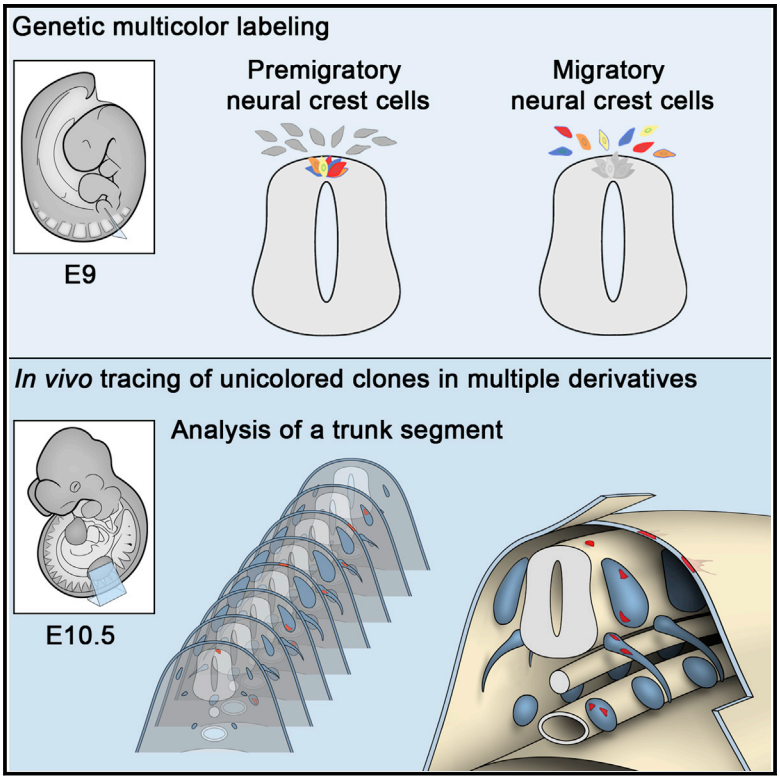
Short Article

Cell Stem Cell

Premigratory and Migratory Neural Crest Cells Are Multipotent In Vivo

Graphical Abstract



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In Brief

The neural crest (NC) gives rise to a broad variety of neural and non-neural cell types during vertebrate development, but whether NC cells are multipotent or rather a heterogeneous population of restricted progenitors is unclear. Baggiolini et al. performed an in vivo lineage tracing study of single premigratory and migrating NC cells and demonstrated that the majority of NC cells are multipotent in vivo.

Highlights

- We traced single NC cells in vivo by using the *R26R-Confetti* mouse model
- Most premigratory and migratory NC cells are multipotent
- Multipotency is confirmed by differentiation marker analysis
- Our results point to the existence of neural crest stem cells (NCSCs) in vivo

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Premigratory and Migratory Neural Crest Cells Are Multipotent In Vivo

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SUMMARY

The neural crest (NC) is an embryonic stem/progenitor cell population that generates a diverse array of cell lineages, including peripheral neurons, myelinating Schwann cells, and melanocytes, among others. However, there is a long-standing controversy as to whether this broad developmental perspective reflects in vivo multipotency of individual NC cells or whether the NC is comprised of a heterogeneous mixture of lineage-restricted progenitors. Here, we resolve this controversy by performing in vivo fate mapping of single trunk NC cells both at premigratory and migratory stages using the *R26R-Confetti* mouse model. By combining quantitative clonal analyses with definitive markers of differentiation, we demonstrate that the vast majority of individual NC cells are multipotent, with only few clones contributing to single derivatives. Intriguingly, multipotency is maintained in migratory NC cells. Thus, our findings provide definitive evidence for the in vivo multipotency of both premigratory and migrating NC cells in the mouse.

INTRODUCTION

Neural crest (NC) cells are a defining feature of vertebrates that give rise to many of the cell types that imbue them with their unique characteristics, such as jaws and peripheral nervous system. In the embryo, NC cells arise from the dorsal margin of the neural plate border during neurulation (Le Douarin et al., 2008), undergo an epithelial to mesenchymal transition (EMT), and migrate extensively throughout the embryo to populate numerous derivatives.

This has raised the important question of what underlies this remarkable ability to contribute to so many diverse derivatives, ranging from craniofacial cartilage to neurons and glia to melanocytes. One model suggests that the entire NC cell population is "multipotent" and capable of forming many or all of the potential derivatives. At the opposite extreme, the NC might instead represent a heterogeneous mixture of "predetermined" cells, each fated to form a particular derivative. Finally, the NC may be comprised of a mixture of these two types of precursor cells.

Over several decades, there has been considerable controversy regarding the correct answer to this pivotal question (Dupin and Sommer 2012). Early studies concluded that NC cells were multipotent in vivo (Bronner-Fraser and Fraser, 1988, 1989; McKinney et al., 2013; Serbedzija et al., 1990) and in vitro (Baroffio et al., 1988; Dupin et al., 2010; Stemple and Anderson, 1992). However, other publications instead reported that the NC was comprised of heterogeneous populations of restricted progenitor cells (Harris and Erickson, 2007; Henion and Weston, 1997; Krispin et al., 2010). In particular, recent studies proposed that premigratory NC cells are fate determined prior to delamination and organized according to a spatio-temporal pattern in the dorsal neural tube (dNT) of chick embryos (Krispin et al., 2010; Nitzan et al., 2013). In this model, each NC cell gives rise only to a specific cell type, depending on the timing of emigration and the site of origin in the dNT.

Despite technical differences potentially explaining these discrepancies, it has so far not been possible to reconcile these studies (Dupin and Sommer, 2012). Early in vivo lineage tracing studies lacked the ability to identify specific cell types other than by location in various derivatives. Whereas clonal analysis in vitro circumvents these problems, the culture techniques analyze cells outside of their endogenous environment and expose cells to culture media, which may alter cell behavior. Moreover, there is very little information regarding the developmental potential of NC cells in mammalian model systems. Lineage-tracing studies were originally performed in chicken embryos by vital dye injection, which is very challenging to carry out in mouse embryos (Serbedzija et al., 1990). With the advent of modern transgenic technology, it is now possible to resolve the controversy regarding NC potentials in the mammalian embryo. Here, we use the *R26R-Confetti* mouse model to perform genetic in vivo fate mapping of NC cells. Our results definitively show that the vast majority of murine NC cells, both prior to and during migration, are multipotent.

RESULTS

Multicolor Labeling of Premigratory and Migratory NC Cells

To achieve temporal tracing of NC cells, we used the *CreER loxP* system, by which activation of CreER recombinase can be

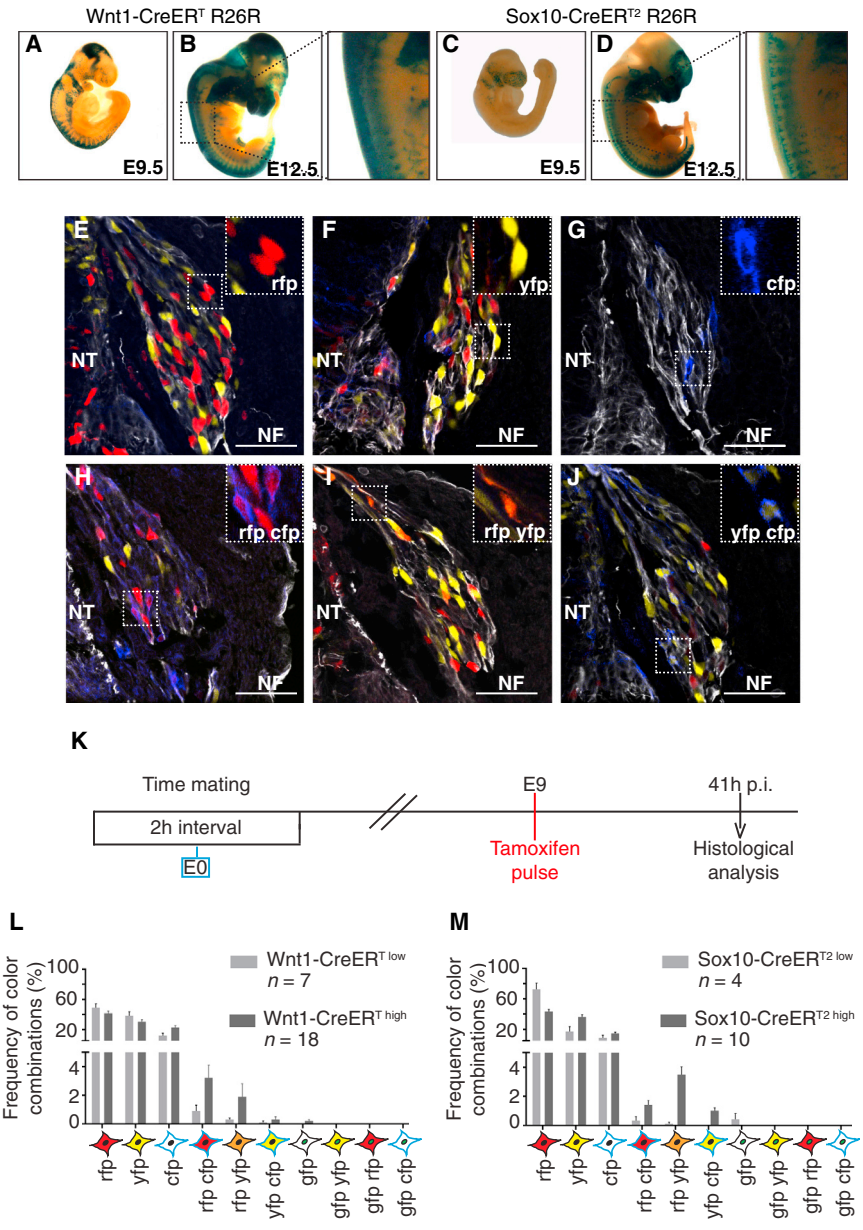

Figure 1. Multicolor Tracing of Premigratory and Migratory NC Cells

(A–D) (A and B) β-Galactosidase expression in premigratory NC cells in E9.5 and E12.5 *Wnt1-CreER^{T} R26R* embryos and in migratory NC cells in *Sox10-CreER^{T2} R26R* embryos ([C] and [D]).

(E–J) In vivo expression of the single-color combinations rfp (E), yfp (F), and cfp (G) and of the mixed color combinations rfp cfp (H), rfp yfp (I), and yfp cfp (J). Neurofilament staining (NF, in white) delineates the structure of the dorsal root ganglia (DRG).

(K) Experimental outline for the multicolor lineage-tracing approach. E0, embryonic day 0; p.i., post injection of TM.

(L and M) Frequencies of the color combinations in the four cases analyzed (*Wnt1-CreER^{T}* and *Sox10-CreER^{T2}* at low and high recombination densities). For numbers of analyzed embryos, see Supplemental Experimental Procedures. Scale bars: 50 μm. See also Figure S1 and Table S1A.

induced in embryos in a cell type- and stage-dependent manner upon tamoxifen (TM) injection of pregnant females. CreER-mediated genomic recombination of reporter alleles leads to marker expression that can be tracked in CreER-expressing cells and all of their daughter cells, allowing fate mapping of these cells in vivo. To trace the fate of premigratory NC cells, we made use of *Wnt1-CreER^{T}* animals. Accordingly, *CreER^{T}*-induced β-galactosidase expression in *Wnt1-CreER^{T}* embryos carrying the *CreER^{T}*-reporter allele *R26R-Rosa* was observed in the dNT and in all NC derivatives (Figures 1A and 1B) (Soriano, 1999; Zervas et al., 2004). To trace NC cells that have already emigrated from the dNT, we used the *Sox10-CreER^{T2}* line (Simon et al., 2012). In the mouse, Sox10 expression follows Wnt1 expression and marks virtually all NC cells immediately after their delamination from the dNT (Hari et al., 2012). Therefore, TM-induced recombination at E.9.0 in *Sox10-CreER^{T2} R26R-Rosa* embryos resulted in β-galactosidase expression in all NC derivatives, but not the dNT (Figures 1C and 1D).

Upon *CreER* activation and recombination across sets of loxP sites in the *R26R-Confetti* reporter mouse, one out of four fluorescent reporter proteins, nuclear GFP, cytoplasmic YFP, cytoplasmic RFP, or membrane-bound CFP, is expressed. To increase the colors available for the tracing, we used animals homozygous for the *R26R-Confetti* allele. In these animals, both alleles are recombined, which leads to expression of two out of the four available fluorescent proteins, allowing a total of 10 color combinations (Figure S1). In both *Wnt1-CreER^{T} R26R-Confetti* (hereafter called *Wnt1-CreER^{T}*) (Figures 1E–1J) and in *Sox10-CreER^{T2} R26R-Confetti* (*Sox10-CreER^{T2}*) embryos (data not shown), expression of the following single color combinations was readily detectable: red (rfp, Figure 1E); yellow (yfp, Figure 1F); and blue (cfp, Figure 1G). In addition, we observed the expression of mixed color combinations, such as red and blue (rfp cfp, Figure 1H), red and yellow (rfp yfp, Figure 1I), and yellow and blue (yfp cfp, Figure 1J). In contrast, color combinations with the fluorescent protein GFP were extremely rare, indicating that not all theoretically possible color combinations were equally represented.

Multicolor Output Depends on Promoter Activity and Recombination Density

The frequency of color combinations observed upon *CreER*-mediated recombination of a multicolor *Cre* reporter influences the probability of whether a cohort of cells marked by a single color derives from one or more founder cells. Therefore, we examined the frequency of different colors expressed in

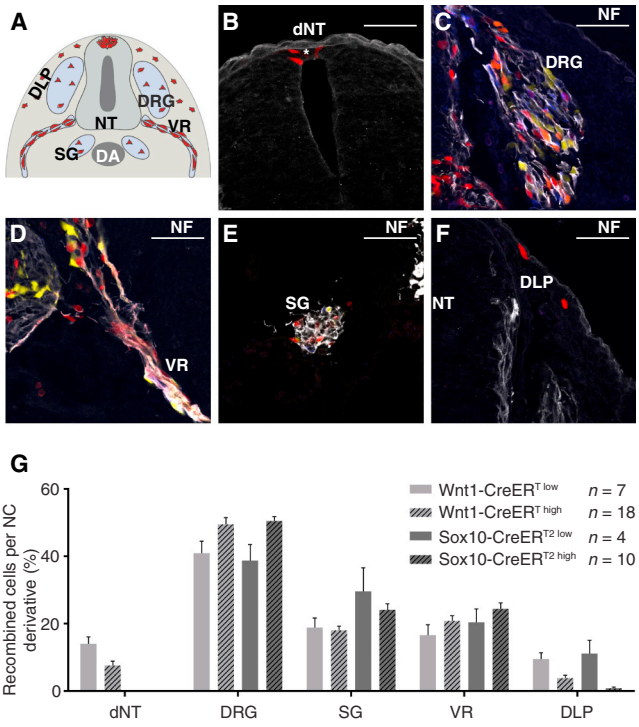

Figure 2. Frequencies of Genetically Traced Cells in Trunk Derivatives of the NC

(A–F) (A) Schematic drawing of a transverse section with NC cells (in red) in the dorsal lateral pathway containing cells of the melanocytic lineage (DLP), sensory dorsal root ganglia (DRG), sympathetic ganglia (SG), and ventral root with Schwann cells (VR). Recombined NC cells are found in vivo in the dNT (B), DRG (C), VR (D), SG (E), and DLP (F).

(G) Percentages of recombined cells per derivative in *Wnt1*-CreER^{T} and Sox10-CreER^{T2} embryos at low and high recombination densities, respectively. For numbers of analyzed embryos, see Supplemental Experimental Procedures. Scale bars: 50 μm. See also Table S1B.

E10.5 *R26R-Confetti* embryos of both *CreER* lines (Figure 1K). A single limiting dose of TM resulted in few recombination events. Quantification of low-TM-dose-treated E10.5 *Wnt1-CreER^{T} R26R-Confetti* embryos (*Wnt1-CreER$^{T\ low}$*) revealed that the mixed color combinations were expressed in only 0.1%–0.9% of the recombined NC cells (Figure 1L; Table S1A). Similarly, in low-TM-dose-treated *Sox10-CreER^{T2} R26R-Confetti* embryos (*Sox10-CreER$^{T2\ low}$*), mixed colors were found at very low frequencies (Figure 1M; Table S1A). In contrast, the pure colors red, yellow, or blue were consistently expressed in recombined NC cells in both *CreER* lines (Figures 1L and 1M; Table S1A).

These findings prompted us to increase the level of recombination for both *CreER* lines, in order to obtain more NC cells expressing rare color combinations. For the *Wnt1-CreER^{T} R26R-Confetti* line, higher recombination density achieved by elevating the TM dose (*Wnt1-CreER$^{T\ high}$*) resulted in increased, but still low, occurrence of the rare color combinations (0.3%–3.2% of all recombined cells) (Figure 1L; Table S1A). Similarly, elevating the TM concentration in the *Sox10-CreER^{T2} R26R-Confetti* line (*Sox10-CreER$^{T2\ high}$*) allowed increased representation of the mixed color combinations (1.0%–3.5%) (Figure 1M; Table S1A). Summarizing, in our system we were able to trace NC cells not only at two different developmental stages, namely at the premigratory and at the migratory stage, but also at two different recombination densities producing different color outputs. The most frequent color combinations allowed clonal tracing when only few recombination events occurred. Rare fluorescent marker combinations, on the other hand, could be used to discern single clones at both low and high recombination densities.

Representation Frequencies of Recombined NC Cells in Trunk Derivatives

NC cells in the trunk of mouse embryos give rise to several structures, such as dorsal root ganglia (DRG), Schwann cells associated with peripheral nerves as, for instance, evident in the ventral root (VR), sympathetic ganglia (SG), and finally cells that migrate along the dorsal lateral pathway (DLP) to generate melanocytes. As expected, all these derivatives were marked in *Wnt1-CreER^{T}* and *Sox10-CreER^{T2}* embryos (Figures 2A–2F; data not shown). Moreover, tracing NC cells at the premigratory stage with the *Wnt1-CreER^{T}* line allowed the observation of recombined cells in the dNT, which we defined as the most dorsal three cell layers of the neural tube (Figures 2A and 2B).

The likelihood to detect daughter cells of a NC progenitor cell in different target structures is possibly dependent on the relative sizes of these structures: The bigger a given compartment, the more likely it might be for a daughter cell to end up in this compartment. In *Wnt1-CreER^{T}* embryos, we observed 7.6%–14.0% of recombined cells in the dNT (Figure 2G; Table S1B), while no recombined cells were found in the dNT of *Sox10-CreER^{T2}* embryos. In all conditions, the majority of recombined cells were found in the biggest trunk NC derivative, the DRG (Figures 2C and 2G; Table S1B). The SG and the VR were populated by comparable numbers of recombined NC cells, while the DLP was the derivative with the lowest number of recombined cells (Figures 2D–2G; Table S1B). Given the number of possible cell divisions in a time window of 41 hr (Figure 1K), the elevated numbers of some recombined cells of the same color in certain derivatives cannot be explained only by differential proliferation in these derivatives. Therefore, the fact that the majority of recombined cells were present in the bigger derivatives is likely due to higher numbers of migratory NC cells populating these derivatives.

Qualitative Assessment of Multicolor Fate Mapping of Single Premigratory NC Cells

Our data reveal that *CreER*-mediated recombination of the *R26R-Confetti* allele allows tracking of NC cells by different color combinations at defined frequencies. We next exploited this system to track the fate of individual NC cells, with a first emphasis on premigratory cells. E10.5 embryos were collected 41 hr post-TM injection (Figure 1K). As previously demonstrated, the mean cell-cycle length of E9.5 NC cells is 10.6 hr (Gonsalvez et al., 2013). The literature does not provide exact error intervals for the cell division rate, and it is likely that during 41 hr of NC development the cell-cycle length varies and becomes cell type and derivative specific. Since these variations are unknown and can hardly be determined, we first applied a fixed assumption that NC cells could divide three times between TM-induced

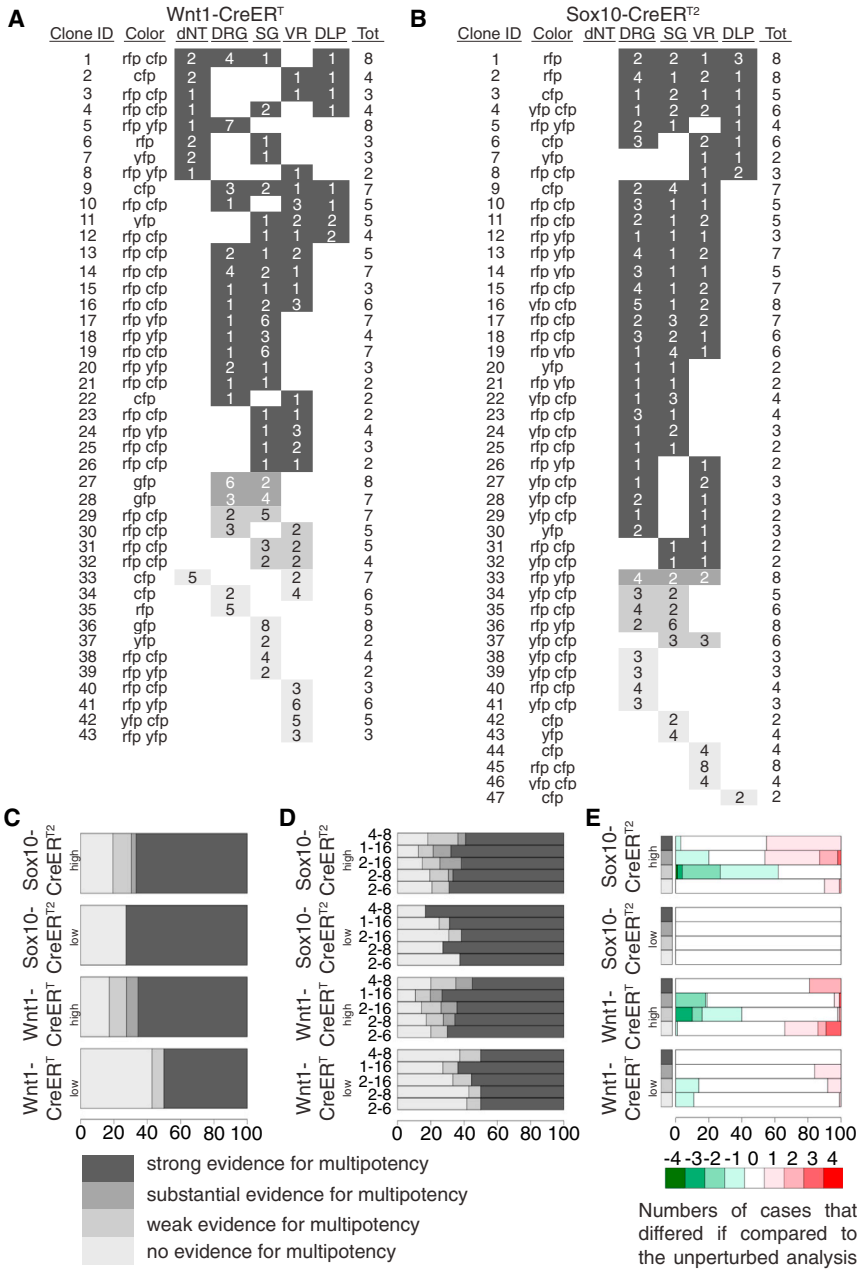

Figure 3. Lineage Tracing Analysis of Premigratory and Migratory NC Cells and Mathematical Evaluation of Fate Determination in NC Cells

(A and B) List of the clonal frameworks for premigratory (A) and migratory (B) NC cells ordered by degree of evidence of multipotency. Both conditions of low and high recombination densities were pooled to compare exclusively premigratory versus migratory NC.

(C) Percentages of clones expressing no, weak, substantial and strong evidence of multipotency for both premigratory and migratory NC cells at low and high recombination densities.

(D) Degrees of evidence of multipotency when the minimum and the maximum size of a clone were changed for premigratory and migratory NC at low and high recombination densities.

(E) Sensitivity assay of the statistical evaluation method. Each of the 16 barplots shows the proportion of cases that changed (ranging from loss of four clones up to gain of four clones) upon 100 different simulations. White indicates no change, red cases that were added and green cases that were lost. See also Figures S2, S3, and S4. For numbers of analyzed embryos, see Supplemental Experimental Procedures.

recombination and the time point of analysis. Hence, we initially considered only equally colored cohorts of cells with a minimum of two and a maximum of eight cells, with the goal that such a stringent analysis would serve as a basis to establish and assess a statistical method able to discern between multipotency and cell fate restriction.

For the analysis of putative clones, we focused on the forelimbs area, taking into account cells of the same color that were present in a unit defined by a trunk segment spanning the width of one DRG (10–14 transverse sections of 10 μm thickness each) (Figure S2; Movie S1). 3D reconstruction confirmed that our recombination protocol allowed marking of a small number of equally colored NC daughter cells disseminating over various trunk derivatives (Figure S2; Movie S1 and S2). Consecutive transverse sections at the level of the forelimbs were imaged (Figure S2Ai–S2Axii), and the number and location of equally colored recombined cells per trunk segment were assessed (Figure 3). For the different conditions used, the density of putative clones ranged between 0.8 ± 0.1 and 1.0 ± 0.3 clones per unit, with most units analyzed containing 0 or 1 clone (Table S2A). *Wnt1-CreER^T* ^{low} embryos displayed many putative clones with progeny in multiple derivatives, including sometimes the dNT and DLP (Figures 3A and S3A). To corroborate these results, we analyzed *Wnt1-CreER^T* ^{high} embryos, in which we observed cohorts of cells (two to eight cells) expressing rare mixed color combinations (Figures 3A and S3C). Strikingly, putative clones were mostly spread over multiple derivatives (Figures 3A and S3C).

Multicolor Fate Mapping of Single Migratory NC Cells

Our findings prompted us to ask whether multipotency might be a unique characteristic of premigratory NC cells or whether this developmental potential is retained upon NC delamination and migration. Therefore, we analyzed the fate of NC cells in *Sox10-CreER^{T2}* embryos (Figure 1K). The clonal density found in *Sox10-CreER^{T2}* embryos was again low (Table S2A). Surprisingly, in *Sox10-CreER^{T2}* ^{low} embryos, many equally colored cell cohorts were dispersed over multiple NC derivatives, in a similar manner to what had been observed in *Wnt1-CreER^T* embryos (Figures 3B and S3B). Similar results were acquired for the

Sox10-CreER$^{T2\ high}$ embryos, suggesting that these observations are independent of the recombination density and the color of the cell cohort (Figures 3B and S3D).

Statistical Evaluation of Cell Fates Adopted by Premigratory and Migratory NC Cells

Our observations suggested that the majority of NC cells are multipotent both at the premigratory stage and, intriguingly, also at the migratory stage. To verify our results, we analyzed each data set considering the color of the observed putative clone, the derivative where we observed it, and its size. Defining the exact cell-cycle length and its variation during a period of 41 hr for each specific derivative would have been extremely difficult and prone to mistakes. Thus, we applied a static framework instead of a complete dynamic modeling approach. To distinguish between a predetermined and a multipotent framework for both *Wnt1-CreER*^{T} and *Sox10-CreER*^{T2} embryos, at low and high recombination levels, we calculated the respective probabilities of observing the specific clone configuration. Because the statistical model is based on count data, these probabilities are equivalent to likelihoods and thus twice the negative log of the likelihood ratio (deviance) was used to discriminate between the two frameworks (see Supplemental Experimental Procedures). To simplify the interpretation, the numerical values of the deviance were discretized into no, weak, substantial, and strong evidence for a framework of multipotency (Figure 3).

Based on this statistical evaluation, we first analyzed the cell cohorts (composed of two to eight cells from the same color) obtained with the *Wnt1-CreER*^{T} embryos, pooling the data for low and high recombination densities. Strikingly, 65.1% (28 cases out of 43) of all uni-colored cell cohorts represented clones of the categories strong or substantial evidence for multipotency (Figures 3A and 3C). 27.9% (12 cases out of 43) of all cohorts analyzed were multipotent clones with more than two fates. In 18.6% (8 cases out of 43) of the clones, a progeny remained in the dNT. Half of these clones also contained cells in ventral structures as well as the DLP, demonstrating the broad developmental potential of the corresponding mother cells. Moreover, all uni-colored cell cohorts with derivatives in the DLP (18.6%, 8 cases out of 43) belonged to the category strong evidence for multipotency and contained NC-derived cells in at least one additional structure. Of all the cases analyzed, only 25.6% (11 cases out of 43) were belonging to the category no evidence for multipotency, indicating that lineage-restricted progenitor cells represent a minor fraction of premigratory NC cells (Figures 3A and 3C).

Unexpectedly, clones with strong or substantial evidence for multipotency were by far the most frequent categories also in the *Sox10-CreER*^{T2} embryos (70.2%, 33 cases out of 47) (Figures 3B and 3C). 31.9% (15 cases out of 47) of all cohorts analyzed were multipotent clones with progeny in only two derivatives (bi-fated) and 38.3% (18 cases out of 47) were clones with progeny in more than two derivatives; 24.2% (8 cases out of 33) of the uni-colored cell cohorts with substantial or strong evidence for multipotency contributed to the DLP (Figure 3B). Of note, all of these were multipotent clones with cells in the DLP and in at least one other structure, and half of the DLP-clones contained cells in as many as three additional NC derivatives. Similar to premigratory NC cells, fate-restricted migratory NC cells showing no evidence for multipotency were 21.3% (10 out of 47) of all clones (Figures 3B and 3C).

To assess the robustness of our statistical evaluation, we performed a sensitivity analysis by altering various parameters in the calculation of the multipotency likelihoods. When the minimum and maximum clone sizes were varied (rather than considering only clones of two to eight cells), the resulting clone categories were still predominantly strong and substantial evidence for multipotency (Figure 3D). Furthermore, we perturbed the values of color frequency (r_{color}) and derivative size (d_{deriv}) (see Supplemental Experimental Procedures) by multiplying the probabilities and fractions by a random number between 1/3 and 3 (uniformly distributed), followed by rescaling. The analysis was carried out as described in the Supplemental Experimental Procedures, and the differences with respect to the evidence classification shown in Figures 3A and 3B were recorded. Figure 3E shows the results for 100 of such simulations and reveals that in both *Wnt1-CreER*^{T} and *Sox10-CreER*^{T2} embryos, the categorization of the clones into no, weak, substantial, and strong evidence for multipotency was not (low recombination densities) or only moderately changed (high recombination densities). Thus, even when challenged by modulating various parameters, our statistical evaluation consistently revealed that the majority of premigratory and migratory NC cells were multipotent rather than fate restricted.

The statistical analysis presented in Figure 3 was performed under the stringent criteria that the maximum clone size was eight cells. However, this clone size might not fully recapitulate the heterogeneity of embryonic cell populations, since it does not take into account the possibility that faster dividing cells might be present in distinct locations. Moreover, parameter modulation in our statistical analysis not only provided clear evidence for multipotency of NC cells but also predicted that cell cohorts larger than the chosen range of two to eight cells could also be actual clones. Therefore, we performed a further analysis, in which we considered all uni-colored cell cohorts found in defined trunk segments of *Wnt1-CreER*^{T} and *Sox10-CreER*^{T2} mice. To increase the probability of clonal tracing, we restricted this analysis to cell cohorts expressing rare colors only. The clonal density was low, ranging from 0.1 ± 0.1 to 1.7 ± 0.3 clones per unit (Table S2B). By applying the statistical analysis mentioned above, we observed that the vast majority of the clones fell into the categories of strong or substantial evidence for multipotency, both in the *Wnt1-CreER*^{T} line (76.4%, 42 cases out of 55) and in the *Sox10-CreER*^{T2} line (75%, 36 cases out of 48) (Figure S4). Thus, including larger clones into our analysis did not affect the proportion of multipotent clones originating from premigratory and migratory NC cells, respectively, further demonstrating the robustness of our statistical analysis.

Multipotency Assessed by Differentiation Marker Analysis

During NC development, fate segregations are accompanied by spatial segregations of the resulting cell lineages. Therefore, a clone simultaneously located to multiple structures represents the progeny of a multipotent mother cell (Figures 3 and 4S).

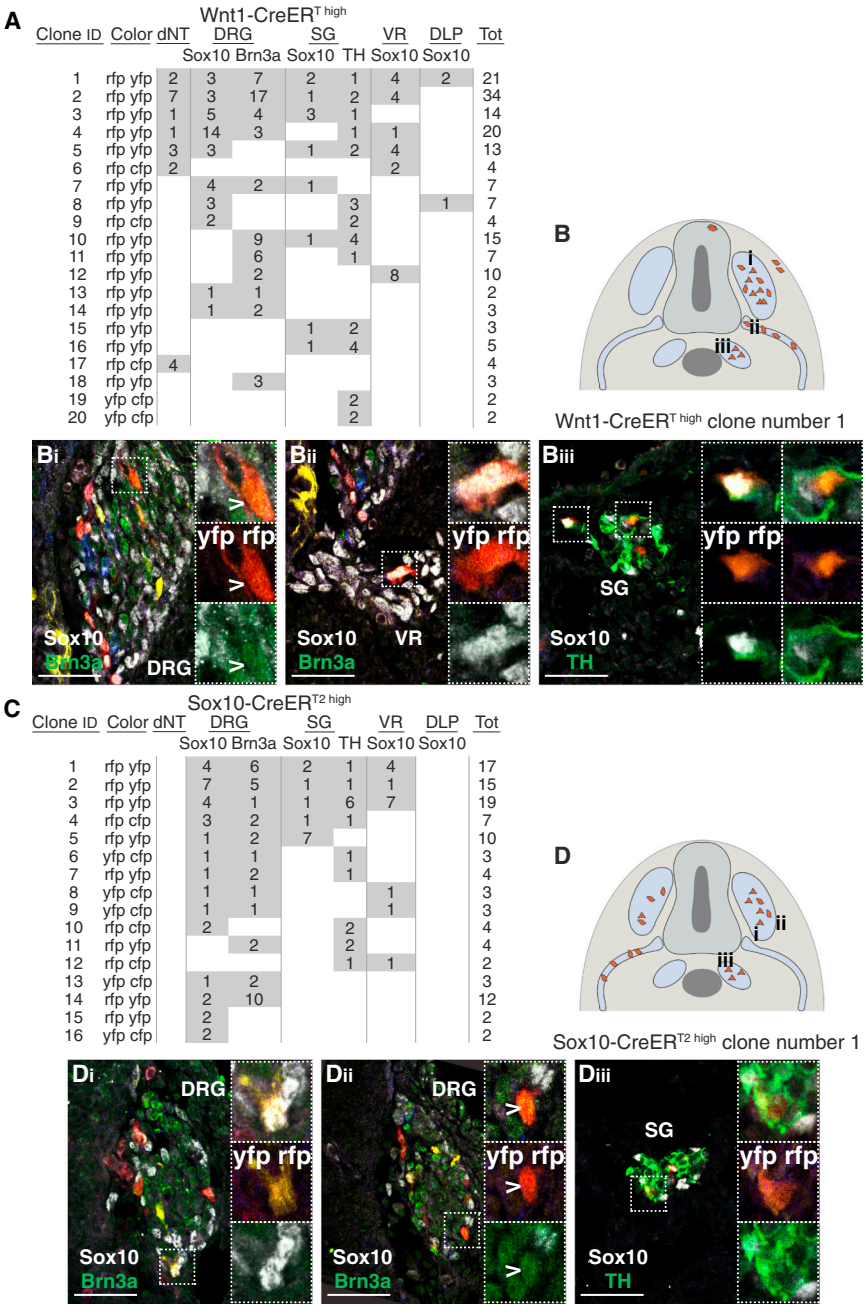

Figure 4. Quantitative Clonal Assays Combined with Differentiation Marker Analysis

(A and C) Lists of the clonal frameworks for premigratory (A) and migratory (C) NC cells ordered by degree of evidence for multipotency. Only clones belonging to the rare color category where analyzed, and no size restriction was applied. Each single clone was analyzed in regard to its location and expression of the following differentiation markers: Brn3a, a sensory neuron marker; TH, a sympathetic neuron marker; and Sox10 that at this developmental stage labels glial and melanocytic lineages.

(B and D) Schemes summarizing the distribution of entire clones respectively found in *Wnt1-CreER^{T}* and *Sox10-CreER^{T2}* embryos at high recombination densities.

(Bi–Biii and Di–Diii) Examples of embryonic sections through NC derivatives that comprise rare color-expressing cells belonging to the clones shown in (B) and (D), respectively. For numbers of analyzed embryos, see Supplemental Experimental Procedures. Scale bars: 50 μm.

However, additional fate decisions are made within certain NC-derived structures, such as the DRG and SG, where neuronal lineages segregate from satellite glia. A multipotent clone with cells in DRG and SG could thus be a neuron-only clone consisting of different types of neurons (sensory, autonomic), a glia-only clone with distinct types of glia (Woodhoo and Sommer, 2008), or a mixed neuron-glia clone. To address this issue, we performed an additional clonal analysis, taking into consideration not only the location of uni-colored NC cells but also the expression of well-defined differentiation markers, such as Brn3a for sensory neurons, tyrosine hydroxylase (TH) for autonomic neurons, and Sox10 for glial and melanocytic cells. Groups of cells belonging to the rare color category were considered, without clonal size restriction (Figure 4). Only 4 out of 20 clones (*Wnt1-CreER^{T}* embryos) and 2 out of 16 clones (*Sox10-CreER^{T2}* embryos) were lineage restricted, respectively, meaning that these clones were not only confined to a single derivative, but they were also expressing only one marker of differentiation. Of note, of the 16 clones in *Wnt1-CreER^{T}* embryos that were not lineage restricted, only one clone contained only neurons and no glia (clone ID 11; Figure 4A), while the other 14 clones were mixed neuron-glia clones. Likewise, one clone in *Sox10-CreER^{T2}* embryos contained sensory and sympathetic neurons but no glia (clone ID 11, Figure 4C), while all other multipotent clones were mixed neuronal and glial. Intriguingly, some of the cases that would have been considered to represent lineage-restricted clones based on their location, turned out to be at least bipotent, expressing multiple markers of differentiation (Figure 4A, clone IDs 13, 14, 15, and 16; Figure 4C, clone IDs 13 and 14). These data substantiate our findings that single premigratory, as well as single migratory NC cells, mostly generate daughter cells that localize to distinct target structures and acquire different fates.

DISCUSSION

A fundamental question in developmental biology is how the distinct cell types of a given organ are established. Although it is thought that organ formation and homeostasis rely on the activity of organ-specific multipotent stem cells, several recent

publications demonstrated that heterogeneous populations of restricted progenitor cells, instead of multipotent mother cells, are often involved in the formation of vertebrate body structures (Lehoczky et al., 2011; Park et al., 2012). This issue is of particular interest with respect to the NC, because this structure represents one of the cell populations in the vertebrate embryo with the broadest developmental potential (Le Douarin et al., 2008). Several studies demonstrated that at least upon isolation, the majority of NC cells display stem cell features, being multipotent and able to self-renew (Dupin and Sommer, 2012). Others, however, reported the presence of many lineage-restricted cells in NC cell cultures (Harris and Erickson, 2007; Henion and Weston, 1997), suggesting that multipotency might be dependent on or even induced by culture conditions. The recent establishment of transgenic mouse lines allowing low-density genetic recombination makes it possible to trace the lineage of single cells without the need to expose the cells to varying conditions. For instance, the *R26R-Confetti* reporter was used to track cells in the postnatal gut (Snippert et al., 2010). Here we applied this system to demonstrate that in vivo the NC cell population is primarily composed of multipotent cells rather than of a mixture of lineage-restricted precursors.

The *R26R-Confetti* mouse model offers the possibility to distinguish several clones from each other in the same specimen. Importantly, clonal analysis can be made in this system without prior cell isolation, transplantation, or any disturbance of the cellular microenvironment that might reactivate a ''stemness'' program (Snippert and Clevers, 2011). However, like in all retrospective lineage-tracing studies, redundant recombination events have to be excluded in the *R26R-Confetti* system to ensure clonal identification. To this end, we took advantage of the fact that theoretically equiprobable fluorescent protein combinations were expressed at different frequencies. In *Wnt1-CreER^{T}* mice, we were able to monitor the development of single premigratory NC cells at a low clonal density in vivo and to compare their fates with those of migratory *Sox10-CreER^{T2}*-traced NC cells. Surprisingly, the range of fates and clonal distribution was very similar for these two settings. Most clones were distributed over several NC target structures and only in a minority of cases premigratory and migratory NC cells were fate restricted. Importantly, our statistical evaluation revealed a very high probability for multipotency, independent of color expression and recombination density. Moreover, subjecting our statistical evaluation to a sensitivity assay by altering multiple parameters, such as expected clone sizes and dimensions of the NC derivatives, confirmed the robustness of our method and the finding that most NC cells are multipotent.

Furthermore, the vast majority of clonal derivatives were not only spread over distinct locations but also acquired distinct fates within given target structures. In particular, combining quantitative clonal assays with expression analysis of differentiation markers showed that the majority of NC cells, at least at the early stages analyzed, can neither be divided into ''sensory-only'' versus ''sympathetic-only,'' nor into ''neuron-only'' versus ''glia-only'' precursors.

In chicken embryos, DLP-colonizing NC cells are separate from ventrally migrating cells and belong to a late emigrating population (Erickson et al., 1992; Henion and Weston, 1997). We did not address here whether late emigrating NC cells exclusively destined to the DLP exist in mice. However, all clones with DLP contribution were multipotent in our study and contained cells in at least one ventral derivative. Thus, even after their emigration from the dNT, at least some mouse NC cells that will generate DLP derivatives maintain the potential to produce ventral neural cells.

Previous studies proposed that premigratory NC cells of the trunk are fate restricted (Krispin et al., 2010; Nitzan et al., 2013). This result differed from earlier work that indicated the presence of multipotent premigratory NC cells, including ''resident'' precursor cells for both CNS and NC in the dorsal neuroepithelium (Bronner-Fraser and Fraser, 1988; Bronner-Fraser and Fraser, 1989). These discrepancies might have been due to technical challenges and to differences in the stages and location of the labeled premigratory NC cells in the dNT. Although we cannot exclude differences in mechanisms of lineage segregation between avian and mammalian systems, our findings support the model in which the majority of NC cells are multipotent not only at the population but also at the single cell level and that multipotency is maintained in NC cells even after their emigration from the neural tube. However, we cannot rigorously exclude the existence of fate-restricted NC cells, as we found a minority of NC cells that appeared to give rise to only one derivative. It is therefore possible that the NC cell population contains a fraction of fate-restricted cells.

Even though most NC cells were multipotent in our study, the actual cell type composition varied in each clone, with some multipotent clones acquiring all possible fates and others producing only two cell types. This reflects the heterogeneous behavior of NC cells also seen in cell culture conditions permissive for multiple fates, where multipotency is frequently observed, but not fully realized by all cells (see e.g., Dupin et al., 2010; Stemple and Anderson, 1992). This heterogeneous behavior can be switched to a virtually homogeneous response when NC cells are exposed to instructive growth factors either in vitro (Shah et al., 1994) or in vivo (Hari et al., 2012). It remains to be shown whether, normally, fate choices by multipotent NC cells in vivo are purely stochastic.

Of note, we did not observe a pattern of restricted fate choices when we compared migratory with premigratory NC cells, speaking against gradual lineage restriction during NC development (Krispin et al., 2010; Le Douarin et al., 2008) at least during the time window analyzed. Therefore, the multiple and variable fates adopted by NC cells appear to reflect the dynamic behavior of stem cells in vertebrates as opposed to more deterministic lineage acquisitions observed in species such as *C. elegans* (Morrison et al., 1997).

Upon recombination at the premigratory stage, we found clones with recombined cells retained in the dNT, in addition to cells in NC derivatives. This may suggest an asymmetric division of NC cells and that a resident ''stem cell'' population is established in the dorsal midline. Moreover, multipotency was maintained in migratory NC cells. Together, these findings are consistent with the hypothesis that NC stem cells (NCSCs) as originally characterized in cell culture (Stemple and Anderson, 1992) might not only be in vitro stem cells (Smith, 2006) but actually exist

in vivo. In support of this hypothesis, undifferentiated NC-derived cells in the sciatic nerve were shown before to be able to self-renew in vivo and to maintain their multipotency as revealed upon isolation (Morrison et al., 1999). However, to demonstrate self-renewal and maintenance of multipotency by single NC cells in vivo without cell isolation or disturbing the cellular microenvironment would be technically challenging due to the dissemination of NC cells within a short time period. Concluding, our study demonstrates that the majority of NC cells are multipotent, both at the premigratory and at the migratory stage.

EXPERIMENTAL PROCEDURES

Mice

Mice homozygous for the *R26R Confetti* allele (Snippert et al., 2010) were crossed with the two inducible mouse lines *Wnt1-CreER^T* (Zervas et al., 2004) and *Sox10-CreER^{T2}* (Simon et al., 2012). All the embryos used in the analyses were derived from a 2 hr time-mating. Lineage tracing of premigratory NC cells at low and high recombination densities was achieved with pregnant *Wnt1-CreER^T R26R-Confetti* homozygous females, injected at E9.0. The animals were injected intraperitoneally (i.p.) with a single limiting dose of 7.5 μg and 50 μg TM/g body weight for low and high recombination densities, respectively. Similarly, to recombine migratory NC cells, we injected i.p. pregnant *Sox10-CreER^{T2} R26R-Confetti* homozygous animals at E9.0 with a single dose of 50 μg or 150 μg TM/g body weight to induce low or high recombination densities, respectively. Finally, embryos were collected at E10.5, 41 hr post-TM injection. Animal experiments were approved by the veterinary office of the Canton of Zurich, Switzerland.

Microscopy

Images were acquired using a Leica CTR600 microscope and a Confocal Laser Scanning Microscopy (Leica CLSM SP5). For the Rosa four-color imaging, scans were performed in a series for fluorescent protein excitation as described in Snippert et al. (2010).

Data Analysis

The data analysis was performed using R version 3.1.1. R Development Core Team (http://www.R-project.org).

SUPPLEMENTAL INFORMATION

Supplemental Information includes four figures, two tables, two movies, and Supplemental Experimental Procedures and can be found with this article online at http://dx.doi.org/10.1016/j.stem.2015.02.017.

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