**PiggyBac** transgenic strategies in the developing chicken spinal cord

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**ABSTRACT**

The chicken spinal cord is an excellent model for the study of early neural development in vertebrates. However, the lack of robust, stable and versatile transgenic methods has limited the usefulness of chick embryos for the study of later neurodevelopmental events. Here we describe a new transgenic approach utilizing the **PiggyBac** (PB) transposon to facilitate analysis of late-stage neural development such as axon targeting and synaptic connection in the chicken embryo. Using PB transgenic approaches we achieved temporal and spatial regulation of transgene expression and performed stable RNA interference (RNAi). With these new capabilities, we mapped axon projection patterns of V2b subset of spinal interneurons and visualized maturation of the neuromuscular junction (NMJ). Furthermore, PB-mediated RNAi in the chick recapitulated the phenotype of loss of agrin function in the mouse NMJ. The simplicity and versatility of PB-mediated transgenic strategies hold great promise for large-scale genetic analysis of neuronal connectivity in the chick.

**INTRODUCTION**

The vast diversity of neuronal cell types exhibiting highly complex synapses present significant challenges to defining molecular mechanisms that promote assembly of specific synaptic connectivity in the vertebrate central nervous system. Unlike genetic powerhouses such as *Drosophila melanogaster* and *Caenorhabditis elegans*, vertebrate model organisms largely lack appropriate genetic tools to analyze neuronal connectivity. Recent pioneering studies demonstrated the feasibility and utility of analyzing neuronal connectivity using fluorescent protein-labeled genetic mosaics in mice (1–5). However, these approaches require generating individual transgenic mouse lines and therefore are not amenable to high-throughput analysis.

The chicken embryo has been widely used for studying early embryogenesis because of its ready availability and accessibility to various manipulations (6). During the past decade, *in ovo* electroporation and avian recombinant retrovirus expression systems have significantly contributed to rapid progress in the understanding of early neural developmental events such as neurogenesis, patterning and migration (7–13). By contrast, progress in the analysis of late development of axon targeting and synapse formation has been somewhat less due to technical limitations with these approaches. To overcome these limits and to increase the throughput of genetic analysis in the chicken embryo, we aimed at developing a simple, efficient and stable transgenic approach to study gene function in the developing chicken spinal cord.

**PiggyBac** (PB) is a highly efficient transposon originally isolated from *Trichoplusia ni* (14). PB has been subsequently shown to be functional in many different species including fly and mouse (15,16). The precise ‘cut and paste’ transposition mechanism makes PB a powerful tool for mutagenesis and transgenic manipulation (16–22). Unlike recombinant retroviral systems, PB can accommodate relatively large DNA fragments without compromising transposition efficiency (16). In addition, PB has two potential advantages over other transposon systems such as *Sleep Beauty* (SB) and *Tol2*. First, PB exhibits significantly higher transposition efficiency in mammalian cells (23). Second, multiple copies of PB can incorporate into the host genome (16,21) providing for the possibility of multiple simultaneous manipulations of the host genome. For these reasons, we decided to develop PB-mediated transgenic approaches to facilitate the analysis of neuronal connectivity in the spinal cord.

Here we show that, in combination with *in ovo* electroporation, PB-mediated transgenics is highly efficient for the chicken embryo. PB transgenic approaches are compatible with heterologous promoters and Cre/loxP technology that enable temporal control of transgene expression and cell-type-specific labeling. In addition, PB transgenes stably express small hairpin RNAs (shRNAs) that enable robust loss of function analysis to be performed in the chick. As proof of principle, we recapitulate...
the neuromuscular junction (NMJ) defects observed in agrin mutant mice using shRNAs in the chick. Thus, PB transgenics is an efficient and versatile approach that can be used for large-scale circuit mapping and functional analysis of the vertebrate nervous system.

**MATERIALS AND METHODS**

**Plasmid construction**

All expression vectors used in this study were constructed by cloning restriction enzyme digested or PCR amplified DNA fragments with standard protocol. *Firefly* and *Renilla luciferase* expression vectors were originally obtained from Promega. *EGFP*, destabilized *GFP* and *DsRed* vectors were derived from Clontech (*pEGFP-N1, pd2EGFP, pDsRedN2*). The PiggyBac and PBase expressing vectors were described previously (21). *pCYL50*, a PB vector containing multiple cloning sites, was used as the parental plasmid to construct all PB derivatives. Annealed double strand oligos encoding shRNAs were cloned downstream of human H1 promoter between BbsI and XhoI sites in a PB vector. To construct *CMV-Fflucl-agrin* reporter, a 650 bp cDNA fragment corresponding to the shared exons of alternatively spliced chicken agrin transcripts was amplified by RT-PCR from HH 30 chicken neuronal RNAs. This agrin cDNA fragment was then digested with EcoRI and cloned into the *CMV-Fflucl* vector. All vectors in this study are summarized in Supplementary Table S1. All cloning was verified by complete or partial sequencing.

**Cell culture and transfection**

DF-1 chicken fibroblast cells were maintained in Dulbecco’s Modified Eagle’s Medium with 10% fetal bovine serum. Cells were transfected with Lipofectamine 2000 (Invitrogen). To test the relative knockdown efficiency of *agrin* shRNAs, DF-1 cells in a 24-well plate were cotransfected with *CMV-Fflucl-agrin* reporter (0.3 μg per well), *Renilla luc* (0.1 μg per well) and individual effector shRNAs (0.3 μg per well) against chicken agrin. For luciferase assay, transfected cells were passaged every 2 days and harvested in passive lysis buffer (PLB, Promega).

**Splinkerette PCR**

To identify PB transposition sites in chicken cells, DF-1 cells were transfected with PB-PGK-Hyg and PBase at a ratio of 2:1 in six-well plates using Lipofectamine 2000 protocol. Twenty-four hours after transfection, 5 × 10⁴ cells were plated on 10 cm dish with Hygromycin (300 μg/ml) selection until visible clones were growing. Genomic DNA was prepared from individual clones and Splinkerette PCR was performed as described previously (21,24). Unique PCR products were TA-cloned for sequencing.

**Chicken embryo electroporation**

*In ovo* electroporation was performed as previously described (25,26). In brief, fertilized white leghorn chicken eggs were incubated at 38°C until HH stage 12 prior to electroporation. Mixtures of plasmids were injected into the central canal of the neural tube and electroporation was performed in the thoracic segment of spinal cord with 5 pulses at 25V, 50 ms each. For electroporation, endotoxin-free plasmid DNA (4 μg/μl) was mixed with 1/10 volume of fast green for micro-injection. For PB transposition, a 2:1 ratio of transposon and transposase was used in all experiments. For activation of *ERT2CreERT2* transgene, 500 μl 4-hydroxytamoxifen (4-OHT, Sigma) at a concentration of 100 mM was dropped on individual chicken embryos. All electroporation experiments were repeated for at least three times with multiple (6–12) chicken embryos.

**Immunohistochemistry and in situ hybridization**

For immunohistochemistry, chicken embryonic tissues were dissected and fixed for 2 h in 4% paraformaldehyde. After extensive PBS washes and cryo-protection with 30% sucrose, samples were embedded in OCT and 12 μm cryostat sections were processed for indirect immunofluorescence staining. The following primary antibodies were used in this study: Mouse anti-GATA3 (1:100, Santa Cruz), Rabbit anti-Myc (1:2000, Sigma), Mouse anti-Flag M2 (1:2000, Sigma), Mouse anti-Iset1/2 (1:100, DSHB), Mouse anti-GFAP (1:1000, Sigma), Rabbit anti-LacZ (1:1000, Chemicon), Rabbit anti-GFP (1:2000, Invitrogen) and Goat anti-luciferase (Promega).

*In situ* hybridization was performed as previously described (27). A chicken agrin cDNA fragment was cloned into the pCR4-TOPO vector and the antisense riboprobe was labeled using digoxigenin-11-UTP (Roche) with T7 RNA polymerase (Roche). Twenty micrometer cryostat sections of shRNA electroporated chicken embryos were used for *in situ* hybridization, and the hybridization signals were visualized with POD-coupled anti-digoxigenin antibody (Roche) and a fluorescent substrate from a Cy3-TSA-plus kit (Perkin Elmer).

**Whole mount staining of NMJ**

To visualize NMJ in gastrocnemius muscles, small muscle bundles were dissected under fluorescent microscope and stained with α-bungatoxin conjugated with Texas Red (1:5000, Molecular Probe) overnight at 4°C. Images were captured on a Zeiss Confocal microscope PASCAL.

**RESULTS**

**PB-mediated transgene expression in the developing chicken spinal cord**

To test the efficacy of PB-mediated transposition in the chicken cells, we cotransfected DF-1 chicken fibroblast cells with a PB transposon that expresses firefly luciferase (PB-FF) and a non-PB *Renilla luciferase* vector (*CMV-Rn*) in the presence of the transposase helper plasmid
CAG-PBase) or negative control (CMV-LacZ) (Figure 1A). The PBase helper plasmid utilizes a CAG promoter to ubiquitously express PBase in trans but itself is transiently expressed at the time of transfection due to the lack of the inverted repeats from PB transposon (21). Dual luciferase assays showed that Ff/Rn luciferase ratios in PBase-cotransfected cells dramatically increased after several passages, demonstrating that PBase was stably integrated into the transfected cells whereas CMV-Rn plasmid was lost over multiple cell divisions (Figure 1B).

Similar results were obtained with a PB version of Rn luciferase and a non-PB Ff luciferase expression vectors (data not shown). Because avian genomes have a very different evolutionary history comparing to mammals, we used Splinkerette PCR to clone a small number of PB transposition sites from stably transfected chicken DF-1 cells. Sequence analysis confirmed that PB transposons integrate at the same TTAA sequence in chicken cells (Supplementary Table S2). Therefore, PB transposon system can efficiently produce stably transfected chicken cells.
In ovo electroporation has been widely used to transiently introduce transgenes into chicken embryos (9). Thus, we next tested whether we could combine the PB transposon with in ovo electroporation to perform long-term transgenic studies in chicken embryos. The chicken neural tubes were electroporated with PB-Ff and CMV-Rn plasmids at stage 12 (around embryonic day 2). The coexpression of PBase increased Ff/Rn ratios about 10-fold at later developmental stages (Figure 1C), suggesting that PB transgenes are stably integrated into the host genome.

To test whether higher luciferase activity results from more expressing cells or a higher level of expression per cell, we constructed a PB that expresses destabilized GFP proteins. When co-introduced with PBase, the electroporated chicken spinal cords were rapidly and highly labeled with GFP (Figure 1D and E). At early developmental stages, robust GFP labeling was seen in both PB and non-PB transgenic embryos due to transient transfection. The PB-GFP electroporated spinal cords remained strongly labeled by GFP throughout embryonic development, whereas few GFP labeled cells were present in PBase-negative chicken embryos as development proceeded to later stages (Figure 1F). Although we routinely obtain nearly 80–90% GFP-labeled cells 2 days after electroporation, electroporation efficiency slightly varies among individual embryos. To rule out the possibility that the difference in electroporation efficiency might have contributed to different levels of destabilized GFP observed in Figure 1F, we co-expressed Myc-tagged and Flag-tagged destabilized GFP in either PB or non-PB vectors. Tagged GFP signals from PB vectors were much more robust than those from non-PB controls throughout embryonic development (Supplementary Figure S1). In PB-GFP labeled hemi-spinal cords, GFP positive cells consist of both progenitors in the ependymal zone as well as postmitotic cells in mantle zone and marginal zone (Figure 1F and Supplementary Figure S1). By contrast, in non-PB transgenic samples, GFP positive cells are usually concentrated in the ventral motor neurons at later developmental stages (Figure 1F and Supplementary Figure S1). Thus, PB-mediated transposition allows persistent transgene expression in different cell types of the developing chicken spinal cord.

We next evaluated whether PB-mediated transposition has an adverse effect on spinal cord development. Approximately 90% of embryos survived at day 4 after electroporation whether embryos were co-electroporated with PB-GFP transposon and PBase or with PB-GFP transposon alone. Immunostaining of precursor marker (Sox2), motor neuron marker (Islet 1/2), interneuron marker (Nkx2.2) and differentiation marker (NF) showed that stable integration of PB-GFP transgenes did not alter spinal cord development at E8 or E20 (Supplementary Figure S2), thus allowing us to further explore the application of PB in the chicken spinal cord.

**Temporal regulation of PB transgene expression**

Constitutive early activation of transgene expression might preclude analysis of late developmental events. Therefore, we decided to establish temporal regulation of PB transgene expression using a previously characterized ERT2CreERT2-loxP inducible system (28). Because multiple copies of PB transposon can simultaneously integrate into different loci of the host genome, we constructed two independent PB transposons that express ERT2CreERT2 and floxed GFP reporter, respectively (Figure 2A). By introducing these two PB transposons with PBase into the chicken spinal cord, ERT2CreERT2-mediated excision led to tightly controlled GFP expression by 4-hydroxytamoxifen (4-OHT) administration at specific developmental stages (Figure 2B) with virtually no leaky GFP expression observed. Residual red fluorescent signals after 4-OHT induction were likely due to the stability of DsRed proteins (Figure 2B). When a similar experiment was performed with Ff-luc floxed GFP reporter, Ff-luc signals were mostly lost after 7-day treatment with 4-OHT (Supplementary Figure S3). Thus, our results indicate that ERT2CreERT2-loxP based binary PB systems robustly regulate the onset of transgene expression in chicken embryos.

**Cell-type-specific control of PB transgene expression**

Approaches to label specific cell types are highly desirable for genetic studies of neural development. Therefore, we asked whether we could use PB transposon system to label a specific cell type during development. Glial fibrillary acidic protein (GFAP) is an intermediate filament protein expressed almost exclusively in astrocytes. GFAP normally begins to express during late embryonic development. Thus, in the chicken spinal cord, GFAP expression is detectable at E15 and become more robust at E19 and E21 (Figure 3B, left panels). The 3-kb upstream sequences of gfap genes from different vertebrate species are highly conserved and the gfap promoter is known to direct astrocyte-specific expression even across different species (29). Because GFAP is expressed in astrocytes late in development, conventional plasmid electroporation is unlikely to yield cell-specific expression (Figure 3B, middle panels). Thus, we constructed a PB transposon in which GFP is under the control of 2.7-kb mouse gfap promoter (Figure 3A). When introduced by electroporation with PBase, robust GFP expression was concomitant with the endogenous GFAP (Figure 3B, right panels). All GFP positive cells are positive for endogenous GFAP (Figure 3C); however, not all GFAP cells are positive for GFP. This is likely due to that PB transposition is <100% after electroporation. Alternatively, the proximal GFAP promoter might lack additional regulatory element for a subset of GFAP-expressing cells. Thus, PB-gfap-GFP is expressed in an astrocyte-specific manner in the chicken spinal cord, demonstrating the utility of PB transposon to achieve cell-type-specific transgene expression.

Transcription factors that specify different neuronal subtypes in the spinal cord have been well characterized (30–33). Many cell-type-specific transcription factors are transiently expressed in a subpopulation of precursor cells at a specific developmental stage. At later developmental stages, expression of a given transcription factor might be
switched off or become less restricted to a specific neuron subtype. Therefore, we next developed a Cre-loxP-based strategy to label specific neuronal subtypes. In this design, a cell-type-specific promoter is used to drive Cre expression transiently in a subset of progenitors. Upon Cre expression, excision of a floxed reporter PB transgene gives rise to a permanent marker in daughter cells for cell lineage analysis (Figure 4A). It has been shown that Stem cell leukemia (Scl), a bHLH transcription factor, is expressed and required for specification of V2b interneurons in the spinal cord (34,35). Importantly, the conserved enhancer and promoter elements of Scl gene have been characterized in both chicken and mammals (36,37). Therefore, to test our strategy, we constructed a modified 5′Scl-Cre transgene (named −7E3/Cre) as described previously (36) (Figure 4A). When −7E3/Cre transgene was coelectroporated with a Cre reporter, PB-CAG-loxP-Luc-loxP-EGFP, a small number of interneurons were labeled with GFP in the ventral spinal cord (Figure 4B). Because majority of V2b interneurons coexpress Scl, GATA2 and GATA3 transcription factors during early embryonic stage and Scl antibodies suitable for immunohistochemistry are not available (34,38), we double-labeled cells for GATA3 and GFP to confirm that a majority of GFP-positive cells were indeed GATA3-positive at E6 (Figure 4C), indicating −7E3/Cre is specifically expressed in V2b interneurons.

We next analyzed the overall projection patterns of V2b interneurons using −7E3/Cre and the PB-CAG-loxP-Luc-loxP-EGFP reporter. We found that Scl-expressing cells comprise a heterogeneous population of neurons that exhibit complex projection patterns (Figure 4D–F). Some neuronal processes of Scl-expressing cells project contralaterally across the midline (Figure 4F: a and b, for transverse sections and c, for longitudinal sections) while other V2b axons appear to project both rostrally and caudally along the ipsilateral side of the spinal cord (see red arrow in Figure 4F: d, for branches and red asterisk in Fig. 4F: e, for a rostral growth cone). The overall projection patterns obtained by directly visualizing −7E3/Cre labeled neurons are consistent with known early ipsilateral axonal projection patterns obtained by fluorescein detran retrograde labeling of GATA2/3 positive cells (39). In addition, our direct GFP labeling method enables us to observe contralateral projections of neuronal processes across the midline that were not previously found with V2b interneurons. Thus, in combination with a PB-floxed reporter, a cell-specific Cre transgene provides a specific and sensitive way to visualize neuronal projection patterns.

**PB-mediated stable RNAi in the chicken spinal cord**

Transient electroporation of siRNA duplexes or shRNA plasmids have been used to study early spinal cord development (40,41). The stability of PB transgenes allows us to expand this line of loss-of-function study to late neural developmental events. To facilitate the use of stable RNAi in the chicken embryos, we developed a PB transposon that consists of human H1 promoter to express shRNA and CAG-EGFP to label transfected cells (Figure 5A). When PB-CAG-EGFP-H1-luc shRNA that expresses a control shRNA against Ff luciferase was stably transfected in the chicken spinal cord, motor axons innervating gastrocnemius muscle fibers were robustly...
labeled by GFP (Figure 5B). Because agrin knock-out leads to an obvious NMJ defect in the mouse (42), we chose agrin as an example to test the effectiveness of stable RNAi. We synthesized five pairs of agrin shRNAs against a common region of differently spliced chicken agrin transcripts (43). Using a luciferase construct that contains the agrin target sequences, we screened agrin shRNAs and identified the most effective shRNA construct (Supplementary Figure S3). We then introduced a stable PB-agrin-shRNA transgene into chicken neural tubes by electroporation with PBase and found the agrin mRNA levels were significantly down-regulated in the electroporation sides of the spinal cord by both RT-PCR and in situ hybridization techniques (Figure 5C and D). At later developmental stage E21, we visualized NMJ maturation in gastrocnemius muscle fibers by confocal microscopy. As expected, knock-down of agrin in spinal motor neurons by PB-agrin-shRNA caused abnormal NMJ formation. In agrin-shRNA expressed samples, acetylcholine receptor (AChR) clusters are fewer and more dispersed at the end-plate band (Figure 5E, lower panels) in comparison with a control (Figure 5E, upper panels). A stable shRNA transgene against agrin is able to recapitulate the NMJ defect seen in agrin knock-out mice. Thus, PB-mediated stable RNAi opens an avenue to perform loss-of-function studies on late neural developmental processes such as NMJ maturation in the chicken embryos.

**DISCUSSION**

In this study, we have shown that PB based transgenic approaches are highly efficient and versatile. The diverse PB transgenic constructs described here provide a starting point to implement this technique to perform gain-of-function and loss-of-function studies of late neural
developmental events in the chicken embryo. The PB transposon has important advantages over other methods in the chick. First, unlike plasmid electroporation, the PB transposon system allows stable, long-term expression of transgenes. Second, PB transposons can accommodate DNA inserts up to 18 kb circumventing the DNA size limit of avian retroviral RCAS system. The large capacity of PB transposons permits the independent regulation of multiple transcripts from one vector. Third, an electroporation based PB transgenic approach allows very rapid transgene expression in comparison with a recombinant lentiviral system. It usually takes 16 h for a lentivirus-transduced transgene to be expressed (44). Fourth, PB system is compatible with heterologous promoters and Cre/loxP technology and therefore permits temporal and cell-type-specific regulation of transgene expression. Fifth, PB transgenes that stably express shRNAs allow loss-of-function studies of late developmental events. Although a similar approach has been reported using the Tol2 transposon system in chicken embryos (45–47), a comparison of SB and PB transposons shows that PB is the most efficient transposon in cultured mammalian cells (23) and chicken cells (data not shown). Collectively, these characteristics make this PB based transgenic system superior to other methods for genetic analysis of chick neural development. The

Figure 4. PB-mediated labeling of V2b interneurons in the spinal cord. (A) A strategy to trace Scl-expressing cell lineage using PB transgenics. The −7E3/Cre transgene that consists of mouse 5′Scl promoter sequences transiently express Cre in Scl-expressing progenitors. Cre-mediated excision leads to GFP expression from PB-loxP-luc-loxP-EGFP reporter. Scl-expressing cells are permanently labeled with GFP because the PB reporter is stably integrated in the progenitors. (B) Activation of GFP expression by −7E3/Cre transgene in the chicken spinal cord. (C) GATA3 partially overlaps GFP positive cells labeled by −7E3/Cre transgene. (D) Schematic illustration of the projection patterns of V2b (Scl-expressing) interneurons in the spinal cord. The orientation of spinal cord and focal planes of confocal images of panel F a–e are marked. Turquoise: transverse section; Purple: longitudinal section. (E) A single Scl-expressing neuron labeled by GFP on a transverse spinal cord section. (F) The projection patterns of neuronal processes from GFP labeled V2b interneurons. a and b, transverse sections; c–e, longitudinal sections. Blue dotted line, midline. Bars are 100 μm in (F).
versatility of the PB system makes it easily adaptable for the study of other neuronal circuits in the chick, such as in the cerebellum or the visual system. Indeed, PB vectors have been successfully used to express large cDNAs such as DSCAM and Sidekicks in chick retina (48).

When PB transposons are used in combination with Cre-loxP recombination, one concern might be that Cre could induce deleterious chromosomal deletion, inversion and translocation between multiple loxP-containing transposons that are integrated into the genome. However, this does not appear to be a big concern for three reasons. First, although it is difficult to determine the number of PB transposons per cell in postmitotic spinal neurons, it is feasible to control the number of integration sites by titrating the amount of PB and PBase expression vectors (21). Second, PB transposons randomly integrate among 64~68 chicken chromosomes throughout the whole genome. Therefore, multiple PB
integrations are likely in trans. It has been previously shown that Cre-loxP recombination in trans is very inefficient that occurs at an ~0.1% frequency of cis-recombination events (49,50). Therefore, Cre-induced chromosomal abnormality should be rare. Third, individual transfected cells in a complex pool likely have completely different PB integration sites, thus rare chromosomal abnormality would only happen in a very small population of transfected cells. At the practical level, this could be overcome by increasing sample size.

There are a couple of avenues to expand the utility of PB system. Combined with other gene deliver methods, for example, in utero electroporation (51), PB transposon may also be used to achieve stable or cell-specific transgene expression in mouse embryos. Because the PB transposon can accommodate large DNA inserts and the PB vector is fully compatible with the BAC recombineering technique (52), it would be advantageous to develop a panel of cell-type-specific promoters in PB vectors to label distinct neuronal subtypes during development. Meanwhile, it would also be a useful to construct a variety of Cre-expressing BAC transgenes that can label specific cell types in conjunction with a floxed PB reporter. Accumulation of these reagents will significantly enhance our ability to perform cell-specific genetic manipulation using PB transgenic approaches.

Novel Brainbow transgenic mice have recently been pioneered to achieve the color-coding of individual cells through combinatorial expression of several fluorescent proteins (XFP) by stochastic action of Cre-loxP recombination (2). Conceptually, similar PB transposons that consist of Brainbow transgenes can be used to label individual neurons in conjunction with a Cre-expressing transgene (e.g. PB-CAG-ERT2CreERT2) by electroporation in ovo or in utero. Due to the large insert size that a PB can accommodate, it is feasible construct such a PB-Brainbow transgene. More importantly, if successful, PB application can simplify and increase the throughput of Brainbow transgenic approaches for mapping neuronal circuits in the brain.

For the vertebrate central nervous system, details of circuit maps and the genetic basis underlying circuit development have been largely missing. The idea of ‘connectomics’ to apply large-scale approaches to neural circuit mapping has been recently proposed (53). The development of PB transgenics described here is a new addition to the toolbox for such efforts.

**SUPPLEMENTARY DATA**

Supplementary Data are available at NAR Online.

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**REFERENCES**

1. Feng,G., Mellor,R.H., Bernstein,M., Keller-Peck,C., Nguyen,Q.T., Wallace,M., Nerbønne,J.M., Lichtman,J.W. and Sanes,J.R. (2000) Imaging neuronal subsets in transgenic mice expressing multiple spectral variants of GFP. Neuron, 28, 41–51.
2. Livet,J., Weissman,T.A., Kang,H., Draft,R.W., Lu,J., Bennis,R.A., Sanes,J.R. and Lichtman,J.W. (2007) Transgenic strategies for combinatorial expression of fluorescent proteins in the nervous system. Nature, 450, 56–62.
3. Zong,H., Espinosa,J.S., Su,H.H., Muzumdar,M.D. and Luo,L. (2005) Mosaic analysis with double markers in mice. Cell, 121, 479–492.
4. Young,P., Qui,L., Wang,D., Zhao,S., Gross,J. and Feng,G. (2008) Single-neuron labeling with inducible Cre-mediated knockout in transgenic mice. Nat. Neurosci., 11, 721–728.
5. Luo,L., Callaway,E.M. and Svyoboda,K. (2008) Genetic dissection of neural circuits. Neuron, 57, 634–660.
6. Stern,C.D. (2005) The chick; a great model system becomes even greater. Dev. Cell, 8, 9–17.
7. Itasaki,N., Bel-Vialar,S. and Krumlauf,R. (1999) ‘Shocking’ developments in chick embryology: electroporation and in ovo gene expression. Nat. Cell Biol., 1, E203–E207.
8. Momose,T., Tonegawa,A., Takeuchi,J., Ogawa,H., Umesono,K. and Yasuda,K. (1999) Efficient targeting of gene expression in chick embryos by microelectroporation. Dev. Growth Differ., 41, 335–344.
9. Nakamura,H., Katarhia,T., Sato,T., Watanabe,Y. and Funahashi,J. (2004) Gain- and loss-of-function in chick embryos by electroporation. Mech. Dev., 121, 1137–1143.
10. Voiculescu,O., Papanyotou,C. and Stern,C.D. (2008) Spatially and temporally controlled electroporation of early chick embryos. Nat. Protoc., 3, 419–426.
11. Federspiel,M.J. and Hughes,S.H. (1997) Retroviral gene delivery. Methods Cell Biol., 52, 179–214.
12. Cepko,C.L., Fields-Berry,S., Ryder,E., Austin,C. and Golden,J. (1998) Lineage analysis using retroviral vectors. Curr. Top Dev. Biol., 36, 51–74.
13. Chen,C.M., Smith,D.M., Peters,M.A., Samson,M.E., Zitz,J., Tabin,C.J. and Cepko,C.L. (1999) Production and design of more effective avian replication-incompetent retroviral vectors. Dev. Biol., 214, 370–384.
14. Cary,L.C., Goebel,M., Corsaro,B.G., Wang,H.G., Rosen,E. and Fraser,M.J. (1989) Transposon mutagenesis of baculoviruses: analysis of Trichoplusia ni transposon IFP2 insertions within the FP-locus of nuclear polyhedrosis viruses. Virology, 172, 156–169.
15. Lobo,N., Li,X. and Fraser,M.J. Jr. (1999) Transposition of the piggyBac element in embryos of Drosophila melanogaster, Aedes aegypti and Trichoplusia ni. Mol. Gen. Genet., 261, 803–810.
16. Ding,S., Wu,X., Li,G., Han,M., Zhuang,Y. and Xu,T. (2005) Efficient transposition of the piggyBac (PB) transposon in mammalian cells and mice. Cell, 122, 473–483.
17. Fraser,M.J., Csizszon,T., Eick,T. and Bauser,C. (1996) Precise excision of TTAAT-specific lepidopteran transposons piggyBac (IF2) and tagalong (TFF3) from the baculovirus genome in cell lines from two species of Lepidoptera. Insect Mol. Biol., 5, 141–151.
18. Handler,A.M. and Harrell,R.A. H (1999) Germline transformation of Drosophila melanogaster with the piggyBac transposon vector. Insect Mol. Biol., 8, 449–457.
19. Thibault,S.T., Singer,M.A., Miyazaki,W.Y., Milash,B., Dompé,N.A., Singh,C.M., Buchholz,R., Demskey,M., Fawcett,R., Francis-Lang,H.L. et al. (2004) A complementary transposon tool kit for Drosophila melanogaster using P and piggyBac. Nat. Genet., 36, 283–287.
20. Wu,S., Ying,G., Wu,Q. and Capecchi,M.R. (2007) Toward simpler and faster genome-wide mutagenesis in mice. Nat. Genet., 39, 922–930.

21. Wang,W., Lin,C., Lu,D., Ning,Z., Cox,T., Melvin,D., Wang,X., Bradley,A. and Liu,P. (2008) Chromosomal transposition of PiggyBac in mouse embryonic stem cells. Proc. Natl Acad. Sci. USA, 105, 9290–9295.

22. Woltjen,K., Michael,J.P., Moseni,P., Desai,R., Mileikovsky,M., Hamalainen,R., Cowling,R., Wang,W., Liu,P., Gertsenstein,M. et al. (2009) piggyBac transposition reprograms fibroblasts to induced pluripotent stem cells. Nature, 458, 766–770.

23. Wu,S.C., Meir,Y.J., Coates,C.J., Handler,A.M., Pelczar,P., Moisyadi,S. and Kaminski,J.M. (2006) piggyBac is a flexible and highly active transposon as compared to sleeping beauty, Tol2, and Mos1 in mammalian cells. Proc. Natl Acad. Sci. USA, 103, 15008–15013.

24. Trombly,M.I., Su,H. and Wang,X. (2009) A genetic screen for components of the mammalian RNA interference pathway in Bloom-deficient mouse embryonic stem cells. Nucleic Acids Res., 37, e34.

25. Nakamura,H. and Funahashi,J. (2001) Introduction of DNA into chick embryos by in ovo electroporation. Methods, 24, 43–48.

26. Chen,J., Lu,Y., Meng,S., Han,M.H., Lin,C. and Wang,X. (2009) Toward simpler transgenes introduced by in vivo electroporation. Proc. Natl Acad. Sci. USA, 104, 1027–1034.

27. Brenner,M., Kiseberth,W.C., Su,Y., Besnard,F. and Messing,A. (1994) GFAP promoter directs astrocyte-specific expression in transgenic mice. J. Neurosci., 14, 1030–1037.

28. Dalla Torre di Sanguinetto,S.A., Dasen,J.S. and Arber,S. (2008) Transcriptional mechanisms controlling motor neuron diversity and connectivity. Curr. Opin. Neurobiol., 18, 36–43.

29. Stepien,A.E. and Arber,S. (2008) Probing the locomotor conundrum: descending the ‘V’ interneuron ladder. Neuron, 60, 1–4.

30. Shirasaki,R. and Pfaff,S.L. (2002) Transcriptional codes and the control of neuronal identity. Annu. Rev. Neurosci., 25, 251–281.

31. Jessell,T.M. (2000) Neuronal specification in the spinal cord: inductive signals and transcriptional codes. Nat. Rev. Genet., 1, 20–29.

32. Smith,E., Hargrave,M., Yamada,T., Begley,C.G. and Little,M.H. (2002) Coexpression of SCL and GATA3 in the V2 interneurons of the developing mouse spinal cord. Dev. Dyn., 224, 231–237.

33. Muroyama,Y., Fujiwara,Y., Orkin,S.H. and Rowitch,D.H. (2005) Specification of astrocytes by bHLH protein SCL in a restricted region of the neural tube. Nature, 438, 360–363.

34. Sinclair,A.M., Gottgens,B., Barton,L.M., Stanley,M.L., Pardanaud,L., Klaine,M., Gering,M., Bahn,S., Sanchez,M., Bench,A.J. et al. (1999) Distinct 5’ SCL enhancers direct transcription to developing brain, spinal cord, and endothelium: neural expression is mediated by GATA factor binding sites. Dev. Biol., 209, 128–142.

35. Muroyama,Y., Fujiwara,Y., Orkin,S.H. and Rowitch,D.H. (2005) Transcriptional mechanisms controlling motor neuron diversity and connectivity. Neuron, 451, 465–469.

36. Gottgens,B., Barton,L.M., Gilbert,J.G., Bench,A.J., Sanchez,M.J., Bahn,S., Mistry,S., Grafham,D., McMurray,A., Vaudin,M. et al. (2000) Analysis of vertebrate SCL loci identifies conserved enhancers. Nat. Biotechnol., 18, 181–186.

37. Peng,C.Y., Yajima,H., Burns,C.E., Zon,L.I., Sisodia,S.S., Pfaff,S.L. and Sharma,K. (2007) Notch and MAML signaling drives Scl-dependent interneuron diversity in the spinal cord. Neuron, 53, 813–827.

38. Chesshuber,C. and Niswander,L. (2004) Plasmid-based short-hairpin RNA interference in the chicken embryo. Genesis, 39, 73–78.

39. Pekarik,V., Bourikas,D., Miglino,N., Josef,P., Preiswerk,S. and Stercke,E.T. (2003) Screening for gene function in chicken embryo using RNAi and electroporation. Nat. Biotechnol., 21, 93–96.

40. Gautam,M., Noakes,P.G., Moscoso,L., Ruff,F., Scheller,R.H., Merlie,J.P. and Sanes,J.R. (1996) Defective neuromuscular synaptogenesis in agrin-deficient mutant mice. Cell, 85, 525–535.

41. Pekarik,V., Bourikas,D., Miglino,N., Josef,P., Preiswerk,S. and Stercke,E.T. (2003) Screening for gene function in chicken embryo using RNAi and electroporation. Nat. Biotechnol., 21, 93–96.

42. Bitgood,M., Noakes,P.G., Moscoso,L., Ruff,F., Scheller,R.H., Merlie,J.P. and Sanes,J.R. (1996) Defective neuromuscular synaptogenesis in agrin-deficient mutant mice. Cell, 85, 525–535.

43. Ruegg,M.A., Tsim,K.W., Horton,S.E., Kroger,S., Escher,G., Gensch,E.M. and McMahan,U.J. (1992) The agrin gene codes for a family of basal lamina proteins that differ in function and distribution. Neuron, 8, 691–699.

44. Pointner,G. and Lansford,R. (2007) Generating transgenic quail using lentiviruses. Methods Cell Biol., 87, 281–293.

45. Sato,Y., Katsai,T., Nakagawa,S., Tanabe,K., Watanabe,T., Kawakami,K. and Takahashi,Y. (2007) Stable integration and conditional expression of electroporated transgenes in chicken embryos. Dev. Biol., 305, 616–624.

46. Harada,H., Takahashi,Y., Kawakami,K., Ogura,T. and Nakamura,H. (2008) Tracing retinal fiber trajectory with a method of transposon-mediated genomics in chick embryos. Dev. Growth Differ., 50, 697–702.

47. Tanabe,K., Takahashi,Y., Sato,Y., Kawakami,K., Takeichi,M. and Nakagawa,S. (2006) Cadherin is required for dendritic morphogenesis and synaptic terminal organization of retinal horizontal cells. Development, 133, 4085–4096.

48. Yamagata,M. and Sanes,J.R. (2008) Dscam and Sidekick proteins direct lamina-specific synaptic connections in vertebrate retina. Nature, 451, 465–469.

49. Zheng,B., Sage,M., Shepeard,E.A., Juretic,Y. and Bradley,A. (2000) Engineering mouse chromosomes with Cre-loxP: range, efficiency, and somatic applications. Mol. Cell Biol., 20, 648–655.

50. Ramirez-Solis,R., Liu,P. and Bradley,A. (1995) Chromosome engineering in mice. Nature, 378, 720–724.

51. Tabata,H. and Nakajima,K. (2001) Efficient in utero gene transfer system to the developing mouse brain using electroporation: visualization of neuronal migration in the developing cortex. Neuroscience, 103, 865–872.

52. Copeland,N.G., Jenkins,N.A. and Court,D.L. (2001) Recombineering: a powerful new tool for mouse functional genomics. Nat. Rev. Genet., 2, 769–779.

53. Lichtman,J.W. and Sanes,J.R. (2008) Ome sweet ome: what can the genome tell us about the connectome? Curr. Opin. Neurobiol., 18, 346–353.