Predetermined embryonic glial cells form the distinct glial sheaths of the *Drosophila* peripheral nervous system

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**SUMMARY**

One of the numerous functions of glial cells in *Drosophila* is the ensheathment of neurons to isolate them from the potassium-rich haemolymph, thereby establishing the blood-brain barrier. Peripheral nerves of flies are surrounded by three distinct glial cell types. Although all embryonic peripheral glia (ePG) have been identified on a single-cell level, their contribution to the three glial sheaths is not known. We used the Flybow system to label and identify each individual ePG in the living embryo and followed them into third instar larva. We demonstrate that all ePG persist until the end of larval development and some even to adulthood. We uncover the origin of all three glial sheaths and describe the larval differentiation of each peripheral glial cell in detail. Interestingly, just one ePG (ePG2) exhibits mitotic activity during larval stages, giving rise to up to 30 glial cells along a single peripheral nerve tract forming the outermost perineurial layer. The unique mitotic ability of ePG2 and the layer affiliation of additional cells were confirmed by *in vivo* ablation experiments and layer-specific block of cell cycle progression. The number of cells generated by this glial progenitor and hence the control of perineurial hyperplasia correlate with the length of the abdominal nerves. By contrast, the wrapping and subperineurial glia layers show enormous hypertrophy in response to larval growth. This characterisation of the embryonic origin and development of each glial sheath will facilitate functional studies, as they can now be addressed distinctively and genetically manipulated in the embryo.

**KEY WORDS:** Flybow, Cell tracing, Glial sheaths, Peripheral nervous system, Hyperplasia, Hypertrophy, Cell-specific mitotic abilities, *Drosophila*

**INTRODUCTION**

During the development of higher metazoan animals, the maintenance and functionality of the nervous system depend on a precise interplay between neurons and glial cells. Whereas neurons are known to perceive, transmit and integrate information encoded as electrical impulses, glial cells have been shown to accomplish multiple tasks in both vertebrates (reviewed by Barres, 2008) and invertebrates (reviewed by Parker and Auld, 2006; Stork et al., 2012). One pivotal role of glial cells in *Drosophila* is the correct insulation of neurons. In the peripheral nervous system (PNS) this is achieved by three distinct glial layers surrounding the peripheral nerves (Banerjee et al., 2006; Stork et al., 2008) (reviewed by Rodrigues et al., 2011). The innermost layer is formed by wrapping glia, which progressively separate the axons of the 30 motoneurons and 42 sensory neurons of each abdominal hemisegment (hs), projecting together along the main peripheral nerve tracts. At the early larval stage, groups of axons are enwrapped by these glial cells, similar to the Remak bundles formed by Schwann cells in the vertebrate PNS, and, later in development, the peripheral axons of *Drosophila* become individually separated and isolated. The second layer is built by subperineurial glia surrounding the entire nerve bundle. They represent the key component of the blood-brain barrier in *Drosophila* and are tightly connected to each other via pleated septate junctions (Bainton et al., 2005; Schwabe et al., 2005; Stork et al., 2008). The outermost glial sheath is established by perineurial glia (Stork et al., 2008), for which a mesodermal origin has been proposed (Edwards et al., 1993). At present, the precise function of this glial sheath is unclear, beside being a barrier for macromolecules (Stork et al., 2008).

Formation of the glial sheaths starts during embryogenesis. Most of the embryonic peripheral glia (ePG) arise from neural stem cells (neuroblasts) of the central nervous system (CNS) (Schmidt et al., 1997). After birth, ePG migrate out of the CNS to their final positions along the peripheral nerves in order to subsequently ensheath the axons along all parts of the PNS. Recently, we showed that a fixed number of 12 ePG are born in abdominal hs A2-A7 (von Hilchen et al., 2008). Each ePG can individually be identified by its origin, the expression of a specific set of markers, and its stereotype migration pattern that results in a characteristic positioning at the end of embryogenesis. However, a clear assignment between embryonic and larval peripheral glia has not been accomplished to date.

Here we have used the Flybow system (Hadjieconomou et al., 2011) to label each ePG individually, and followed their development until third instar. We reveal the embryonic origin of all three glial layers and describe the larval differentiation of each peripheral glial cell. Wrapping and subperineurial glia maintain a constant number from embryo to late L3 larvae and undergo enormous hypertrophy that correlates to the length of the peripheral nerves. By contrast, the perineurial sheath originates from a single ePG (ePG2) that remains mitotically active throughout larval development. It represents a transient precursor that produces cells in accordance with the length of the peripheral nerve. This unique ability was further confirmed by *in vivo* ablation experiments and...
cell-specific block of mitosis. In addition, we provide examples to show that at least some ePG survive metamorphosis and persist until adulthood.

MATERIALS AND METHODS
Fly stocks and genetics
The following fly strains were used: wild-type OregonR, urv2-Gal4 (Sun et al., 1999), repo-Gal4 (Sepp et al., 2001), GlI-Gal4 (Sepp and Auld, 1999), moody-Gal4 (Schwabe et al., 2005), 46F-Gal4 (Xie and Auld, 2011), Mz97-Gal4 (Ito et al., 1995), UAS-gapr::GFP (Bloomington Drosophila Stock Center (BDSC)), UAS-stinger-GFP (nGFP) (Barolo et al., 2000), UAS-Cycl4-RNAi (Vienna Drosophila RNAi Center, 32421GD) and UAS-Rbf (Dut et al., 1996).

For in vivo ablation of ePG2, the Mz97-Gal4 insertion was combined with UAS-ngfp and repo-Gal4. For single-cell tracing via the Flybow system, repo-Gal4 (either recombined with nGFP on the third chromosome or alone) was combined with heat shock mP5 and crossed to homozygous UAS-FB1.1 flies (Hadjeconomou et al., 2011). Whenever required, GFP-tagged balancer chromosomes (BDSC) were used for identification of genotypes.

Generation of anti-Repo antibodies
repo full-length cDNA was cloned into pQE31 (Qiagen) in frame with 6×His at the N-terminus and expressed in E. coli strain SG13009 (Qiagen). Purification of recombinant protein was performed using the NiNTA kit (Qiagen). Protein was injected into guinea pigs by Pineda Antibody Service (Berlin, Germany), followed by two booster injections after 30 days. Animals were sacrificed, serum collected and the IgG fraction isolated. Specificity of the antibody was controlled in vivo by immunohistochemistry of wild-type and glial cells missing mutant embryos as well as in vitro on western blots (data not shown).

Immunohistochemistry
Embryos were fixed as described (Rogulja-Ortmann et al., 2007). Second and third instar larvae (L2/L3) were opened along the dorsal midline and flattened to a silicon ground using minuten fine pins. Larvae were fixed for 45 minutes in 4% formaldehyde in PBS and incubated for at least 1 hour in PBS containing 0.5% Triton X-100 and 10% milk powder. Stained larvae were scanned with a Leica TCS SP5 confocal microscope. For complex staining patterns of L3 larvae, an overhead transparency was fixed to the computer monitor to draw labelled cells stepwise throughout the stack. Primary antibodies were mouse anti-Fas2 (1D4; 1:10) and mouse anti-22C10 (1:10), both from the Developmental Studies Hybridoma Bank (Iowa City, USA), mouse anti-GFP (Promega; 1:500), rabbit anti-NrxIV (1:500; gift from C. Klämbt, University of Münster, Germany), guinea pig anti-Repo (1:1000) and mouse anti-phospho-Histone H3 (Cell Signaling Technology; 1:1000).

Secondary antibodies were Cy3-, Cy5- or FITC-conjugated (all from donkey; Jackson ImmunoResearch; 1:250). For imaging, a Leica TCS SP1I or SP5 confocal microscope was used. Images were processed using Leica Confoal Software and Adobe Photoshop.

Labelling single peripheral glial cells using Flybow
Overnight egg collections from hs-mP5C;CyO, Dfd-EYFP, repo-Gal4 (nGFP) crossed with UAS-FB1.1 were heat shocked for 80 minutes at 37°C in a water bath followed by 1 hour incubation at 18°C. Then, embryos were kept at 25°C for ~4-5 hours to enable development until embryonic stage 16-17. Documentation of cell labelling events was carried out in vivo with a Leica DM 5500B fluorescence microscope connected to a Leica DFC 350 FX camera. Only recombination events that led to expression of mCherry were analysed. Embryos with labelled glial cells were then individually transferred to breeding vessels containing Instant Drosophila Medium BLUE, FORMULA 4-24 (Carolina Biological Supply, Burlington, NC, USA) and cultivated at 25°C until L3 stage. Finally, animals were dissected as described above and recorded on a Leica TCS SP5 confocal microscope. If required, additional antibody staining for Repo, NrxIV or 22C10 was performed. Some individuals were kept for documentation of glial labelling in the imago.

Ablation of single peripheral glial cells in the embryo
UV ablation of single ePG was performed as described (Soustelle et al., 2008). In one hs ePG2 was irradiated for 45 seconds using a UV power of 2 mW. Larvae were transferred to breeding vessels containing standard fly food and kept at 25°C until they reached L3. Dissection, antibody staining and documentation were performed as described above.

RESULTS
Extension of peripheral nerves and the pattern of associated glia during larval development
During embryogenesis of Drosophila, a fixed number of 12 ePG per hs arise from known central neuroblasts and sensory organ precursors in the trunk. They display individual identities reflected in the expression of specific marker genes. In addition, in vivo recordings revealed that each ePG migrates along peripheral nerve tracts in a stereotypical fashion, resulting in a characteristic positioning in the CNS at the end of embryogenesis (von Hilchen et al., 2008) (Fig. 1A,A′). During larval stages the number of glial cells along each peripheral nerve increases and these cells contribute to three different glial layers or sheaths around the nerves (Stork et al., 2008). However, to date it has not been elucidated whether (all) ePG survive during larval development, from which progenitors additional cells derive, and to which glial sheath they contribute.

Regarding the overall morphology of the CNS, no gross changes between the embryonic and late third instar (L3) stages are recognisable, as all nerve tracts established during embryogenesis are well preserved (Fig. 1). The main difference is an enormous elongation of peripheral nerves, in particular the section proximal to the region where segmental nerves (SNa-SNd) separate from intersegmental nerves (ISN) (Fig. 1B). This extreme longitudinal extension is accompanied by massive growth of the larval body to preserve the integrity of neuromuscular as well as sensory connectivity. The corresponding region in the embryo is significantly shorter (Fig. 1A,B). Hence, we call this region the nerve extension region (NER). During larval development, growth of the NER gradually increases from anterior to posterior abdominal hs (the peripheral nerves of hs A8 and A9 fasciculate together). For instance, the NER of A7 increases ~50-fold in length during larval development (compare Fig. 1A,B).

Another difference between embryo and larva is in the increasing number of glial nuclei along the NER, apparently correlating with the total length of this section (Fig. 1D). In the embryo and L1 larva three ePG (ePG1-ePG3) always populate the NER of hs A2-A7, whereas their number progressively increases up to five cells in L2 and up to a median of 23 cells along A7 in L3 larvae (n=11 hs, Fig. 1D). Even more glial nuclei can be observed in A8/A9, with a median of 80 nuclei (n=17 hs, Fig. 1D). In contrast to the varying numbers of glial nuclei along the NER, a constant number is found in the more distal part of the peripheral nerves, henceforth called the muscle field area (MFA) (Fig. 1A,B). In the embryo, nine ePG (ePG4-ePG12) are present in the MFA (Fig. 1A′). In L3 the same number of glial nuclei (median of nine, n=13 larvae) can be detected in this region (Fig. 1C). The constant number of glial cells in the MFA supports the idea of a one-to-one relation between embryonic and larval cells. The increasing number of glial nuclei along the NER raises the question of the correlation between embryonic and larval identities and of the origin of these additional cells.

Identification of individual peripheral glia using molecular markers
In the past, different marker lines were used to label the perineurial, subperineurial or wrapping glia in the larval CNS (Stork et al., 2008; Xie and Auld, 2011) (reviewed by Rodrigues et al., 2011). Here, we
compared some of these markers between embryonic and larval stages on a single-cell level in order to follow individual ePG throughout development (Fig. 2; supplementary material Fig. S1, Movie 1).

The enhancer construct nrv2-Gal4, a marker commonly used for the innermost wrapping glia (Stork et al., 2008; Sun et al., 1999), drives expression in three glial cells per embryonic abdominal hs with slight variability (Fig. 2, n = 101 hs/eight embryos). Based on position, these nrv2-Gal4-positive ePG can be identified as ePG1, ePG5 and ePG9. The same number of nrv2-Gal4-positive cells can be detected in L3 larvae at comparable positions. This suggests that ePG1 in the NER, ePG5 at the branching point of the SN, and ePG9...
more distal at the ISN persist until late larval stages to build the wrapping glia layer (Fig. 2A’).

For labelling of subperineurial glia, several marker strains exist, of which moody-Gal4 and Gli-Gal4 are described here. Both subperineurial markers drive expression in three ePG in the embryo, which are ePG3 in the NER and ePG4 and ePG7 in the MFA (Fig. 2B, n = 39 hs/four embryos; 2C, n = 37 hs/four embryos). Expression of moody-Gal4 starts late during embryonic development and often not all three ePG show a detectable signal at early stage 17. By contrast, Gli-Gal4 is also expressed in ePG10, and occasionally in ePG1, ePG5 or ePG9. In the larva both Gal4 lines constantly drive expression in ePG3 and, in around half of the hs, also in a second cell along the NER (n = 40 hs/four larvae). In the MFA, three moody- and Gli-positive glia can consistently be recognised at the position of ePG4, ePG7 and ePG10 (Fig. 2B’, n = 28 hs/five larvae; 2C’, n = 14 hs/three larvae). In rare cases (8%), ePG5 is labelled in addition.

For labelling of perineurial glia along the peripheral nerves, the enhancer-trap line 46F-Gal4 has recently been described (Xie and Auld, 2011). Analysis on a single-cell level revealed faint expression of 46F-Gal4 in stage 17 embryos (suggesting a late onset of Gal4 expression), which was restricted to ePG2 in the NER and to ePG4 and ePG10 in the MFA (Fig. 2D, n = 115 hs/nine embryos).

Remarkably, in L3 all glial cells along the NER are 46F-Gal4 positive (except two, presumably ePG1 and ePG3) (Fig. 2D’, n = 22 hs/four larvae). In the MFA, expression is detected in all glial cells in a variable fashion, except for ePG9, which never expresses 46F-Gal4. In the MFA almost all glia can be labelled by this marker line (asterisks), except for ePG9. SNc, segmental nerve c; VNC, ventral nerve cord.

The origin, proliferation behaviour and differentiation of glia cell types in the larval NER

The Flybow technique provides the possibility to genetically and continuously label cell clones or single cells (Hadjieconomou et al.,
and to follow their development. We used the Flybow1.1 construct to label single ePG, identify them in vivo based on their characteristic position at the end of embryogenesis and follow these cells throughout larval stages. As mentioned above, the NER shows striking differences between embryo and larva with respect to glial proliferation/hyperplasia and growth/hypertrophy (both depending on the length of the nerve).

The proximal-most ePG in the NER (ePG1) is positive for nrv2-Gal4, indicating that this cell contributes to the wrapping glial layer in late larval stages. Single-cell labellings of ePG1 at late stage 17 (n=6) revealed that this cell does not divide and resulted in a proximal wrapping glia in L3 being the only glia located within the fascicle enwrapping axons along the entire NER (Fig. 3A-C). Particularly in posterior hs, this goes along with the enormous hypertrophy of this cell, with an expansion of as much as 1 mm or more in length (supplementary material Fig. S2, Movie 2).

Flybow labelling of ePG2 (n=8) shows that this glial cell gives rise to the outermost perineurial layer, surrounding the complete NER. Furthermore, this cell appears to be the precursor of all additional glial nuclei arising during larval development in the NER (Fig. 3D-F). This hyperplasia is inferred from the observation that embryonic ePG2 labelling always resulted in mCherry labelling of all glial nuclei in the NER except for two. One mCherry-negative glial cell lies between the wrapping and perineurial layer, suggesting that this cell is part of the subperineurial sheath (Fig. 3E-H').

Labelling of ePG3 (n=3) revealed that this cell does not divide and forms the subperineurial layer within the NER (Fig. 3G-I). Like ePG1, ePG3 undergoes enormous hypertrophy to ensheath and seal the major part of the nerve bundles along the NER. The most proximal part of the NER is not covered by ePG3 protrusions but is...
surrounded by the membrane extensions of a subperineurial glia of the ventral nerve cord (VNC) (supplementary material Fig. S3). The nucleus of this cell might also lie in the periphery, resulting in two (instead of one) moody-Gal4-positive or Gli-Gal4-positive subperineurial glia along the NER (Fig. 2B', C').

Taken together, ePG1, ePG2 and ePG3 differentially respond to larval growth (hyperplasia versus hypertrophy) and form distinct layers along the NER.

Origin and unique mitotic activity of perineurial glia along the NER
Ablation experiments were performed to confirm that additional glial nuclei along the NER of larvae originate from ePG2. High-energy UV irradiation was used to eliminate ePG2 in the embryo, a method previously used to ablate glial cells in the developing fly wing (Aigouy et al., 2008; Aigouy et al., 2004).

Fig. 4. Ablation experiments and subgroup-specific block of mitosis determine that all additional glial nuclei along the NER in larva belong to the perineurial glia and arise from ePG2. (A) Maximum projection of endogenous nGFP in the living Drosophila embryo driven by repo-Gal4 to visualise glial nuclei and by Mz97-Gal4 for clear identification of abdominal hs due to expression in oenocytes (oe). (A') Higher magnification of the boxed area in A showing the NER of hs A5. In this hs, ePG2 can be recognised as the most posterior glial cell. For ablation, ePG2 was UV irradiated (yellow flash). (B) This results in a loss of ePG2 (asterisk), whereas the remaining glial cells along the NER are unaffected. (C-E') The same animal after dissection at L3 stage, showing endogenous nGFP (green), anti-Repo (red) and anti-Fas2 (blue) staining. Since nerves in A4 and A5 are closely attached (boxed region in C), nerve A5 is highlighted by dotted lines in magnifications (D,E'; Repo staining alone in D',E'). Only two remaining glial cells (ePG1, ePG3) are found along the proximal part of the NER in A5 (D',E'). The distal part of the NER is completely free of glial nuclei. In the MFA, glial number is unaltered (E,E'; the most proximal ePG4 and ePG5 are marked). In all images anterior is up. (F,G) Quantification of the results obtained from pan-glial or subgroup-specific knockdown of CycA (F) and ectopic expression of UAS-Rbf (G). Boxplots (explanation as Fig. 1D) show the numbers of PG nuclei along the NER of hs A2-A7. For each hs non-parametric statistics were performed (Kruskal-Wallis one-way analysis of variance on ranks followed by Dunn's multiple pairwise comparison test), consistently demonstrating a significant decrease in glial number compared with wild type (P<0.05) only when using either pan-glial (repo>) or perineurial glia (46F>) specific driver lines. For each genotype at least four larvae were analysed. Numbers of evaluated hs are given beneath boxplots.
Indeed, in 11 out of 14 specimens ablation of ePG2 at embryonic stage 16 resulted in a dramatic reduction of glial nuclei along the corresponding NER in L3 (supplementary material Fig. S4). In four of these just two remaining glial nuclei (ePG1 and ePG3) were found (example shown in Fig. 4). These results are in line with Flybow labelling of ePG2 and confirm that a single mitotically active glial cell (ePG2) is the origin of additional glial nuclei in the NER of L3. The loss of ePG2 and hence the loss of perineural glia along the NER cannot, or only partially, be compensated for by other glial cells (the origin of which is presently unknown).

In order to confirm that all additional glial cells along the NER are perineural glia arising from ePG2, we performed subgroup-specific inhibition of mitosis either by knocking down Cyclin A (CycA) or by ectopic expression of Retinoblastoma-family protein (Rbf). Larval glia proliferation along the NER can be blocked completely by pan-glial knockdown of CycA (repo>CycA-RNAi) resulting in a median number of three PG in hs A2-A6 (and four in A7) of L3 larvae. A similar result is observed upon perineurial glia-specific (46F>CycA-RNAi) knockdown of CycA, whereas CycA knockdown in wrapping (nrv2>CycA-RNAi) or subperineurial (Gli>CycA-RNAi) glia does not affect glial number along the NER significantly (Fig. 4F).

Furthermore, preventing the G1-to-S phase transition by ectopic expression of UAS-Rbf (reviewed by Dyson, 1998) in all glial cells (repo>Rbf) or exclusively in the perineural glia (46F>Rbf) resulted in a reduction of glial nuclei along the NER similar to CycA knockdown (Fig. 4G), with a median of four to six PG per hs. Neither wrapping (nrv2>Rbf) nor subperineurial (Gli>Rbf) glia expression of Rbf affected glial numbers significantly.

We conclude that the perineural layer is built by progeny of ePG2. Since ePG2 derives from a CNS neuroblast [NBS-6 (Schmidt et al., 1997; von Hilchen et al., 2008)] the perineural layer is not formed by mesodermal cells as proposed previously (Edwards et al., 1993). Owing to the continuous perineural sheath formed by the derivatives of ePG2 (Fig. 3E-E‴) we were not able to clarify whether ePG2 undergoes complete cytokinesis or just karyokinesis during larval development.

**The origin and differentiation of glial cells in the larval MFA**

The number of glial nuclei in the muscle field of L3 (see Fig. 1C) as well as marker expression suggest that all ePG in the embryonic MFA (ePG4-ePG12) persist during larval development. We aimed to confirm this using the Flybow technique. Hence, we traced the origin/identities and contribution of each identified ePG to the three distinct glial sheathes in the larval MFA.

**Wrapping glia**

In addition to a single wrapping glia in the NER (ePG1), two more can be identified in the MFA via Flybow due to their characteristic larval morphology. These cells are ePG5 (Fig. 5A-C, n=6) and ePG9 (Fig. 5D-F, n=1), both extending within the nerve bundle being surrounded by cd8-EGFP-positive subperineurial and perineurial glia (see transverse section in Fig. 5B,E). ePG5 protrusions extend into the NER, surround all SN branches and reach distally up to the region where sensory axons of the lateral chordotonal organ (Ich) fuse with the ISN (Fig. 5B). Fine ePG5 projections even penetrate the Ich (Fig. 5B‴). Membrane extensions of ePG9 separate the axons along the distal part of the ISN (Fig. 5E-F).

**Subperineurial glia**

Flybow labellings of ePG4, ePG7 and ePG10 reveal that these cells build the subperineurial sheath along the SN and ISN, each covering discrete nerve branches. ePG4 (n=5) exclusively covers the nerve branches of SNa and SNc (Fig. 6A-C). ePG7 (Fig. 6D-F, n=7; supplementary material Movie 3) surrounds SNb and SNd, the proximal part of the ISN and the Ich in L3. In addition, ePG7 protrusions extend from the ISN anteriorly to come into contact with ePG12 at the transversal nerve (TN) (Fig. 6E,F). Along this connection between ISN and TN, neurons can be detected that express the 22C10 (Futsch – FlyBase) epitope (supplementary material Fig. S5), indicating that ePG7 protrusions ensheath sensory neurons in this area. ePG10 represents subperineurial glia that completely cover the distal part of the ISN (Fig. 6G-L, n=6). In addition, ePG10 surrounds the sensory neurons of the dorsal

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**Fig. 5. Origin and morphology of wrapping glia in the MFA.** (A,A‴,D,D‴) Maximum projections showing the mCherry-labelled wrapping glia ePG5 and ePG9, respectively, in living *Drosophila* embryos at stage 17 in overview (A,D) and at higher magnification (A‴,D‴). Anterior is up. (A‴) Multiple labelling of ePG can be seen in hs A4 (asterisk) beside ePG5 in hs A3. These events were not analysed further. (B-B‴) In the same individual in L3 stage, ePG5 membranes enwrap axons along the distal part of the NER, all SNs, the proximal part of the ISN and along the lateral chordotonal organ (open arrowhead in B‴), which is connected to the ISN (arrowhead in B‴). (C) Illustration of ePG5 morphology in L3. (E,E‴) ePG9 membranes enwrap axons along the distal part of the ISN. (F) Schematic of ePG9 morphology.
chordotonal organ (dch) (Fig. 6H). This coincides with previous observations made by Han et al. (Han et al., 2011) showing that the sensory neuron ddaC and additional sensory neurons of the dch are ensheathed during embryonic and larval development by glial membranes. These can now be linked to ePG10.

Subperineurial glia express the cell-adhesion molecule Neurexin IV (NrxIV), a structural component of septate junctions required for the proper establishment of the blood-brain barrier (Banerjee et al., 2011; Banerjee et al., 2006; Baumgartner et al., 1996; Stork et al., 2008). Antibody staining against NrxIV on Flybow clones of ePG4, ePG7 and ePG10 confirms their subperineurial identity (supplementary material Fig. S6).

Perineurial glia
The outermost perineurial sheath in the MFA is formed by ePG6 and ePG8, which are both clearly positioned on top of the subperineurial layer (see Fig. 6E). Labelling ePG6 (Fig. 7A-C, n=7) demonstrates that this cell surrounds the proximal part of the ISN and occasionally a short section of the NER. Moreover, ePG6 extends protrusions that incompletely cover SNa, SNC, occasionally also SNb and SNd, as well as parts of the lch (Fig. 7B). The larval morphology of ePG8 is shown in Fig. 7D-F (n=4). In particular, the distal part of the ISN is covered by ePG8 processes. Occasionally, ePG8 protrusions project proximally along the ISN to some extent. Such projections may even reach and partially cover the SNb (Fig. 7E). Moreover, fine protrusions of ePG8 sometimes ensheath parts of the lch (Fig. 7E).

This mesh-like ensheathment by perineurial glia in the MFA appears to be incomplete (see Fig. 7E,E’). A similar morphology has been described in the Drosophila brain, where perineurial glia do not form a tight layer but rather a cellular mesh (Hartenstein, 2011).

Peripheral glia ensheathing DLN and TN
The remaining ePG11 and ePG12 each ensheath a distinct nerve tract. ePG11 covers the dorsal longitudinal nerve (DLN) (Fig. 7G-I, n=6). ePG12 surrounds at least the distal part of the TN in the MFA (Fig. 7J-L, n=5). The TN does not fasciculate with other nerves in the NER but projects alone, entering the VNC dorsally through the dorsal median cells (Luer et al., 1997) (supplementary material Fig. S7). It is not reasonable to classify ePG11 and ePG12 into any of the described layers as each cell forms only a single sheath around their respective nerves. In addition, marker gene expression in these two cells does not allow their allocation to one of the three glial subtypes.

The origin and larval development of each individual ePG and their contribution to the three glial layers is summarised in Table 1.

Tracing VNC glia and ePG to adulthood
We also attempted to trace individual glial cells into the adult. The specimen presented in Fig. 8 shows ePG6 in A5 as an example. It is clearly identifiable due to its position in the embryo (Fig. 8A,A’),
survives metamorphosis, and can be detected in the adult fly (Fig. 8B) covering the proximal part of the ISN. In the same specimen, a second glial cell is labelled within the VNC. Based on its position in the embryo this cell can be identified as a medialmost cell body glia (MM-CBG) (Ito et al., 1995) (Fig. 8C,C/H11032), which derives from NB6-4 (Dittrich et al., 1997). In the corresponding hs of the imago, the mCherry-labelled MM-CBG can still be detected (Fig. 8D-E/H11032). It exhibits a sponge-like morphology surrounding neuronal somata in the cortex of the adult VNC (for the morphology of this glial subtype in L3, see also supplementary material Movie 4).

These examples show that the Flybow technique, in combination with the in vivo identification of individual cells in the late embryo and their known origin, allows identified cells to be traced from the embryonic stem cell to the imago.

**DISCUSSION**

In this study we used the Flybow system (Hadjieconomou et al., 2011) to trace individual embryonic glial cells up to third instar larvae and even into the imago. We concentrated on ePG of abdominal hs A2-A7 for several reasons. First, this glial subgroup comprises a defined population of 12 cells (per hs) of known origin and identity (von Hilchen et al., 2008). Second, it was already well described that peripheral nerves are covered by three distinct glial layers formed from inside out by wrapping, subperineurial and perineurial glia, with molecular markers available to distinguish them (Bainton et al., 2005; Stork et al., 2008; Xie and Auld, 2011). However, to date it has not been shown whether and to what extent cell specification of ePG contributes to functional differences and hence to the generation of these glial layers. Finally, the number of ePG increases during larval development in correlation with the length of the peripheral nerve. Yet, to date, neither the origin of these additional cells nor the mechanism that controls the number of glial cells in response to peripheral nerve growth has been deciphered.

Using the Flybow system to label individual ePG in the embryo and subsequently analyse their larval morphology reveals that all 12 ePG survive at least until the third instar larval stage. We further
unravel the embryonic origin of all three glial layers that ensheathe the peripheral nerves at late third instar. The results presented in this study show that ePG1 in the NER and ePG5 and ePG9 in the MFA give rise to the larval wrapping glial layer. The subperineurial sheath is formed by ePG3 along the NER and by ePG4, ePG7 and ePG10 in the MFA. Neither wrapping nor subperineurial glia of the PNS proliferate during larval development but show enormous hypertrophy along with an increase in nerve length. With respect to the outermost perineurial sheath, our findings clearly exclude a mesodermal origin of this layer (Edwards et al., 1993), as we show that it is formed by ePG2 (and progenies) along the NER and by ePG6 and ePG8 along the MFA, all three derived from ventral neuroectodermal neuroblasts (NBs).

This detailed knowledge about the embryonic origin of all three glial sheaths will help to decipher their various functions. Our results show that determination of the three glial layers in the PNS takes place already in the embryo, as each layer is constantly formed by a discrete set of ePG. This enables us to answer the question of the origin of these layers, as raised in previous studies (Hartenstein, 2011). Wrapping and subperineurial glia share common progenitors: NB1-3 and a ventral sensory organ precursor (vSOP) (Table 1). Besides, NB1-3 gives rise to additional glial cells in the VNC (Beckervordersandforth et al., 2008). By contrast, perineurial glia have a separate pool of progenitors. Both perineurial glia in the MFA (ePG6 and ePG8) arise from NB2-5, which does not produce any other glial cell (Schmidt et al., 1997). The perineurial layer of the NER (ePG2) has its origin in NB5-6, which does not produce additional peripheral glia but gives rise to additional glia in the VNC. These belong to the subperineurial glia (DL, VL and MV-SPG) (Beckervordersandforth et al., 2008; Ito et al., 1995). However, classification of VNC glia includes the term ‘subperineurial glia’ for all surface-associated cells. Although we find that some subperineurial glia in the VNC also cover the proximal part of the NER (supplementary material Fig. S3), it still needs to be shown whether surface-associated glia (arising from NB5-6 and other NBs) contribute to the subperineurial and/or the outermost perineurial sheath.

In contrast to the CNS, where all three major glial classes (surface glia, cortex glia and neuropil glia) undergo proliferation during larval development (Pereanu et al., 2005) (reviewed by Hartenstein, 2011), our cell-tracing results demonstrate that in the PNS just a single cell, ePG2, along the NER divides. Division of this cell during larval stages was confirmed by staining for phosphorylated Histone H3 (pH3) in addition to Repo- and subtype-specific marker staining. Although pH3-positive peripheral glia were only rarely detectable, they always belonged to the perineurial glia (n=5/17 larvae, data not shown). Suppression of mitosis, either by knocking down CycA or ectopic expression of Rbf in all glia (driven by repo-Gal4), prevents the generation of additional cells along the NER. This can be phenocopied by perineurial glia-specific (using 46F-Gal4), but not by subperineurial- or wrapping glia-specific.

Table 1. Summary of the origin, marker expression, proliferation and specification of each larval glial sheath

<table>
<thead>
<tr>
<th>Region</th>
<th>Wrapping glia</th>
<th>Subperineurial glia</th>
<th>Perineurial glia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embryonic peripheral glia</td>
<td>ePG1, ePG5, ePG9</td>
<td>ePG3, ePG4, ePG10</td>
<td>ePG2, ePG6, ePG8</td>
</tr>
<tr>
<td>Origin</td>
<td>NB1-3, vSOP1 and vSOP3</td>
<td>NB1-3, vSOP1, vSOP3</td>
<td>NB5-6, NB2-5</td>
</tr>
<tr>
<td>Proliferation</td>
<td>No, No</td>
<td>No</td>
<td>Yes, No</td>
</tr>
</tbody>
</table>

1,2,3Lineage affiliation where cells forming one layer arise from different progenitors.

Fig. 8. Tracing glial cells from embryo to imago. (A, A', C') Maximum projections of living Drosophila embryos at stage 17 presenting mCherry-labelled ePG6 and MM-CBG in the VNC, respectively, in overview (A, C) and at higher magnification (A', C'). Anterior is up. (B) ePG6 (nucleus marked by an arrow) is still present in the imago surrounding the proximal part of the ISN. (D-E') The MM-CBG persists until adulthood, exhibiting a sponge-like morphology. Individual neuronal somata surrounded by MM-CBG membranes can be seen in the transverse section at the level of the nucleus (E). The nucleus of a surface glia (open arrowhead in E') covering the labelled CBG is shown in a more ventral transverse section.
expression of either transgene. Ablation experiments further confirm the perineurial origin, as embryonic ablation of ePG2 results in a reduction, or frequently even in complete loss, of perineurial glia nuclei along the NER in larva. However, we could not determine which other progenitor for perineurial glia accounts for the additional cells in some of the ePG2 irradiated hs. Block of cell cycle progression in all perineurial glia results in three cells along the NER (as seen in the embryo), indicating that any failure in producing additional perineurial glia cannot be compensated for by other glial subtypes. Alternatively, additional cells in irradiated hs might arise from incomplete damage of ePG2, as irradiation does not always lead to instant cell death.

Another uncertainty remains as to whether perineurial glia undergo cytokinesis or just karyokinesis, as they form a continuous sheet along the NER that does not allow the identification of single cells within. Yet, recent results (Xie and Auld, 2011) support full cytokinesis, as they observe individual perineurial cells being detached from each other as a consequence of Integrin β-subunit knockdown.

A further question concerns the control of perineurial glia proliferation. Apparently, the total number of glial nuclei along the NER is not merely dependent on the overall length of the axonal fibres as Tubby larvae with a substantially shorter NER display no significant reduction in glial number (data not shown). Contrary to this finding, it is reported that brave (GlcAT-P) mutants, which exhibit significantly shorter peripheral nerves, have fewer glia along the nerve while their spacing and distribution appear unaffected (Pandey et al., 2011). Glial cell numbers along the NER increase from anterior segment A1 (with a short NER) to the posteriormost segments A8/A9 (with a ~10 times longer NER), suggesting not a predetermined but rather a dynamic process that probably relies on glia-glia or glia-neuron interactions. A non-autonomous function of peripheral glia in determining perineurial sheath thickness has been shown by Lavery and colleagues (Lavery et al., 2007). According to their model, perineurial growth depends on activation of the Ras pathway within the Gli-Gal4-positive subperineurial glia, which is mediated by PI3K and Akt and results in an inhibition of the transcription factor Foxo, which, in turn, is assumed to directly or indirectly suppress the expression of growth factor(s) promoting perineurial cell growth. It remains to be shown whether this mechanism might underlie additional perineurial nuclei arising along the NER. Recent results show that, in the brain, FGF signalling (a known activator of Ras) acts synergistically with InR/Tor to regulate perineurial glia proliferation (Avet-Rochex et al., 2012). Further experiments need to be performed in order to establish whether these signalling cascades control perineurial glia proliferation in the PNS as well.

There is a lack of clarity regarding perineurial glial function. Experimental data indicate that they might contribute to the blood-brain barrier, at least for large molecules of ~300 kDa (Stork et al., 2008). However, perineurial glia apparently play no pivotal role in the formation of a sealed blood-brain barrier, as they do not cover peripheral nerves completely until the late larval stage (Stork et al., 2008). Our Flybow labellings of perineurial glia reveal that the ensheathment provided by these cells in the MFA is even incomplete in L3. However, at least some cells of the larval perineurial layer survive metamorphosis and persist to the adult. Thus, they could become more essential later on during metamorphosis or in the adult in blood-brain barrier formation or by providing mechanical stability to peripheral nerves. In the future, the precise elimination of distinct glial layers will help to unravel the function of the various glia in larvae and in the imago.

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Competing interests statement
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Author contributions
The project was conceived by C.M.v.H., G.M.T. and B.A. Experiments were conducted by C.M.v.H. and A.E.B. Ablations were conceived and performed with the help of A.G. The manuscript was written by C.M.v.H., G.M.T. and B.A.

Supplementary material
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References


