (see van der Voom and Ploegh, 1992; Duronio et al., 1992 for reviews) ranging from the membrane related signal transduction of G proteins to the nuclear transcriptional apparatus of TUP1 (Kleheher et al., 1992) and the Drosophila TFIIID subunit TAFq80 (Dyilacht et al., 1993). In addition, since groucho has obvious vertebrate orthologues (see Fig. 1) the functional significance of the relatedness of WD40 domain proteins is not clear. It is supposed that this motif is involved in protein-
A role for groucho in signal transduction

Two lines of data suggested a role for groucho in signal transduction of cell fate determination. First, the sequence homology of the gene product to the β subunit of G proteins (Hartley et al., 1988) and second, the specific interaction between groucho and Notch point mutations (Xu et al., 1990). Notch is known to act at the cell surface (Fehon et al., 1991) and in an autonomous fashion (Hoppe and Greenspan, 1990; Heitzler and Simpson, 1991), as would be expected for a receptor. This specific interaction between point mutations of the groucho gene and Notch point mutations insinuated that the two gene products might physically combine. Previous immunohistochemical approaches had shown this to be the case for Notch and Delta, since antibodies specific to one can co-precipitate the other, and specific cellular aggregates form when the two are over-expressed in mixed cell cultures (Fehon et al., 1990). We have attempted to co-precipitate Notch and groucho protein from Drosophila embryos or Kc tissue culture cells using antibodies to Notch or to groucho. Under the conditions used, we were unable to detect each protein in its complementary immunoprecipitate (Fig. 3). This result does not exclude the potential interaction of Notch and groucho, but suggests that if such interaction exists, it is non-stoichiometric.

Mammalian G proteins have been previously assayed by their ability to bind guanosine nucleotide phosphate (Offermans et al., 1991), and by their sensitivity to ADP-ribosylation by cholera toxin and pertussis toxin (Gierschik, 1992). Both of these are features of the α subunit of G proteins, but using conditions which favour the heterotrimetric αβγ form (low Mg2+ and GDP), it is possible to immunoprecipitate all three subunits with an antibody to one. We have reacted total Drosophila cell extracts with pertussis toxin and [32P]NAD and tested the ability of mon-
oclonal anti-groucho antibodies to precipitate $^{32}$P]-ADP-ribose-protein under conditions which should favour the association (low Mg$^{2+}$, GDP) or dissociation (high Mg$^{2+}$, GTP or GTPyS) of G proteins. We found no specific labelling of proteins in the immunoprecipitate above background (data not shown), suggesting that the anti-groucho antibodies fail to co-immunoprecipitate pertussis toxin-sensitive α subunits. In a similar assay, we reacted total protein extracts with 8-azido-$^{32}$P]-GTP which binds covalently to protein on photoactivation, and immunoprecipitated the labelled extract. Once again, no specifically labelled protein was coprecipitated by anti-groucho antibodies (data not shown).

**groucho expression in the nucleus**

The immunoprecipitation experiments designed to investigate a relationship between groucho and G proteins did not provide any evidence for such a link. In addition, previous immunohistochemical work argued that groucho protein was almost exclusively in the nucleus, contrary to what would be expected for G protein-mediated signal transduction (Delidakis et al., 1991). Given the ubiquitous staining patterns within the embryo, we have looked at other developmental stages of the fly to ascertain whether it plays a purely embryonic role. In the imaginal discs of the third instar larvae (eye/antenna, wing, leg, haltere), all the nuclei appear to stain (for example, see Fig. 4). In addition, most, if not all, cells of the larval CNS express this antigen. We have also stained ovaries and the protein is found in the somatic and germ cell components - in the follicle cell nuclei and the polypliod giant nurse cell nuclei (Fig. 4). The nurse cell nuclear staining reveals a curious subnuclear organisation which does not seem to correspond to chromatin (as adjudged by counter-staining with DAPI). In addition, the oocyte nucleus stains quite strongly (Fig. 4).

One possibility remained that the nuclear localisation of groucho might represent an active uptake in response to Notch-mediated cell surface signals. A corollary of this hypothesis might be that in neurogenic mutants where the cellular interaction mechanism is presumably blocked, the protein would no longer be sent to the nucleus. We have used our antibodies to stain mutants for the zygotic neurogenic genes Notch, big brain, mastermind, neuralized, and Delta. In none of these cases do we see absence of groucho protein, or abnormal distribution within the embryo, or within the cell (assayed by indirect immunofluorescence, see Figs. 3, 4). Immunoprecipitations of Notch and groucho protein from embryonic extracts. Immunoprecipitates or complete protein extracts were subjected to SDS-PAGE and transferred to nitrocellulose. Blots were stained with monoclonal antibodies against Notch (lanes A-D) or rabbit polyclonal anti-groucho (lanes E-H). Lanes A,E: total protein extract from 0-14 hour embryos. Lanes B,F: immunoprecipitate using monoclonal anti-Notch. Lanes C,G: immunoprecipitate using monoclonal anti-groucho. Lanes D,H: immunoprecipitate using a second independently isolated monoclonal anti-groucho. These data demonstrate that Notch protein cannot be detected in anti-groucho immunoprecipitates (lane C,D) and similarly that groucho protein cannot be detected in anti-Notch immunoprecipitates.

**Fig. 3.** Immunoprecipitations of Notch and groucho protein from embryonic extracts. Immunoprecipitates or complete protein extracts were subjected to SDS-PAGE and transferred to nitrocellulose. Blots were stained with monoclonal antibodies against Notch (lanes A-D) or rabbit polyclonal anti-groucho (lanes E-H). Lanes A,E: total protein extract from 0-14 hour embryos. Lanes B,F: immunoprecipitate using monoclonal anti-Notch. Lanes C,G: immunoprecipitate using monoclonal anti-groucho. Lanes D,H: immunoprecipitate using a second independently isolated monoclonal anti-groucho. These data demonstrate that Notch protein cannot be detected in anti-groucho immunoprecipitates (lane C,D) and similarly that groucho protein cannot be detected in anti-Notch immunoprecipitates.

**groucho expression in post-embryonic tissues.** Monoclonal anti-groucho was used to stain wing imaginal discs (A), the third instar larval CNS (B) and ovaries (C) and detected by laser scanning confocal microscopy. (A) Ubiquitous nuclear staining of the wing imaginal disc - absence of staining in the folds of the discs is due to the fact that some nuclei are out of the plane of optical section. (B) Staining of the larval CNS is also widespread. A larger staining cell, presumably a neuroblast, is shown by an arrowhead. (C) groucho expression in the ovary. The antibody stains both the follicle cells (fc) and the nurse cells (nc). The nuclear sub-cellular localisation is most apparent in the large, multi-nucleolate nurse cells and even in the smaller follicle cells an absence of staining in the nucleolus is evident. The oocyte nucleus (ooc) is also strongly stained in this stage 10 oocyte.

**Fig. 4.** groucho expression in post-embryonic tissues. Monoclonal anti-groucho was used to stain wing imaginal discs (A), the third instar larval CNS (B) and ovaries (C) and detected by laser scanning confocal microscopy. (A) Ubiquitous nuclear staining of the wing imaginal disc - absence of staining in the folds of the discs is due to the fact that some nuclei are out of the plane of optical section. (B) Staining of the larval CNS is also widespread. A larger staining cell, presumably a neuroblast, is shown by an arrowhead. (C) groucho expression in the ovary. The antibody stains both the follicle cells (fc) and the nurse cells (nc). The nuclear sub-cellular localisation is most apparent in the large, multi-nucleolate nurse cells and even in the smaller follicle cells an absence of staining in the nucleolus is evident. The oocyte nucleus (ooc) is also strongly stained in this stage 10 oocyte.

**Fig. 5.** We have not, however, performed the control of eliminating the maternal contribution provided by many of these genes. Since zygotic mutants result in abnormal cell fate determination, we expected the zygotic condition to be sufficient to see abnormal groucho localisation if this were relevant. Thus, nuclear localisation of groucho does not appear to require neurogenic function. An alternative
oclonal anti-groucho antibodies to precipitate [32P]ADP-ribose under conditions which should favour the association (low Mg2⁺, GDP) or dissociation (high Mg2⁺, GTP or GTPγS) of G proteins. We found no specific labelling of proteins in the immunoprecipitate above background (data not shown), suggesting that the anti-groucho antibodies fail to co-immunoprecipitate pertussis toxin-sensitive G subunits. In a similar assay, we reacted total protein extracts with 8-azido-[32P]GTP which binds covalently to protein on photoactivation, and immunoprecipitated the labelled extract. Once again, no specifically labelled protein was coprecipitated by anti-groucho antibodies (data not shown).

**groucho expression in the nucleus**

The immunoprecipitation experiments designed to investigate a relationship between groucho and G proteins did not provide any evidence for such a link. In addition, previous immunohistochemical work argued that groucho protein was almost exclusively in the nucleus, counter to what would be expected for G protein mediated signal transduction (Delidakis et al., 1991). Given the ubiquitous staining patterns within the embryo, we have looked at other developmental stages of the fly to ascertain whether it plays a purely embryonic role. In the imaginal discs of the third instar larvae (eye/antenna, wing, leg, haltere), all the nuclei appear to stain (for example, see Fig. 4). In addition, most, if not all, cells of the larval CNS express this antigen. We have also stained ovaries and the protein is found in the somatic and germ cell components - in the follicle cell nuclei and the polyplid giant nurse cell nuclei (Fig. 4). The nurse cell nuclear staining reveals a curious subnuclear organisation which does not seem to correspond to chromatin (as adjudged by counter-staining with DAPI). In addition, the oocyte nucleus stains quite strongly (Fig. 4).

One possibility remained that the nuclear localisation of groucho might represent an active uptake in response to Notch mediated cell surface signals. A corollary of this hypothesis might be that in neurogenic mutants where the cellular interaction mechanism is presumably blocked, the protein would no longer be sent to the nucleus. We have used our antibodies to stain mutants for the zygotic neurogenic genes Notch, big brain, mastermind, neurelated, and Delta. In none of these cases do we see absence of groucho protein, or abnormal distribution within the embryo, or within the cell (assayed by indirect immunofluorescence, see Fig. 5).

**Fig. 3.** Immunoprecipitations of Notch and groucho protein from embryonic extracts. Immunoprecipitates or complete protein extracts were subjected to SDS-PAGE and transferred to nitrocellulose. Blots were stained with monoclonal antibodies against Notch (lanes A-D) or rabbit polyclonal antimurine groucho (lanes E-H). Lanes A,E: total protein extract from 0-14 hour embryos. Lanes B,F: immunoprecipitate using monoclonal anti-Notch. Lanes C,G: immunoprecipitate using monoclonal anti-groucho. Lanes D,H: immunoprecipitate using monoclonal anti-Notch.

**Fig. 4.** groucho expression in post-embryonic tissues. Monoclonal anti-groucho was used to stain wing imaginal discs (A), the third instar larval CNS (B) and ovaries (C) and detected by laser scanning confocal microscopy. (A) Ubiquitous nuclear staining of the wing imaginal disc - absence of staining in the folds of the disc is due to the fact that some nuclei are out of the plane of optical section. (B) Staining of the larval CNS is also widespread. A larger staining cell, presumably a neuroblast, is shown by an arrowhead. (C) groucho expression in the ovary. The antibody stains both the follicle cells (fc) and the nurse cells (nc). The nuclear sub-cellular localisation is most apparent in the large, multi-nucleolate nurse cells and even in the smaller follicle cells an absence of staining in the nucleolus is evident. The oocyte nuclei (ooc) is also strongly stained in this stage 10 oocyte.

**Fig. 5.** We have not, however, performed the control of eliminating the maternal contribution provided by many of these genes. Since zygotic mutants result in abnormal cell fate determination, we expected the zygotic condition to be sufficient to see abnormal groucho localisation if this were relevant. Thus, nuclear localisation of groucho does not appear to require neurogenic function. An alternative
hypothesis suggests that removal of the nuclear targets for the cell surface machinery would be necessary to see abnormal localisation of groucho protein. We and others have suggested that such targets could be represented by two sets of helix-loop-helix (bHLH) proteins; one set encoded by the Achaete-scute complex (AS-C) representing neural determinators and the other, the E(spl) bHLH genes, representing epidermal determinants (Hartley, 1990; Campos-Ortega and Knust, 1991). However, staining embryos deficient for either cluster of bHLH genes shows an apparently normal intracellular localisation of groucho protein (not shown). Thus, groucho nuclear localisation does not require AS-C gene function.

Enhancer of split bHLH gene expression

The examination of Enhancer of split bHLH gene expression has been illuminating as regards its function in cell fate determination at neurogenesis (Godt et al, 1991, Knust et al., 1992). Each of the seven genes has a similar, but not identical pattern of expression. We have examined Enhancer of split m5, m7 and m8 expression by whole mount in situ hybridisation (see for example, Fig. 6). In agreement with previous studies, we find an initial row of expression in cells of the cellular blastoderm that have been called mesectoderm since they abut both mesoderm and ectoderm. These cells also seem to express another bHLH gene product from the single minded gene, which appears to regulate cell fate of mesectodermal cells (Nambu et al., 1991). Since bHLH proteins can form heterodimers, it is possible that this coincidence is informative. In addition to mesectodermal expression, there is a dorsal wedge of expression in cells that may be the precursors of the amnioserosa. After gastrulation, the three genes are expressed in clusters of cells in the neurogenic ectoderm initially in medial and lateral rows and later in more intermediate cells. This expression pattern is extremely dynamic and superficially resembles topographical maps corresponding to neuroblast segregation from this region (Hartenstein and Campos-Ortega, 1984; Doe, 1992). Of the three genes, m5 is expressed in the largest number of cells and m8 in the smallest number. The m8 expression pattern appears not to be a subset of the m5 pattern however, since hybridising with probes to both genes labels more cells than one sees with a probe to m5 alone. Since the expression pattern is very dynamic, we cannot be sure whether the genes are expressed in ectoderm immediately before, during or immediately after neuroblast segregation. However, we have never seen labelling in the neuroblast cell layer, implying that the expression is specific to the epidermal precursors, which make up the bulk of the neurogenic ectoderm (Hartenstein and Campos-Ortega, 1984). In addition to expression in the ectoderm, we also see expression in the mesoderm cell layer, in a discrete number of single cells analogous to that reported for other Drosophila bHLH genes, like the myoD homologue, nautilus (Michelson et al., 1990). This expression pattern is consistent with the requirement for neurogenic gene function during myogenesis (Corbin et al., 1991).

Enhancer of split bHLH expression in neurogenic mutants

Since the expression of Enhancer of split bHLH genes in the neurogenic ectoderm appears restricted to the epidermal precursors, we expected abnormal expression in neurogenic mutants which do not differentiate epidermis from this region. We examined m5 expression in embryos laid by Notch heterozygous mothers. Since we were unable to unambiguously identify homo- or hemizygous mutant embryos in our stainings, we looked over a number of embryos for obvious defects but found none. We therefore conclude that m5 expression is superficially normal in Notch mutants. In contrast, some embryos (approximately 1/4 as would be expected if they were the homozygous mutants) derived from heterozygous neutralized parents did show defects in m5 expression. In these embryos, whilst the early mesectodermal expression appeared superficially normal, the neurogenic ectoderm and later mesoderm expression was undetectable (see Fig. 7). From this, we deduce that neutralized is required for normal Enhancer of split m5 expression. In a more detailed analysis, Godt et al. (1991) have shown that Enhancer of split m4, m5, m7 and m8 expression starts off normal in Notch mutant embryos, but is less normal in neutralized mutants.

DISCUSSION

The Enhancer of split complex is pivotal in directing cells to adopt a fate suitable to their environment. From DNA sequence homology to the β subunits of G proteins, it seemed attractive to speculate that one member of the gene complex, groucho, might play a role in signal transduction of signals mediated by the transmembrane Notch protein (Hartley et al., 1988). We have been unable to demonstrate such a role using immunoprecipitation to look for G protein activity either as a substrate for pertussis toxin catalysed ADP ribosylation or in GTP binding using a photactivatable analogue. Furthermore, we were unable to co-immunoprecipitate groucho and Notch, indicating that these proteins are not stably associated with each other, as might be expected if groucho were involved in directly mediating Notch action in the cytoplasm. It is important to note that these data do not eliminate the possibility of groucho
directly transducing information from the cell surface. Nevertheless, taken with the observation that the protein is almost exclusively nuclear when judged by immunohistochemistry and laser scanning confocal microscopy, such a model seems unlikely. Similarly, selective nuclear import (such as the dorsal nuclear uptake gradient which determines dorsal/ventral polarity; St. Johnston and Nüsslein-Volhard, 1992) does not seem to be a likely possibility for groucho mediated signal transduction, since none of the neurogenic mutants affect its nuclear localisation. On the other hand, some sort of intimacy between Notch and groucho seems likely, given the nature of genetic interactions between them (Xu et al., 1990). Nuclear function is not a precedent for proteins that share the WD40 motif. In yeast, a number of WD40 proteins have been described whose function is in the nucleus - CDC4, PRP4 and TUP1 which appear to be involved in the nucleoskeleton (Choi et al., 1990), premRNA splicing (Rosenberg et al., 1991) and transcriptional repression (Keleher et al., 1992), respectively. TUP1 is particularly interesting as a model for groucho function. It appears to act as a general transcriptional repressor, required by a variety of DNA sequence specific trans-regulators, to repress expression from promoters adjacent to their binding site (Keleher et al., 1992). One can imagine that groucho might similarly co-ordinate the transregulatory functions of Enhancer of split bHLH proteins, given the nature of genetic interaction between them, perhaps to inhibit neural potential indirectly, or Achaete-scute directly. Consistent with this

Fig. 6. Expression of Enhancer of split m5 in the embryo. (A) An embryo just after gastrulation at stage 6-7 viewed from below. This whole-mount in situ hybridization shows E(spl)m5 expression in two rows of cells abutting the ventral midline, the so-called mesectoderm, which gives rise to midline structures in both the CNS and the epidermis. In addition, out of the plane of focus, there is a wedge of expression on the dorsal surface of the embryo. (B) A later, stage 9 embryo where neurogenesis is commencing, viewed from the ventral surface. E(spl)m5 expression is throughout the germ band, predominantly in three rows. This pattern corresponds to the sites from which neuroblasts are segregating into the embryonic interior. As such it is very dynamic and later, interstitial cells start to hybridize, at the time when neuroblasts are born from this different part of the germ band ectoderm. (C) A similarly staged embryo viewed from the dorsal surface showing the three rowed pattern in the abdominal segments of the germ band and, in addition, expression in the procephalic neurogenic region (arrowed) which gives rise to the brain. (D) An older, stage 11 embryo still showing residual m5 expression in the epidermal precursors on the ventral side, and much expression in the procephalic region. Note the complete absence of labelling of the neuroepithelium in the germ band which is organised immediately below the outer cell layer. In addition, conspicuous staining is seen in the mesoderm (arrowed) in discrete cells repeated in each segment.

Fig. 7. Enhancer of split m5 expression is absent in the germ band of neutralized embryos. (A) A wild-type embryo at stage 9 hybridised to E(spl)m5. The arrow indicates the expression throughout the germ band, specifically in the outer cell layer which gives rise to the epidermis. (B) An embryo derived from a cross between neutralized- heterozygotes at a slightly earlier part of stage 9. No staining is observed, suggesting that neutralized is required for E(spl)m5 expression.
model is the observed derepression of *Achaete-scute* expression in *Enhancer of split* deficient embryos (Cabrera, 1990, Skeath and Carroll, 1992) and the observation that *E(sp)l*m8 is capable of binding oligonucleotides corresponding to the "E box" found upstream of *Achaete-scute* and other bHLH genes (cited in Tietze et al., 1992).

The function of the *Enhancer of split* bHLH genes in cell fate determination is strongly suggested by their complex expression patterns. Initially expressed in ventral domains and dorsal domains probably corresponding to mesectoderm and amnioserosa respectively, they are later activated in clusters of cells in the neurogenic ectoderm, apparently specifically in the epidermal precursors. This expression is virtually coincident with or immediately succeeds neuroblast segregation. Thus it is exactly what one would expect if these genes are expressed in response to induction by the nascent neuroblasts, as the means of inhibiting the neural potential of these cells (lateral inhibition) and/or promoting their epidermal potential. However, in some of the neurogenic mutants, this expression is at least initially normal, despite the fact that no epidermal precursors arise in such mutants. Thus, the initial presence of *E(sp)l*bHLH transcript *per se* is insufficient to allow epidermal determination. Yet these genes appear to act at the end of a pathway leading to epidermal determination (de la Concha et al., 1988). Therefore, it seems likely that the function of *Notch*, *Delta* and *mastermind* is to post-transcriptionally activate these bHLH genes, either through translation, or post-translational modification. In contrast, *E(sp)l*bHLH expression in the neurogenic ectoderm of *neutralized* mutants appears to be undetectable. Hence, the function of *neutralized* appears to be to activate directly the expression of these genes, and the neurogenic phenotype of *neutralized* mutants would result from an inability to activate them. This model is consistent with the observation that the *neutralized* gene product has homology to known transcription factors (Price et al., 1993), and the known genetic interactions between *neutralized* and *E(sp)l*D, and allele of the m8 bHLH gene (Knust et al., 1987). Since *neutralized* is expressed in a wider territory than any individual *E(sp)l*bHLH gene (Boullanne et al., 1991; Price et al., 1993), it would have to activate transcription of these genes in co-operation with other, as yet unknown, factors. Given this scenario there are two levels to neurogenic gene function - firstly, activation of transcription of *Enhancer of split* bHLH genes in the cells that must respond to them (in this case the epidermal precursors) and a second post-transcriptional activation step necessary for their ability to function in dictating epidermal fate. This second step requires *Notch*, *Delta* and *mastermind* and presumably the ability of the cells to interact. One mystery following from this idea is why cells need to bother with cellular interactions mediated by *Notch* and *Delta* if they already express epidermal determinants (in the form of *E(sp)l*bHLH proteins) without requiring either *Notch* or *Delta*. Presumably this reflects an error checking necessity of cells to test they are doing the right thing in determining their own and/or surrounding cells' fate by "reading their environment" prior to activating gene expression programs appropriate to their position.

We thank Spyros Artavanis-Tsakonas for confocal microscopy and biochemical enthusiasm. We also thank Alan Cheshire for fly maintenance. This work was supported by the Medical Research Council.

REFERENCES


Duronio, R.J., Gordon, J.J. and Boguski, M.S. (1992). Comparative analysis of the beta Transducin family with identification of several new members including *PWP1*, a nonessential gene of *Saccharomyces cerevisiae* that is divergently transcribed from *NMT1*. *Proteins* 13, 41-56.


