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Quantitative assessment of *Fgfr1* expression in Neurons and Glia

Lisha Choubey [1] , **Jantzen C Collette** [1] , **Karen Muller Smith** Corresp. [1]

[1] Department of Biology, University of Louisiana at Lafayette, Lafayette, LA, United States of America

Corresponding Author: Karen Muller Smith
Email address: karenmsmith@gmail.com

Fibroblast growth factors (FGFs) and their receptors (FGFRs) have numerous functions in the developing and adult CNS. For example, the FGFR1 receptor is important for proliferation of radial glial cells in the cortex and hippocampus, oligodendrocyte proliferation and regeneration, midline glia morphology and soma translocation, Bergmann glia morphology, and cerebellar morphogenesis. In addition, FGFR1 signaling in astrocytes is required for postnatal maturation of interneurons expressing parvalbumin (PV). FGFR1 is implicated in synapse formation in the hippocampus, and alterations in the expression of *Fgfr1* and its ligand, *Fgf2* accompany major depression. Understanding which cell types express *Fgfr1* during development may elucidate its roles in normal development of the brain as well as illuminate possible causes of certain neuropsychiatric disorders. Here, we used a BAC transgenic reporter line to trace *Fgfr1* expression in the developing murine CNS. The specific transgenic line employed was created by the GENSAT project, *tgFGFR1-EGFPGP338Gsat*, and includes a gene encoding enhanced green fluorescent protein (*EGFP*) under the regulation of the *Fgfr1* promoter, to trace *Fgfr1* expression in the developing CNS. This model reveals that *Fgfr1* is primarily expressed in glial cells, in both astrocytes and oligodendrocytes, along with some neurons. Dual labeling experiments indicate that the proportion of GFP+ (*Fgfr1*+) cells that are also GFAP+ increases from postnatal day 7 (P7) to 1 month, illuminating dynamic changes in *Fgfr1* expression during postnatal development of the cortex. In postnatal neurogenic areas, GFP expression was also observed in SOX2, doublecortin (DCX), and brain lipid-binding protein (BLBP) expressing cells. *Fgfr1* is also highly expressed in DCX positive cells of the dentate gyrus, but not in the rostral migratory stream. *Fgfr1* driven GFP was also observed in tanycytes and GFAP+ cells of the hypothalamus, as well as in Bergmann glia and astrocytes of the cerebellum. Understanding which cell types express *Fgfr1* may elucidate its role in neuropsychiatric disorders and brain development.

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Short title: *Fgfr1* expression in Neurons and Glia

Lisha Choubey[1], Jantzen Collette[1], Karen Müller Smith[1*]

1. Department of Biology, University of Louisiana at Lafayette, Lafayette, LA, USA

*Corresponding author

Email: karen.smith@louisiana.edu (KMS)

Running head: *Fgfr1* is expressed in neurons and glia

Key words: Fibroblast Growth Factor, astrocyte, oligodendrocyte, doublecortin, SOX2, cortex, hippocampus, SVZ

Abstract

Background. Fibroblast growth factors (FGFs) and their receptors (FGFRs) have numerous functions in the developing and adult CNS. For example, the FGFR1 receptor is important for proliferation of radial glial cells in the cortex and hippocampus, oligodendrocyte proliferation and regeneration, midline glia morphology and soma translocation, Bergmann glia morphology, and cerebellar morphogenesis. In addition, FGFR1 signaling in astrocytes is required for postnatal maturation of interneurons expressing parvalbumin (PV). FGFR1 is implicated in synapse formation in the hippocampus, and alterations in the expression of *Fgfr1* and its ligand, *Fgf2* accompany major depression. Understanding which cell types express *Fgfr1* during development may elucidate its roles in normal development of the brain as well as illuminate possible causes of certain neuropsychiatric disorders.

Methods. Here, we used a BAC transgenic reporter line to trace *Fgfr1* expression in the developing postnatal murine CNS. The specific transgenic line employed was created by the GENSAT project, *tgFGFR1-EGFPGP338Gsat*, and includes a gene encoding enhanced green fluorescent protein (*EGFP*) under the regulation of the *Fgfr1* promoter, to trace *Fgfr1* expression in the developing CNS. Unbiased stereological counts were performed for several cell types in the cortex and hippocampus.

Results. This model reveals that *Fgfr1* is primarily expressed in glial cells, in both astrocytes and oligodendrocytes, along with some neurons. Dual labeling experiments indicate that the proportion of GFP+ (*Fgfr1*+) cells that are also GFAP+ increases from postnatal day 7 (P7) to 1 month, illuminating dynamic changes in *Fgfr1* expression during postnatal development of the cortex. In postnatal neurogenic areas, GFP expression was also observed in SOX2, doublecortin (DCX), and brain lipid-binding protein (BLBP) expressing cells. *Fgfr1* is also highly expressed

in DCX positive cells of the dentate gyrus, but not in the rostral migratory stream. *Fgfr1* driven GFP was also observed in tanycytes and GFAP+ cells of the hypothalamus, as well as in Bergmann glia and astrocytes of the cerebellum.

Conclusions. The *tgFGFR1-EGFPGP338Gsat* mouse model expresses GFP that is congruent with known functions of FGFR1, including hippocampal development, glial cell development, and stem cell proliferation. Understanding which cell types express *Fgfr1* may elucidate its role in neuropsychiatric disorders and brain development.

Introduction

Differential binding of Fgfs to Fgf receptor isoforms may confer a high degree of selectivity leading to signaling events that lead to a multitude of specific cellular responses (Fortin et al., 2005). Multiple *Fgf* ligands and three of the *Fgfrs* (Fgfr1, Fgfr2, and Fgfr3) are expressed in the CNS (el-Husseini et al., 1994, Belluardo et al., 1997, Bansal et al., 2003). This complex system of Fgfs and Fgfrs plays a pivotal role in the normal development, maturation, and function of the central nervous system (CNS) (Iwata and Hevner, 2009, Stevens et al., 2010b, Hebert, 2011). FGF signaling is implicated in patterning of the CNS, in determining neuronal and glial cell fate, in influencing cerebral cortex size through maintenance of radial glial stem cells, in cerebellar development, and in regional patterning of the neocortex and midbrain-hindbrain boundaries (Vaccarino et al., 1999, Fukuchi-Shimogori and Grove, 2001, Korada et al., 2002, Storm et al., 2003, Shin et al., 2004, Gutin et al., 2006, Smith et al., 2006,

Storm et al., 2006, Cholfin and Rubenstein, 2007, Muller Smith et al., 2008, Kang et al., 2009, Stevens et al., 2010a, Rash et al., 2011, Muller Smith et al., 2012, Rash et al., 2013, Kang et al., 2014, Smith et al., 2014).

Loss of FGFR1 function by *hGFAP-Cre*-induced deletion of $Fgfr1^{flox/flox}$ alleles in the dorsal telencephalon of mice results in decreased hippocampal size and volume, without altering hippocampal patterning, and also results in a reduction in the number of dividing progenitor cells of the ventricular zone and dentate gyrus (Ohkubo et al., 2004). The *hGFAP-Cre* transgene targets the radial glial of the dorsal telencephalon during mid neurogenesis (Ohkubo et al., 2004). *Fgfr1* mutants also exhibit a disruption in corpus callosum and hippocampal commissure due to abnormal midline glia development (Smith et al., 2006, Tole et al., 2006). The midline glial cells fail to undergo soma translocation and formation of the indusium griseum leading to midline commissural axon guidance defects (Smith et al., 2006). Furthermore, these mice exhibit postnatal loss of maturation in GABAergic interneurons expressing parvalbumin (PV) and exhibit behavioral hyperactivity (Muller Smith et al., 2008, Smith et al., 2014). Hyperactivity and a decrease in number of interneurons in the cortex co-occur in patients with schizophrenia, bipolar disorder, and Tourette syndrome (Benes et al., 2000, Volk et al., 2000, Kalanithi et al., 2005, Akbarian and Huang, 2006, Hashimoto et al., 2008, Kataoka et al., 2010, Gonzalez-Burgos et al., 2011, Volk and Lewis, 2013). Interestingly, *Fgfr1* expression was found to be increased in the prefrontal cortex of individuals with schizophrenia (Volk et al., 2016). Dual inactivation of floxed alleles of *Fgfr1* and *Fgfr2* with the *hGFAP-Cre* transgene results in abnormal cerebellar morphogenesis including reduced size of the cerebellum due to a defect in proliferation of both cerebellar glia and granule cell precursors, abnormal orientation and morphology of Bergmann glia, and loss of laminar architecture (Muller Smith et al., 2012). This phenotype is similar to that

observed in Fgf9 mutants (Lin et al., 2009). FGFRs are implicated in maintaining astrocytes in a non-reactive state, and in impeding glial scar formation (Kang et al., 2014). *Fgfr1* deletions targeted to oligodendrocyte lineages do not disrupt oligodendrocyte birth, but affect myelin sheath thickness, as well as remyelination and recovery in chronic demyelination models (Furusho et al., 2012, Furusho et al., 2015). Therefore, FGFR1 has important roles in glial function and development including stem cell proliferation, migration, morphology, and support of neural maturation..

FGF signaling is implicated as a contributing factor in affective disorders, including depression. Patients with major depressive disorder (MDD) and bipolar disorder have altered gene expression of FGFs and FGFRs (Evans et al., 2004, Gaughran et al., 2006). *In situ* hybridization revealed that mRNA for *Fgfr1,* and its ligand *Fgf2*, were both down regulated in the hippocampus of rats that had undergone the social defeat paradigm (Turner et al., 2008). Microinjections of FGF2 into the lateral ventricles of rats resulted in an increase in *Fgfr1* mRNA in the dentate gyrus within 24 hours post FGF2 injections and was accompanied by acute antidepressant-like effects in the force swim test (Elsayed et al., 2012). Intracerebroventricular infusions of FGF2 into mice were sufficient to block the anhedonia-like behavior caused by chronic unpredictable stress (CUS). Furthermore, intracerebroventricular infusions of FGF2 blocked CUS-induced inhibition of proliferating glia in the prefrontal cortex, and produced antidepressant actions in the novelty suppressed feeding test and forced swim test (Elsayed et al., 2012). Furthermore, increased anxiety, dysregulation of the hypothalamic pituitary axis and decreased hippocampal glucocorticoid receptor expression is observed in FGF2 knockout mice. These effects are reversible by administration of FGF2 (Salmaso et al., 2016). FGF22 and FGF7 are presynaptic organizing molecules that promote differentiation of excitatory and inhibitory

113 presynaptic terminals in the hippocampal CA3 region through combinatorial signaling of sets of
114 FGFRs (Umemori et al., 2004, Terauchi et al., 2010, Dabrowski et al., 2015). Given the data that
115 FGF2/FGFR1 signaling is important for the regulation of mood and affect, and that FGFR1
116 signaling may participate in synaptogenesis, a better understanding of the cell types expressing
117 *Fgfr1* is important to improving our understanding of its actions.

118 Previous estimates of *Fgfr1* expression have been derived from *in situ* hybridization
119 studies and from immunochemistry using antibodies against FGFR1 (Gonzalez et al., 1995,
120 Belluardo et al., 1997, Bansal et al., 2003, Ohkubo et al., 2004, Blak et al., 2005). In embryonic
121 mice, *Fgfr1* is strongly expressed in the hippocampal hem, choroid plexus, cortical ventricular
122 zone, and cortical midline (el-Husseini et al., 1994, Bansal et al., 2003, Ohkubo et al., 2004,
123 Smith et al., 2006). During brain development, expression of *Fgfr*s change within the
124 oligodendrocyte lineage in a spatial and temporal fashion (Bansal et al., 2003). *Fgfr1* is
125 expressed in all three stages: proliferation, migration, and differentiation of oligodendrocytes
126 (OL) (Fortin et al., 2005). An *in situ* hybridization study showed that *Fgfr1* is not expressed
127 where *Olig2*-positive and *Pdgfra*-positive OL progenitors arise in the ventral ventricular zone
128 (Bansal et al., 2003). In adult mice, the strongest *Fgfr1* expression is observed in the
129 hippocampus (Ohkubo et al., 2004). Based on a literature review, Turner and colleagues
130 surmised that neuronal populations in the adult hippocampus and cortex mostly express *Fgfr1*, in
131 contrast to other FGF receptors that are considered to be expressed primarily in glia (Turner et
132 al., 2012a).

133 Despite clear advances in our understanding of FGF signaling derived from *in situ*
134 hybridization, it suffers from poor cell-type resolution. Likewise, although
135 immunocytochemistry using antibodies raised to FGFR1 have proven to be important, cross-

reactivity to other FGFRs remains a concern. To circumvent these issues, we investigated *Fgfr1* expression in PV+ interneurons, employing a transgenic reporter line, *tgFGFR1-EGFPGP338Gsat* bacterial artificial chromosome (BAC), that was obtained from GENSAT, http://www.gensat.org (Smith et al., 2014). In this transgenic line, the gene encoding enhanced green fluorescent protein (*EGFP*) is regulated under the same promoter as *Fgfr1*. Thus, GFP fluorescence should indicate expression of genes encoding *Fgfr1*. We previously showed that in *tgFGFR1-EGFPGP338Gsat mice,* PV+ interneurons did not colocalize with GFP+ cells. Thus, the decrease in PV+ interneurons due to inactivation of *Fgfr1* occurs non-cell-autonomously (Smith et al., 2014). We also observed that a large number of glia appeared to express *Fgfr1* in adult mice. In the present study, we extend our studies and present a quantitative analysis of the relative expression of *Fgfr1* in neurons versus glial cells during postnatal development of the telencephalon. We show that *Fgfr1* is differentially expressed, primarily in GFAP+ astrocytes and OLIG2+ cells, with a minority of cells colocalizing with NeuN+ neurons. Furthermore, SOX2+ cells, BLBP+ cells and DCX+ cells in the cortex, hippocampus, subventricular zone (SVZ), and hypothalamus of mice are colocalized with the GFP signal, indicating that these cells also express *Fgfr1*.

Methods and Materials

Animals

Wild type Swiss Webster mice were crossed with mice expressing enhanced green fluorescent protein (EGFP) under the same promoter as *Fgfr1* (*tgFGR1-EGFPGP338Gsat*). The transgenic line, *tgFGR1-EGFPGP338Gsat* was generated from the GENSAT project (GENSAT.org) by microinjecting bacterial artificial chromosome with *Fgfr1* promoter driving

EGFP into the pronucleus of fertilized mouse eggs. GENSAT produces transgenic BAC-EGFP reporter and BAC-Cre recombinase driver mouse lines with the aim to map the expression of genes in the CNS of mice (Heintz, 2004). This line was obtained from the Mutant Mouse Resource Center (MMRRC.org) at UC Davis. This study was conducted in an ethical manner, utilizing the recommendations of The Guide for the Care and Use of Laboratory Animals of the National Institutes of Health. Animals were euthanized under the University of Louisiana at Lafayette IACUC committee APS numbers 2012-8717-046, 2013- 8717-053, 2014-8717 040, 2015-8717-033. Tissue collected for this study was performed under ketamine/xylazine cocktail for P7 and older animals.

Genotyping

The mice were genotyped by polymerase chain reaction (PCR) for GFP and through GFP screening with goggles containing a GFP filter (BLS LTD). For PCR based genotyping, tails of mice were collected and DNA was extracted from the tail using 50mM sodium hydroxide (95°C for 30 min), followed by neutralization with 1M TRIS (pH 7.6). Master mix for 1 reaction of PCR for amplifying *GFP* was created using 2.5 µl of 10x PCR buffer, 0.5 µl of 10mM dNTP mix, 1 µl of eGFP forward and reverse primer mix (Forward:AAGTTCATCTGCACCACCG and Reverse: TGCTCAGGTAGTGGT
TGTCG), 0.2 µl of 5 units/ µl Hot start Taq Polymerase and 18.8 µl of distilled water. Two microliters of DNA sample were added to 23 µl of Master mix per PCR tube and the samples were amplified in the Applied Biosystems 96 Well Thermocycler. In adult *tgFGR1-EGFPGP338Gsat* positive mice, we found we could reliably genotype mice due to GFP expression in the eye, using GFP goggles (available from BLS).

Immunostaining

P7 mice were anesthetized with ketamine/xylazine (100 mg and10mg per kg of body weight respectively) and euthanized by cervical dislocation. Brains were dissected out and in 4% PFA overnight. Adult mice were euthanized by cardiac perfusion under deep anesthesia (ketamine/xylazine as above). Mice were perfused with cold 1x Phosphate Buffered Saline (PBS) followed by 4% PFA in 1x PBS. Brains were post fixed overnight and cryoprotected as described above. Brains collected from P7 and one-month ages were cryprotected in 20% sucrose/1xPBS, and cryopreserved with exposure to dry ice and embedded in optimal cutting temperature (OCT) at the time of sectioning. The tissue was thick sectioned (50 µm, free floating) in a cryostat (Microm, HM 505 E) in a series of 10 vials containing 1xPBS. Samples were stored in PBS with 0.2% sodium azide at 4°C, and protected from light exposure.

Prior to antibody incubation, sections were blocked with 10% serum in PBS with 0.2% triton x (Sigma Aldrich) and 0.1% tween 20 (Sigma Aldrich), except for anti-Gad67 staining which did not include detergents. Primary antibodies (**Table 1**) were detected with Alexa conjugated secondary antibodies (Jackson labs and Abcam) or AMCA conjugated secondary antibodies (Vector) in 5% serum. VECTASHIELD DAPI used for double staining and VECTASHIELD without DAPI used for triple staining when mounting sectioned tissue onto polyprep slides.

Cell Counting

Unbiased estimated counts of astrocytes expressing glial fibrillary acidic protein (GFAP), neurons expressing NeuN, and oligodendrocytes and oligodendrocyte precursors expressing Olig2 were obtained using StereoInvestigator software (Microbrightfield) coupled with a AxioCam MRm on the Zeiss axioimager microscope equipped with an ApoTome.2. Tops of cells were counted in three-dimensional counting boxes, which were set to specific parameters

(**Table 2**). For counts of the cortex and hippocampus, 50 µm sections were sampled every 20th (cortex) and every 10th section (Hippocampus). Fluorescence images were acquired through StereoInvestigator imaging software.

To determine the percentage of GFP+ cells that were neuronal stem cells expressing Sox2 and neuroblasts expressing DCX, we acquired z stack images of the anterior dentate gyrus hemisphere and a section 500 µm posterior to this first section. The z stack images obtained to count SOX2 markers were 19 µm thick with each slice 1 µm thick. The z stack images acquired to count DCX markers were 10 µm thick with each slice 1 µm thick.

Statistical Analysis

Data from the StereoInvestigator software were entered into Excel, imported to JMP Pro 11, and analyzed by student t-tests or ANOVA using SAS.

Results

Fgfr1 is expressed in various cells types of the dentate gyrus, CA, and subventricular zone (SVZ) at P7

Previous *in situ* studies indicated high levels of *Fgfr1* mRNA in the hippocampus, including dentate gyrus (DG) and cornu ammonis (CA regions). To investigate the cell types expressing *Fgfr1* in the hippocampus of P7 control and *tgfgfr1-EGFP*+ mice, samples were stained by immunocytochemistry for cell-type markers to identify each of the following: GFAP+ stem cells and astrocytes, NeuN+ neurons, BLBP+ stem cells, and DCX+ neuroblasts. The cell-type marker staining (red fluorescence) was imaged alongside GFP immunostaining (green fluorescence) to reveal which cell types express *Fgfr1* and with DAPI counterstaining (blue fluorescence) to image nuclei (**Fig.** 1). The colocalization of a cell type marker and Fgfr1

expression is indicated by yellow fluorescence caused by overlapping red and green fluorescence. GFAP and GFP immunostaining showed GFP+ cells in the GFAP+ stem cells of the subgranular zone (SGZ) of the DG of *tgfgfr1-EGFP*+ mice (**Fig. 1A-C, Video S1**) with little to no green fluorescence in GFP- controls (**Fig. 1D-F**). In the CA region of the hippocampus, GFAP+/GFP+ cells were primarily observed surrounding the stratum pyramidale, in the stratum radiatum, stratum oriens, as well as the white matter above the CA region (**Fig. 1 G-I**) with little to no green fluorescence in GFP- littermate controls (**Fig. 1 J-L**). There was strong GFP fluorescence in the stratum pyramidale of the CA region. This GFP staining colocalized with NeuN+ cells (neurons) (**Fig. 2A-C**) with little to no green fluorescence in GFP- littermate controls (**Fig. 2D-F**). NeuN+ /GFP+ cells were also observed in some, but not all, granule cell layer neurons of the developing DG of *tgfgfr1-EGFP*+ mice (**Fig. 2G-I**) with little to no green fluorescence in GFP- controls (**Fig. 2J-L**). Stereological analysis of *tgfgfr1-EGFP* expression in GFAP+ cells of the dentate gyrus showed that of GFP+ cells, 24% ± 8% are GFAP positive, and of GFAP+ cells, 50% ± 8% are GFP+. Of GFP+ cells in the CA, 50% ± 5% are GFAP positive and of GFAP+ cells in the CA, 43% ± 9% are GFP positive (**Table 3**). One-way ANOVA statistical analysis revealed that the total number of GFAP+ cells in the DG and CA of *tgfgfr1-EGFP*+ are not significantly different from their littermate controls (**Table 3**). This analysis suggests that the insertion of *tgfgfr1-EGFP* is not lethal to GFAP+ stem cells and astrocytes.

We further explored Fgfr1 promoter driven expression of GFP in the postnatal neurogenic niches of the DG and SVZ of the lateral ventricles at P7. Immunostaining for DCX (neuroblasts) and GFP extensively colocalized in the SGZ and granule cell layer (GCL) of the DG (**Fig. 3A** and **3B**, low and high magnification respectively**)** with nearly all DCX positive cells co-expressing GFP. Postnatally, the SVZ of the lateral ventricles gives rise to olfactory bulb

interneurons. GFP+ cells were observed in the SVZ, consistent with previous studies of postnatal *Fgfr1* expression (Fagel et al., 2009). However, DCX did not colocalize with GFP staining in the SVZ of the lateral ventricles (**Fig. 3C**), in contrast to what was observed in the DG of the hippocampus. Immunostaining with BLBP (stem cells) and GFP antibodies revealed strong colocalization of Fgfr1 driven GFP in the subgranular zone (SGZ) of the dentate gyrus (DG) (**Fig. 3D** and **3E**, low and high magnification, respectively) as well as BLBP+ cells of the SVZ (**Fig. 3F**).

Fgfr1 is expressed in cortical GFAP+ astrocytes and NeuN+ neurons at P7

To determine which cortical cells express *Fgfr1*, we stained the cortical tissue of P7 *tgfgfr1-EGFP*+ and control mice with GFAP and NeuN antibodies. Whereas GFP+ cells colocalized with GFAP+ astrocytes throughout the cortex (**Fig. 4A-C**), GFP+ cells colocalized with NeuN+ cells (neurons) mostly in layers 5 and 6 of the cortex at this age (**Fig. 4D-F**). Stereological analysis of the cortex region revealed that of GFP+ cells in the cortex, 32% ± 4% are GFAP positive. Of the cortical GFAP+ cells, 93% ± 2% are GFP positive. This analysis indicates that most *Gfap* expressing astrocytes also express *Fgfr1*. The total number of cortical GFAP+ cells of *tgfgfr1-EGFP*+ mice was not significantly different from the number of cells in littermate controls (**Table 3**), suggesting that the insertion of the transgene does not significantly alter the number of astrocytes expressing *Gfap*.

We examined whether *tgfgfr1-EGFP*+ was expressed in oligodendrocytes and their precursors by staining for OLIG2 in the cortex. We found that OLIG2+ staining colocalized with GFP in the cortex (**Fig. 4G-I**) and SVZ and subcortical white matter (**Fig. 4J**). At P7, radial glia of the cortex are undergoing soma translocation to become astrocytes, and can be detected with

BLBP. BLBP and GFP immunostaining revealed strong colocalization throughout the cortex (**Fig. 4K-M**). At P7, GFP staining colocalized with BLBP+ stem cells and Bergmann Glia in the developing cerebellum (**Fig. 4N**). This finding is consistent with the participation of Fgfr1/Fgfr2 signaling in Bergmann Glia morphology and cerebellar development (Muller Smith et al., 2012). Furthermore, GFP+ cells colocalized with GFAP+ astrocytes of the cerebellum, but not within granule cell layer or molecular layer neurons that stain with NeuN. GFP+ cells likely colocalized with NeuN- Purkinje neurons based on the location and size of GFP+ cells in the Purkinje layer (**Fig. S1** and **Video S2**).

Fgfr1 **is expressed in specific cell types of the hippocampus and SVZ at 1 month**

We next investigated *Fgfr1* expression in 1-month *tgfgfr1-EGFP*+ mice. Immunostaining for SOX2+ cells (stem cells), DCX+ cells (neuroblasts), NeuN+ neurons, GFAP+ astrocytes and stem cells, and OLIG2+ oligodendrocytes was performed in combination with GFP immunostaining to determine which cell types express *Fgfr1* in the dentate gyrus, CA, and SVZ. GFP+ cells colocalized with SOX2+ cells (**Fig. 5A-E**) and DCX+ cells (**Fig. 5F-J**) in the SGZ and granule cell layers. To determine the percentage of GFP+ cells that were SOX-2 positive and DCX positive, we obtained z stack images of an anterior dentate gyrus hemisphere and posterior dentate gyrus hemisphere, and performed counts from these images. Of the GFP+ cells counted in the z stack, 33% ± 2% are SOX2 positive. Conversely, the majority of SOX2+ cells, 71% ± 2%, are GFP positive (**Fig. 5E**). Of the GFP+ cells counted in the z stack, 64% ± 0.9% are DCX positive and of DCX+ cells, 86% ± 2% are GFP positive (**Fig. 5J**). Triple staining with GFP, GFAP and NeuN antibodies revealed that GFAP+ cells (stem cells) and NeuN+ cells (neurons) colocalized with GFP+ cells in the SGZ (**Fig. 5K-N**) and in the CA region (**Fig. 5O-R**),

297 respectively. GFP+ cells did not colocalize with OLIG2+ cells (oligodendrocytes) in the dentate
298 gyrus (**Fig. S2**). Taken together, these results indicate that GFP (*Fgfr1*) was expressed in stem
299 cells and neuroblasts of the DG. Stereological analysis of *tgfgfr1-EGFP* expression in NeuN+
300 cells of the dentate gyrus showed that of GFP+ cells, 16% ± 6% are NeuN positive and of
301 NeuN+ cells, 5% ± 0.7% are GFP positive. Of GFP+ cells in the CA, 25% ± 7% are NeuN
302 positive and of NeuN+ cells, 15% ± 6% are GFP positive. Stereological analysis of *tgfgfr1-*
303 *EGFP* expression in GFAP+ cells of the dentate gyrus showed that of GFP+ cells, 51% ± 3% are
304 GFAP positive and of GFAP+ cells, 85% ± 4% are GFP positive. Of GFP+ cells in the CA, 61%
305 ± 9% are GFAP positive and of GFAP+ cells, 81% ± 3% are GFP positive. These findings
306 indicate that most GFAP positive astrocytes express *Fgfr1* at 1 month. The total number of
307 SOX2+ cells, DCX+ cells, NeuN+ cells and GFAP+ cells of *tgfgfr1-EGFP*+ mice were not
308 significantly different from their littermate controls in the DG and CA (Sox2: p=0.23, DCX:
309 p=0.88 and **Table 3**).

310 Many GFAP+ cells also express GFP in the SVZ (**Fig. 6A-H**) of 1 month *tgfgfr1-*
311 *EGFP*+ mice. Colocalized GFP positive cells and GFAP positive fibers were observed both
312 within the SVZ and in the white matter above it (**Fig.** 6**D**, 6**G**, and 6**H**). There was also
313 significant colocalization of GFP with SOX2+ cells (**Fig. 6I-L**) indicating that GFAP+ and
314 SOX2+ stem cells of the SVZ express *Fgfr1*. NeuN+/GFP+ cells were not observed in the SVZ.
315 Similar to what was found at P7, GFP+ cells did not colocalize with DCX+ cells (neuroblasts) in
316 the SVZ (**Fig. 6M-O**) or in the DCX+ cells of rostral migratory stream (RMS) as it enters the
317 olfactory bulb (**Fig. 6P**). In the rostral migratory stream, GFP staining surrounds the DCX+ cells
318 as would be expected from astrocytes surrounding the migrating neuroblasts.
319

Fgfr1 is expressed in cortical GFAP+ astrocytes, NeuN+ neurons and OLIG2+ cells at 1 month

To determine which cortical cells express *Fgfr1*, we examined cortical tissue of 1-month old *tgfgfr1-EGFP*+ and control mice immuonostained with GFAP, NeuN or OLIG2 antibodies alongside GFP antibodies. Analysis of *Fgfr1* expression in the cortex revealed that GFP+ cells colocalized with GFAP+ and NeuN+ cells (**Fig. 7A-E,** compared to control **D**). Of note, GFP immunofluorescence appeared less brightly fluorescent in cells colocalizing with NeuN compared to those colocalizing with GFAP. GFP+ cells also colocalized with OLIG2+ cells (**Fig. 7G-H**) with little to no green fluorescence occurring in littermate controls (**Fig. 7I**). Stereological analysis of the cortex revealed that of GFP+ cells, 57% ± 7% are GFAP positive. Of the GFAP+ astrocytes, 83% ± 6% are GFP positive. Of GFP+ cells, 25% ± 4% are NeuN positive and of NeuN+ cells, 12% ± 2% are GFP positive. Of GFP+ cells, 29% ± 0.9% are OLIG2 positive and of OLIG2+ cells, 58% ± 0.08% are GFP positive. The total number of cortical GFAP+, NeuN+, and OLIG2+ cells of *tgfgfr1-EGFP*+ mice were not significantly different from their littermate controls (**Table 3**).

Fgfr1 is expressed in various cell types of the hypothalamus at P7 and 1 month

Comparing *Fgfr1* expression in different regions of the P7 and 1-month old mice, we observed GFP expression in cells of the hypothalamus and among cells lining the third ventricle, within the arcuate nucleus and medial eminence (**Fig. 8, Fig. S3 and Video S3**). In 1-month *tgfgfr1-EGFP*+ mice, GFP+ cells strongly colocalized with SOX2+ cells throughout the hypothalamus and third ventricle and arcuate nucleus (**Fig. 8D-I**). GFAP+ tanycytes, including those of the arcuate nucleus were among the hypothalamic cells observed to express *Fgfr1* both

at 1 month and at P7 (**Fig. 8J-L**). Tanycytes participate in neuroendocrine regulation and transport of molecules from the CSF to the hypothalamus, release of gonadotropin-releasing hormone, and production of triiodothyronine (T3) in the brain (Rodriguez et al., 2005). GFP expression was not observed in NeuN+ or OLIG2+ cells of the hypothalamus (**Fig. 8M-O, Fig. S3 A-D**). At P7, we also observed colocalization of BLBP and GFP in the hypothalamus near the third ventricle, but not many in the medial eminence (**Fig. S3 E,F, Video S3**).

Calretinin (CR) and somatostatin (SST) neurons express *Fgfr1* in one-month old mice.

The NeuN+/GFP+ neurons observed at 1 month were not restricted to any specific cortical layer, and a minority population of GFP colocalized with NeuN+ neurons. We therefore sought to determine if inhibitory neurons express *Fgfr1*. Tissue from one-month old *tgfgfr1-EGFP*+ mice and their control littermates was stained for GAD67. Some GAD67+ cells colocalized with GFP in the cortex (**Fig. 9A, B**), but not in the hippocampus (**Fig. 9C**) or SVZ (**Fig. 9D**). Our previous investigations determined that GFP was not colocalized with PV+ interneurons (Smith et al., 2014). This led to the experiments in which staining the one-month old tissue with calretinin (CR) and somatostatin (SST) was performed alongside GFP immunostaining. CR+ inhibitory neurons express GFP in the cortex (**Fig. 9E, F**), DG (**Fig. 9G**), and SVZ (**Fig. 9H**). Some SST+ inhibitory neurons express GFP in the anterior cingulate of the cortex (**Fig. 9I, J**), but none were observed in the DG (**Fig. 9K**).

Discussion

Through immunostaining for GFP in *tgFgfr1-EGFP*+ mice of the *tgFGFR1-EGFPGP338Gsat* line, we examined the cell specific expression of *Fgfr1* in the cortex,

hippocampus, SVZ, hypothalamus, and cerebellum from P7 to one-month of age. In postnatal brains, *Fgfr1* is highly expressed in the hippocampus, SVZ, hypothalamus, and in numerous cells of the cortex. In the hippocampus, *Fgfr1* was expressed in DCX+ neuroblasts, in GFAP+ stem cells and astrocytes, and Sox2+ stem cells of the SGZ, and in neurons of the CA. Furthermore, *Fgfr1* was expressed in astrocytes, neurons, and oligodendrocytes. *Fgfr1* expression in cortical neurons was not restricted to a single layer and colocalized with CR+ and SST+ inhibitory neurons. *Fgfr1* expression was also observed in Bergmann glia and GFAP+ astrocytes of the cerebellum.

The *tgFgfr1-EGFP*+ line has been shown to be a robust model in identifying which cell types express *Fgfr1,* corroborating the findings of previous *in situ* hybridization studies (el-Husseini et al., 1994, Gonzalez et al., 1995, Belluardo et al., 1997, Bansal et al., 2003, Ohkubo et al., 2004). This transgenic line gives the added benefit of allowing simple identification of the subtype of cells expressing *Fgfr1* by immunofluorescence staining since GFP is regulated by the *Fgfr1* promoter. Unlike the use of antibodies for FGFR1, which may have cross reactivity with similar FGFR family members, we can have greater confidence that we are identifying *Fgfr1* expression accurately within a cell. Total neuronal and glial cell counts were not significantly different between the *tgfgfr1-EGFP*+ mice and their control littermates. Therefore, the insertion of this transgene into the host DNA does not cause toxicity amongst the neuronal and glial cells observed.

Previous studies have shown that inactivation of FGFR1/FGFR2 and FGFR1/FGFR2/FGFR3 signaling in the developing dorsal VZ results in premature depletion of radial glial stem cells and a smaller cortex, whereas loss of *Fgfr1* alone is sufficient to result in reduced hippocampal volume and reduced hippocampal stem cell proliferation during

embryogenesis and the early postnatal period (Ohkubo et al., 2004, Kang et al., 2009, Stevens et al., 2010b, Rash et al., 2011). Our studies of *Fgfr1* expression in embryos and at P1 will be described elsewhere. At P7, *Fgfr1* was expressed in BLBP positive cells. At this age, the BLBP+ radial glial cells are undergoing soma translocation and differentiating into astrocytes of the cortical parenchyma. BLBP is also expressed in Bergmann glia of the cerebellum, which are cells that have dual roles as stem cells and as a scaffold for granule cell neuron migration and alignment of Purkinje neuron dendrites. At P7, BLBP positive cells expressed *Fgfr1* in stem cells and Bergmann Glia of the cerebellum. These findings are consistent with the demonstrated occurrence of cooperative signaling between FGFR1 and FGFR2 in the formation of the cerebellum, and specifically, in the morphology and pial attachment of Bergmann glia of the cerebellar anlage (Lin et al., 2009, Muller Smith et al., 2012).

At P7, and one-month, *Fgfr1* was expressed in the dentate gyrus and CA regions of the hippocampus, as well as in the SVZ, hypothalamus, and all layers of the cortex. At P7, *Fgfr1* was expressed in the granule cell layer of the dentate gyrus, whereas at 1 month, *Fgfr1* was expressed primarily in the subgranular zone or in the granule zone adjacent to it. The *Fgfr1* expressing cells in the granule cell layer of P7 mice sparsely colocalized with GFAP positive astrocytes and NeuN positive neurons, and the majority colocalized with DCX positive neuroblasts, of which there are many more at P7 than in the more mature brain of a 1-month old mouse. At one month, the *Fgfr1* expressing cells in the subgranular zone colocalized with SOX2+ and GFAP+ stem cells, as well as in the DCX positive neuroblasts. The expression of *Fgfr1* seems to be downregulated from DCX+ cells as they mature into NeuN expressing neurons. The *Fgfr1* expressing cells in the CA region at P7 and 1 month colocalize with GFAP positive astrocytes and NeuN positive neurons in the stratum pyramidale.

GFAP positive astrocytes and BLBP stem cells in the SVZ at P7 are expressing *Fgfr1*, indicating that stem cells of the SVZ express *Fgfr1*. GFAP positive astrocytes at 1 month also express *Fgfr1*. At P7 and 1 month, *Fgfr1* expressing cells in the SVZ do not colocalize with DCX positive neuroblasts and NeuN positive neurons. Thus, DCX positive cells express *Fgfr1* in one of the postnatal neurogenic regions – dentate gyrus. The difference in *Fgfr1* expression observed between DCX positive cells of the DG and SVZ implies that the staining in DCX positive cells of the hippocampus is not due to residual GFP protein that has not been degraded once a daughter cell born from a stem cell stops expressing *Fgfr1*. Therefore, we can further accurately identify *Fgfr1* expression within cells using this transgenic model. *Fgfr1* expressing cells were also colocalized with SOX2 positive cells at 1 month. In the SVZ, there may be additional cell types not investigated in the current study, including glial progenitor cells such as O4 or Nestin, which may colocalize with *Fgfr1* expression.

FGFR signaling participates in development of hippocampal synaptic transmission and synaptogenesis (Cambon et al., 2004, Umemori et al., 2004, Terauchi et al., 2010). Activation of FGFR1 promotes synapse formation in hippocampal neurons (Cambon et al., 2004, Terauchi et al., 2010, Dabrowski et al., 2015). Changes in *Fgfr1* expression, and FGF2 levels in the hippocampus are linked to major depression and anxiety, as well as to responses to antidepressants (Evans et al., 2004, Newton and Duman, 2004, Gaughran et al., 2006, Turner et al., 2008, Elsayed et al., 2012). It is hypothesized that *Fgf2* and *Fgfr1* are downregulated in depression and anxiety, , and this downregulation can be partially reversed by antidepressant treatment (Turner et al., 2012b, a). The chronic unpredictable stress model causes anhedonia and is a model of depression that results in decreased (mRNA) *Fgfr1* levels in the prefrontal cortex (Elsayed et al., 2012). Antidepressant treatment resulted in increased (mRNA) *Fgf2* levels, and

435 the antidepressant effects could be blocked by an FGFR1 inhibitor. These authors further showed
436 that FGF2 administration also had an antidepressant effect (Elsayed et al., 2012).

437 Most GFAP positive astrocytes in the cortex coexpressed *Fgfr1*, and the majority of the
438 *Fgfr1* expressing cells were GFAP+ astrocytes. A minority of *Fgfr1* expressing cells were NeuN
439 positive neurons at P7 and one month. While it was previously believed that *Fgfr2* is expressed
440 in glia and that *Fgfr1* is mostly expressed by neuronal populations in the adult cortex, our
441 findings support the view that most of the cortical cells expressing *Fgfr1* in the adult brain are, in
442 fact, astrocytes or oligodendrocytes (Turner et al., 2012a). In this study we see that most GFAP
443 positive astrocytes express *Fgfr1* and a small proportion of NeuN positive neurons express *Fgfr1*
444 in one month old mice. A higher percentage of *Fgfr1* expressing cells are GFAP positive
445 astrocytes than NeuN positive neurons. Thus, astrocytes constitute a majority of *Fgfr1*
446 expressing cells in the adult brain. This idea is consistent with previous mRNA profiling of
447 astrocytes in which *Fgfr1* was identified as a gene with enriched expression in astrocytes as
448 compared to other cell types in the brain (Lovatt et al., 2007, Cahoy et al., 2008, Doyle et al.,
449 2008).

450 An imbalance of excitatory and inhibitory neurons, along with hyperactivity has been
451 documented in certain neurological disorders (Benes et al., 2000, Volk et al., 2000, Kalanithi et
452 al., 2005, Akbarian and Huang, 2006, Hashimoto et al., 2008, Kataoka et al., 2010, Gonzalez-
453 Burgos et al., 2011, Volk and Lewis, 2013). Inactivation of *Fgfr1* leads to a decrease in the
454 abundance of parvalbumin interneurons and is associated with an increase in hyperactivity
455 (Muller Smith et al., 2008). A subsequent study demonstrated that in these individuals, a
456 decrease in interneurons occurs postnatally and that *Fgfr1* expression does not occur in
457 parvalbumin expressing interneurons (Smith et al., 2014). Thus the decrease in *Fgfr1* expression

and decrease in parvalbumin interneurons occurs in a non-cell autonomous manner. Here, we tested other interneuron markers, including GAD67, calretinin, and somatostatin. At one month, GAD67, a marker for inhibitory neurons, colocalizes with *Fgfr1* expressing cells in the cortex and not in the dentate gyrus. Calretinin interneurons express *Fgfr1* throughout the cortex, and in the dentate gyrus, whereas somatostatin interneurons express *Fgfr1* at the anterior cingulate of the cortex. Brandt et al., 2003 demonstrated newborn calretinin positive cells in the dentate gyrus do not express GABA (Brandt et al., 2003), offering a probable explanation as to why GAD67 is not observed colocalizing with *Fgfr1* expressing cells in the DG.

The hypothalamus, responsible for controlling hormonal production, stress regulation, and feeding behaviors, has been found to contain a neural stem/progenitor cell niche (Robins et al., 2013). Our results show that GFAP positive astrocytes are *Fgfr1* expressing cells. The morphology and location of the *Fgfr1* expressing cells are consistent with the cells being tanycytes of the hypothalamus (Robins et al., 2013). The medial eminence of the hypothalamus contains *Fgfr1* expressing cells that also express SOX2. *Fgfr1* expressing cells that were not identified are similar in morphology and location to the neurons that release gonadotropin-releasing hormone (GNRH1). These results are in congruence with a study, which demonstrated FGFR1's role in targeting of GNRH1 axons to the medial eminence (Gill and Tsai, 2006, Ojeda et al., 2008). Therefore, understanding FGFR signaling can give further insight to the hypothalamic regulation of homeostasis.

Conclusion

FGFR1 has been implicated as having multiple functions in CNS development, homeostasis, and behavior, but defining the cellular basis of its functions depends on having a

clear understanding of which cell types the *Fgfr1* gene is expressed in, and when. The GENSAT project was envisioned as a resource that would provide the tools for such detailed studies (Heintz, 2004). Here, we have extended the previously published *in situ* based studies and online resources with a detailed examination of the *tgFGR1-EGFPGP338Gsat* line. Our data are congruent with *in situ* studies, but with the added feature of double immunofluorescence with glial and neuronal markers, and a quantification of the relative expression in glial versus neuronal cells in the young adult brain. We here find *Fgfr1* promoter driven GFP expression in a variety of stem cells of the CNS including the young adult SVZ, young adult SGZ, cerebellar Bergmann Glia, and SOX2+ cells of the hypothalamus. An additional study of Fgfr1 expression in embryonic and perinatal stem cells will be described elsewhere. We also find that *Fgfr1* is expressed predominantly in glia in the young adult brain, although significant expression in DCX+ positive neuroblasts of the hippocampus was also observed. This was in stark contrast to DCX+ neuroblasts of the RMS. Our findings may shed light on the participation of FGF2/FGFR1 signaling in determining anxiety and mood, where a neuronal role for FGFR1 has been hypothesized (Turner et al., 2012a). Future studies are needed to determine whether *Fgfr1* expression colocalizes with other markers, such as S100β, O4, and NG2 at embryonic and postnatal time points. Since *Gfap* is not expressed in all astrocytes, S100β (glial specific marker primarily expressed in astrocytes, but also in some ependymal cells) would be a good marker to further explore *Fgfr1* expression. The *tgFgfr1-EGFP*+ model can also be used to study additional stages in development, or *Fgfr1* expression after environmental manipulations previously shown to alter *Fgfr1* expression, including animal models for induced depression such as social defeat stress.

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References

Akbarian S, Huang HS (2006) Molecular and cellular mechanisms of altered GAD1/GAD67 expression in schizophrenia and related disorders. Brain Res Rev 52:293-304.

Bansal R, Lakhina V, Remedios R, Tole S (2003) Expression of FGF receptors 1, 2, 3 in the embryonic and postnatal mouse brain compared with Pdgfralpha, Olig2 and Plp/dm20: implications for oligodendrocyte development. Dev Neurosci 25:83-95.

Belluardo N, Wu G, Mudo G, Hansson AC, Pettersson R, Fuxe K (1997) Comparative localization of fibroblast growth factor receptor-1, -2, and -3 mRNAs in the rat brain: in situ hybridization analysis. J Comp Neurol 379:226-246.

Benes FM, Todtenkopf MS, Logiotatos P, Williams M (2000) Glutamate decarboxylase(65)-immunoreactive terminals in cingulate and prefrontal cortices of schizophrenic and bipolar brain. J Chem Neuroanat 20:259-269.

Blak AA, Naserke T, Weisenhorn DM, Prakash N, Partanen J, Wurst W (2005) Expression of Fgf receptors 1, 2, and 3 in the developing mid- and hindbrain of the mouse. Dev Dyn 233:1023-1030.

Brandt MD, Jessberger S, Steiner B, Kronenberg G, Reuter K, Bick-Sander A, von der Behrens W, Kempermann G (2003) Transient calretinin expression defines early postmitotic step of neuronal differentiation in adult hippocampal neurogenesis of mice. Mol Cell Neurosci 24:603-613.

Cahoy JD, Emery B, Kaushal A, Foo LC, Zamanian JL, Christopherson KS, Xing Y, Lubischer JL, Krieg PA, Krupenko SA, Thompson WJ, Barres BA (2008) A transcriptome database for astrocytes, neurons, and oligodendrocytes: a new resource for understanding brain development and function. J Neurosci 28:264-278.

Cambon K, Hansen SM, Venero C, Herrero AI, Skibo G, Berezin V, Bock E, Sandi C (2004) A synthetic neural cell adhesion molecule mimetic peptide promotes synaptogenesis, enhances presynaptic function, and facilitates memory consolidation. J Neurosci 24:4197-4204.

Cholfin JA, Rubenstein JL (2007) Genetic regulation of prefrontal cortex development and function. Novartis Found Symp 288:165-173; discussion 173-167, 276-181.

Dabrowski A, Terauchi A, Strong C, Umemori H (2015) Distinct sets of FGF receptors sculpt excitatory and inhibitory synaptogenesis. Development 142:1818-1830.

Doyle JP, Dougherty JD, Heiman M, Schmidt EF, Stevens TR, Ma G, Bupp S, Shrestha P, Shah RD, Doughty ML, Gong S, Greengard P, Heintz N (2008) Application of a translational profiling approach for the comparative analysis of CNS cell types. Cell 135:749-762.

el-Husseini Ae-D, Paterson JA, Shiu RP (1994) Basic fibroblast growth factor (bFGF) and two of its receptors, FGFR1 and FGFR2: gene expression in the rat brain during postnatal development as determined by quantitative RT-PCR. Mol Cell Endocrinol 104:191-200.

545 Elsayed M, Banasr M, Duric V, Fournier NM, Licznerski P, Duman RS (2012) Antidepressant
546 effects of fibroblast growth factor-2 in behavioral and cellular models of depression. Biol
547 Psychiatry 72:258-265.
548 Evans SJ, Choudary PV, Neal CR, Li JZ, Vawter MP, Tomita H, Lopez JF, Thompson RC,
549 Meng F, Stead JD, Walsh DM, Myers RM, Bunney WE, Watson SJ, Jones EG, Akil H
550 (2004) Dysregulation of the fibroblast growth factor system in major depression. Proc
551 Natl Acad Sci U S A 101:15506-15511.
552 Fagel DM, Ganat Y, Cheng E, Silbereis J, Ohkubo Y, Ment LR, Vaccarino FM (2009) Fgfr1 is
553 required for cortical regeneration and repair after perinatal hypoxia. J Neurosci 29:1202-
554 1211.
555 Fortin D, Rom E, Sun H, Yayon A, Bansal R (2005) Distinct fibroblast growth factor (FGF)/FGF
556 receptor signaling pairs initiate diverse cellular responses in the oligodendrocyte lineage.
557 J Neurosci 25:7470-7479.
558 Fukuchi-Shimogori T, Grove EA (2001) Neocortex patterning by the secreted signaling molecule
559 FGF8. Science 294:1071-1074.
560 Furusho M, Dupree JL, Nave KA, Bansal R (2012) Fibroblast growth factor receptor signaling in
561 oligodendrocytes regulates myelin sheath thickness. J Neurosci 32:6631-6641.
562 Furusho M, Roulois AJ, Franklin RJ, Bansal R (2015) Fibroblast growth factor signaling in
563 oligodendrocyte-lineage cells facilitates recovery of chronically demyelinated lesions but
564 is redundant in acute lesions. Glia 63:1714-1728.
565 Gaughran F, Payne J, Sedgwick PM, Cotter D, Berry M (2006) Hippocampal FGF-2 and FGFR1
566 mRNA expression in major depression, schizophrenia and bipolar disorder. Brain Res
567 Bull 70:221-227.
568 Gill JC, Tsai PS (2006) Expression of a dominant negative FGF receptor in developing GNRH1
569 neurons disrupts axon outgrowth and targeting to the median eminence. Biol Reprod
570 74:463-472.
571 Gonzalez AM, Berry M, Maher PA, Logan A, Baird A (1995) A comprehensive analysis of the
572 distribution of FGF-2 and FGFR1 in the rat brain. Brain Res 701:201-226.
573 Gonzalez-Burgos G, Fish KN, Lewis DA (2011) GABA neuron alterations, cortical circuit
574 dysfunction and cognitive deficits in schizophrenia. Neural Plast 2011:723184.
575 Gutin G, Fernandes M, Palazzolo L, Paek H, Yu K, Ornitz DM, McConnell SK, Hebert JM
576 (2006) FGF signalling generates ventral telencephalic cells independently of SHH.
577 Development 133:2937-2946.
578 Hashimoto T, Arion D, Unger T, Maldonado-Aviles JG, Morris HM, Volk DW, Mirnics K,
579 Lewis DA (2008) Alterations in GABA-related transcriptome in the dorsolateral
580 prefrontal cortex of subjects with schizophrenia. Mol Psychiatry 13:147-161.
581 Hebert JM (2011) FGFs: Neurodevelopment's Jack-of-all-Trades - How Do They Do it? Front
582 Neurosci 5:133.
583 Heintz N (2004) Gene expression nervous system atlas (GENSAT). Nat Neurosci 7:483.
584 Iwata T, Hevner RF (2009) Fibroblast growth factor signaling in development of the cerebral
585 cortex. Dev Growth Differ 51:299-323.
586 Kalanithi PS, Zheng W, Kataoka Y, DiFiglia M, Grantz H, Saper CB, Schwartz ML, Leckman
587 JF, Vaccarino FM (2005) Altered parvalbumin-positive neuron distribution in basal
588 ganglia of individuals with Tourette syndrome. Proc Natl Acad Sci U S A 102:13307-
589 13312.

590 Kang W, Balordi F, Su N, Chen L, Fishell G, Hebert JM (2014) Astrocyte activation is
591 suppressed in both normal and injured brain by FGF signaling. Proc Natl Acad Sci U S A
592 111:E2987-2995.
593 Kang W, Wong LC, Shi SH, Hebert JM (2009) The transition from radial glial to intermediate
594 progenitor cell is inhibited by FGF signaling during corticogenesis. J Neurosci 29:14571-
595 14580.
596 Kataoka Y, Kalanithi PS, Grantz H, Schwartz ML, Saper C, Leckman JF, Vaccarino FM (2010)
597 Decreased number of parvalbumin and cholinergic interneurons in the striatum of
598 individuals with Tourette syndrome. J Comp Neurol 518:277-291.
599 Korada S, Zheng W, Basilico C, Schwartz ML, Vaccarino FM (2002) Fibroblast growth factor 2
600 is necessary for the growth of glutamate projection neurons in the anterior neocortex. J
601 Neurosci 22:863-875.
602 Lin Y, Chen L, Lin C, Luo Y, Tsai RY, Wang F (2009) Neuron-derived FGF9 is essential for
603 scaffold formation of Bergmann radial fibers and migration of granule neurons in the
604 cerebellum. Dev Biol 329:44-54.
605 Lovatt D, Sonnewald U, Waagepetersen HS, Schousboe A, He W, Lin JH, Han X, Takano T,
606 Wang S, Sim FJ, Goldman SA, Nedergaard M (2007) The transcriptome and metabolic
607 gene signature of protoplasmic astrocytes in the adult murine cortex. J Neurosci
608 27:12255-12266.
609 Muller Smith K, Fagel DM, Stevens HE, Rabenstein RL, Maragnoli ME, Ohkubo Y, Picciotto
610 MR, Schwartz ML, Vaccarino FM (2008) Deficiency in inhibitory cortical interneurons
611 associates with hyperactivity in fibroblast growth factor receptor 1 mutant mice. Biol
612 Psychiatry 63:953-962.
613 Muller Smith K, Williamson TL, Schwartz ML, Vaccarino FM (2012) Impaired motor
614 coordination and disrupted cerebellar architecture in Fgfr1 and Fgfr2 double knockout
615 mice. Brain Res 1460:12-24.
616 Newton SS, Duman RS (2004) Regulation of neurogenesis and angiogenesis in depression. Curr
617 Neurovasc Res 1:261-267.
618 Ohkubo Y, Uchida AO, Shin D, Partanen J, Vaccarino FM (2004) Fibroblast growth factor
619 receptor 1 is required for the proliferation of hippocampal progenitor cells and for
620 hippocampal growth in mouse. J Neurosci 24:6057-6069.
621 Ojeda SR, Lomniczi A, Sandau US (2008) Glial-gonadotrophin hormone (GnRH) neurone
622 interactions in the median eminence and the control of GnRH secretion. J
623 Neuroendocrinol 20:732-742.
624 Rash BG, Lim HD, Breunig JJ, Vaccarino FM (2011) FGF signaling expands embryonic cortical
625 surface area by regulating Notch-dependent neurogenesis. J Neurosci 31:15604-15617.
626 Rash BG, Tomasi S, Lim HD, Suh CY, Vaccarino FM (2013) Cortical gyrification induced by
627 fibroblast growth factor 2 in the mouse brain. J Neurosci 33:10802-10814.
628 Robins SC, Stewart I, McNay DE, Taylor V, Giachino C, Goetz M, Ninkovic J, Briancon N,
629 Maratos-Flier E, Flier JS, Kokoeva MV, Placzek M (2013) alpha-Tanycytes of the adult
630 hypothalamic third ventricle include distinct populations of FGF-responsive neural
631 progenitors. Nat Commun 4:2049.
632 Rodriguez EM, Blazquez JL, Pastor FE, Pelaez B, Pena P, Peruzzo B, Amat P (2005)
633 Hypothalamic tanycytes: a key component of brain-endocrine interaction. Int Rev Cytol
634 247:89-164.

635 Salmaso N, Stevens HE, McNeill J, ElSayed M, Ren Q, Maragnoli ME, Schwartz ML, Tomasi
636 S, Sapolsky RM, Duman R, Vaccarino FM (2016) Fibroblast Growth Factor 2 Modulates
637 Hypothalamic Pituitary Axis Activity and Anxiety Behavior Through Glucocorticoid
638 Receptors. Biol Psychiatry.
639 Shin DM, Korada S, Raballo R, Shashikant CS, Simeone A, Taylor JR, Vaccarino F (2004) Loss
640 of glutamatergic pyramidal neurons in frontal and temporal cortex resulting from
641 attenuation of FGFR1 signaling is associated with spontaneous hyperactivity in mice. J
642 Neurosci 24:2247-2258.
643 Smith KM, Maragnoli ME, Phull PM, Tran KM, Choubey L, Vaccarino FM (2014) Fgfr1
644 inactivation in the mouse telencephalon results in impaired maturation of interneurons
645 expressing parvalbumin. PLoS One 9:e103696.
646 Smith KM, Ohkubo Y, Maragnoli ME, Rasin MR, Schwartz ML, Sestan N, Vaccarino FM
647 (2006) Midline radial glia translocation and corpus callosum formation require FGF
648 signaling. Nat Neurosci.
649 Stevens HE, Smith KM, Maragnoli ME, Fagel D, Borok E, Shanabrough M, Horvath TL,
650 Vaccarino FM (2010a) Fgfr2 is required for the development of the medial prefrontal
651 cortex and its connections with limbic circuits. J Neurosci 30:5590-5602.
652 Stevens HE, Smith KM, Rash BG, Vaccarino FM (2010b) Neural stem cell regulation, fibroblast
653 growth factors, and the developmental origins of neuropsychiatric disorders. Front
654 Neurosci 4.
655 Storm EE, Garel S, Borello U, Hebert JM, Martinez S, McConnell SK, Martin GR, Rubenstein
656 JL (2006) Dose-dependent functions of Fgf8 in regulating telencephalic patterning
657 centers. Development 133:1831-1844.
658 Storm EE, Rubenstein JL, Martin GR (2003) Dosage of Fgf8 determines whether cell survival is
659 positively or negatively regulated in the developing forebrain. Proc Natl Acad Sci U S A
660 100:1757-1762.
661 Terauchi A, Johnson-Venkatesh EM, Toth AB, Javed D, Sutton MA, Umemori H (2010) Distinct
662 FGFs promote differentiation of excitatory and inhibitory synapses. Nature 465:783-787.
663 Tole S, Gutin G, Bhatnagar L, Remedios R, Hebert JM (2006) Development of midline cell
664 types and commissural axon tracts requires Fgfr1 in the cerebrum. Dev Biol 289:141-151.
665 Turner CA, Calvo N, Frost DO, Akil H, Watson SJ (2008) The fibroblast growth factor system is
666 downregulated following social defeat. Neurosci Lett 430:147-150.
667 Turner CA, Watson SJ, Akil H (2012a) The fibroblast growth factor family: neuromodulation of
668 affective behavior. Neuron 76:160-174.
669 Turner CA, Watson SJ, Akil H (2012b) Fibroblast growth factor-2: an endogenous
670 antidepressant and anxiolytic molecule? Biol Psychiatry 72:254-255.
671 Umemori H, Linhoff MW, Ornitz DM, Sanes JR (2004) FGF22 and its close relatives are
672 presynaptic organizing molecules in the mammalian brain. Cell 118:257-270.
673 Vaccarino FM, Schwartz ML, Raballo R, Nilsen J, Rhee J, Zhou M, Doetschman T, Coffin JD,
674 Wyland JJ, Hung YT (1999) Changes in cerebral cortex size are governed by fibroblast
675 growth factor during embryogenesis. Nat Neurosci 2:246-253.
676 Volk DW, Austin MC, Pierri JN, Sampson AR, Lewis DA (2000) Decreased glutamic acid
677 decarboxylase67 messenger RNA expression in a subset of prefrontal cortical gamma-
678 aminobutyric acid neurons in subjects with schizophrenia. Arch Gen Psychiatry 57:237-
679 245.

Volk DW, Edelson JR, Lewis DA (2016) Altered expression of developmental regulators of parvalbumin and somatostatin neurons in the prefrontal cortex in schizophrenia. Schizophr Res.

Volk DW, Lewis DA (2013) Prenatal ontogeny as a susceptibility period for cortical GABA neuron disturbances in schizophrenia. Neuroscience 248C:154-164.

Table 1. Antibodies used for Immunofluorescence Detection

Antigen	Raised In	Dilution	Source	Marker of
NueN	Mouse	1:125	Millipore	Neuron
GFAP	Rabbit	1:500	Dako Cytomation	Astrocyte
GFP	Chicken	1:250	Abcam Inc.	GFP
Sox2	Rabbit	1:250	Millipore	Neuronal precursor
Olig2	Mouse	1:1000	Millipore	Oligodendrocyte
DCX	Mouse	1:250	Abcam Inc	Neuroblast
GAD67	Mouse	1:1000	Millipore	Inhibitory neuron
Calretinin	Rabbit	1:1000	Millipore	Inhibitory neuron
Somatostatin	Rat	1:200	Millipore	Inhibitory neuron
BLBP	Rabbit	1:1000	Abcam Inc.	Stem cells
Tbr2	Rabbit	1:500	Abcam Inc.	Excitatory neuron

Table 2. Parameters used for Stereological Cell Counts

Time Point	Area	Counting Frame (µm)	Grid Size (µm)	Dissector Height (µm)	Guard Zone Height (µm)	Section Thickness (µm)
P7	Cortex	75 x 75	650 x 700	15	1	50
	DG	75 x 75	250 x 250	15	1	50
	CA	75 x 75	500 x 500	15	1	50
1 month	Cortex	75 x 75	1000 x 1000	15	1	50
	DG	75 x 75	275 x 200	15	1	50
	CA	75 x 75	350 x 250	15	1	50

Table 3. Stereology Results for Hippocampal DG, CA, and Cortex

Age	Area	Marker	# of Marker + cells	P-value	# of GFP+ cells	% of GFP+ cells expressing Marker	% of Marker+ cells expressing GFP
P7	DG	GFAP	5614 ± 467	0.37	15974 ± 7447	24% ± 8%	50% ± 8%
	CA	GFAP	51258 ± 1741	0.42	46413 ± 14851	50% ± 5%	43% ± 9%
	Cortex	GFAP	412147 ± 22494	0.25	1220518 ± 53849	32% ± 4%	93% ± 2%
1 Month	DG	NeuN	755542 ± 228698	0.52	243542 ± 12945	16% ± 6%	5% ± 0.7%
		GFAP	149161 ± 22540	0.53	243542 ± 12945	51% ± 3%	85% ± 4%
	CA	NeuN	670709 ± 59607	0.27	379768 ± 27634	25% ± 7%	15% ± 6%
		GFAP	286614 ± 39645	0.86	379768 ± 27634	61% ± 9%	81% ± 3%
	Cortex	GFAP	1777872 ± 876236	0.66	2321696 ± 1056829	57% ± 7%	83% ± 6%
		NeuN	4962422 ± 2264757	0.97	2321696 ± 1056829	25% ± 4%	12% ± 2%
		Olig2	800755 ± 137359	0.85	1574962 ± 195563	29% ± 0.9%	58% ± 0.08%

Table 4. Qualitative comparison of *Fgfr1* expression

Time Point	Area	*Fgfr1* Expression in Cell Types					
		BLBP	**GFAP**	**SOX2**	**DCX**	**NeuN**	**Olig2**
P7	DG	++	++	NA	+++	+	
	CA		++	NA		++	
	SVZ	+++	+	NA			++
	Cortex	+++	++	NA		+	++
	Hypothalamus		++	NA			
1 month	DG		++	++	++		
	CA		+			+	
	SVZ		++	++			
	Cortex		++			+	+
	Hypothalamus		++	++			

NA = not analyzed

Figure 1. *Fgfr1* expression in GFAP+ cells of the hippocampus at P7. GFAP (**A**,**D**) GFP (**B**,**E**) immunostaining of the DG in P7 tgfgfr1-EGFP+ mice (**A-C**, n=3) and tgfgfr1-EGFP- littermate controls (**D-F**, n=3) demonstrated strong GFAP/GFP colocalization in cells of the SGZ (arrowheads) and their radial fibers into the GCL (small arrows). GFAP and GFP immunostaining of the CA region in tgfgfr1-EGFP+ mice (**G-I**, n=3) and tgfgfr1-EGFP- controls (**J-L,** n=3). GFP+ staining was observed in stratum pyramidale (SP) as well as in cells above (stratum oriens, SO) and below (stratum radiatum, SR) this layer (**H**). GFAP+/GFP+ colabeling (arrowheads) was observed in primarily in the SO and SR within the CA region, and in the white matter dorsal to the hippocampus. Scale bar is 25 μm. SGZ = subgranular zone, GCL = granule cell layer, SP=stratum pyramidale.

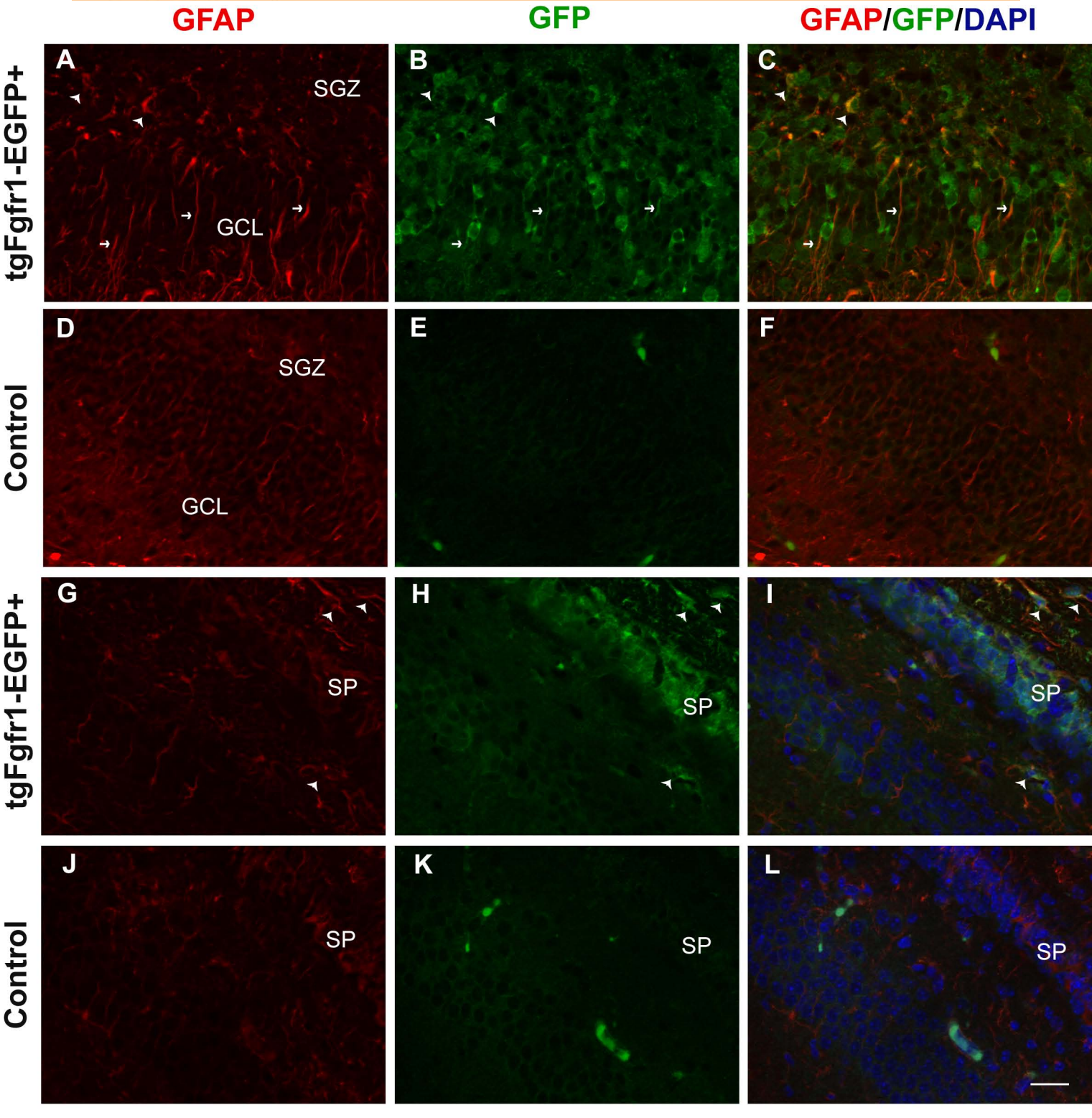

Figure 2. *Fgfr1* expression in NeuN+ cells of the hippocampus at P7. NeuN (**A**,**D**) and GFP (**B**,**E**) immunostaining of the CA region in tgfgfr1-EGFP+ mice (**A-C**, n=3) and tgfgfr1-EGFP- controls (**D-F,** n=3). NeuN+/GFP+ staining was observed in stratum pyramidale (SP) of the CA region. NeuN (**G**, **J**) and GFP (**H**, **K**) immunostaining of the DG in tgfgfr1-EGFP+ mice (**G-I**, n=3) and tgfgfr1-EGFP- controls (**J-L,** n=3). There was some colabeling in the granule cell layer between GFP+ and NeuN+ cells. Scale bar is 25 μm in A-D and 50 μm in G-L. SP=stratum pyramidale.

Figure 2

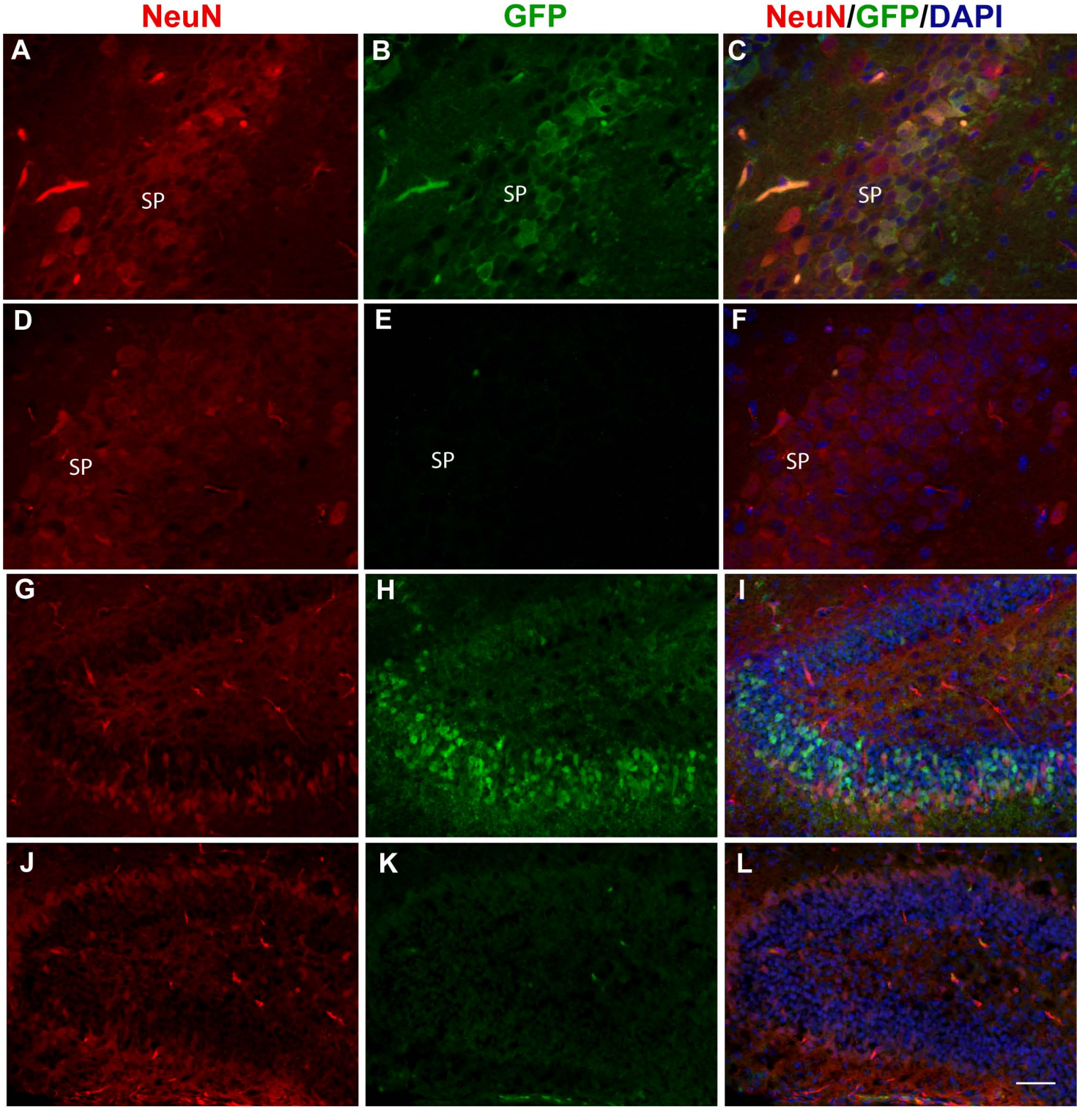

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Figure 3. *Fgfr1* expression in neuroblasts of the hippocampus, and stem cells of the hippocampus and SVZ at P7. DCX and GFP colocalize in neuroblasts of the P7 mice in the granule cell layer of the DG in the hippocampus (**A**, low magnification, and **B,** high magnification), but not in the SVZ of the lateral ventricles (**C**). Many of the BLBP+ cells colocalize with GFP in the stem cells of the SGZ of the DG (**D**, low magnification, and **E,** high magnification), as well as stem cell in the SVZ (**F**). Scale bar is 50µm in **A**,**C**,**D**,**F** and 25µm in **B** and **E**.

Figure 3

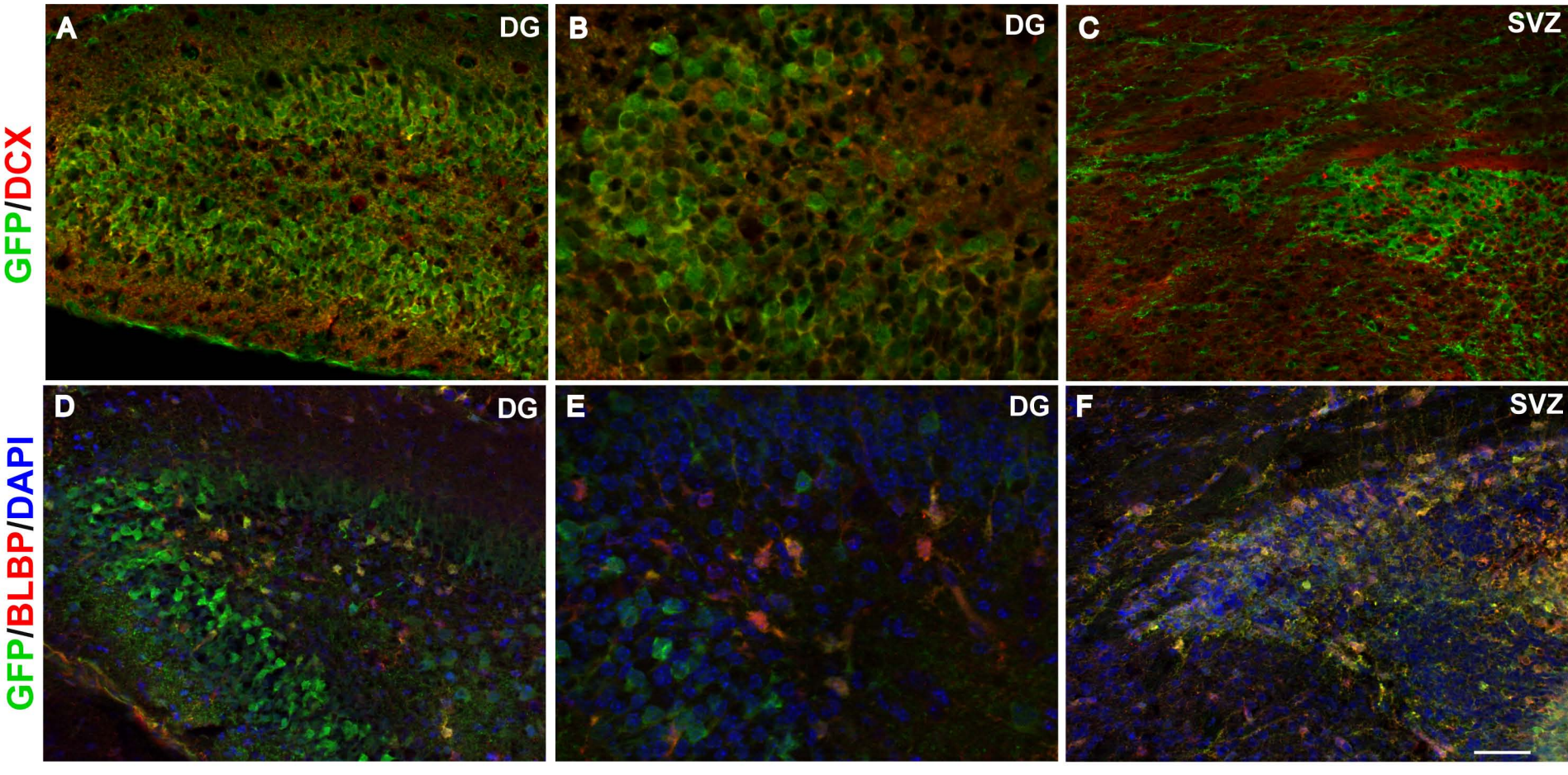

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Figure 4. *Fgfr1* expression in cortex of P7 mice. Cortical GFAP, NeuN, BLBP and GFP immunostaining in P7 *tgfgfr1-EGFP*+ mice (**A, B, D, E, G-J**, n=3) and *tgfgfr1-EGF*- controls (**C, F,** n=3). GFP+ cells colocalize with GFAP+ cells (**A, B**). GFP+ cells weakly colocalize with NeuN+ at layers 5 and 6 of the cortex (**D, E**)**.** GFP+ cells colocalize with Olig2+ cells in the cortex (**G-I**) and the subcortical white matter and SVZ **(J**). GFP+ cells colocalize with BLBP+ cells throughout the layers of the cortex (**K-M**) as well as the BLBP+ cells and Bergmann glia of the cerebellum (**N**). Scale bar is 50μm. 1, 2, 3, 4, 5, 6 = layers of the cortex.

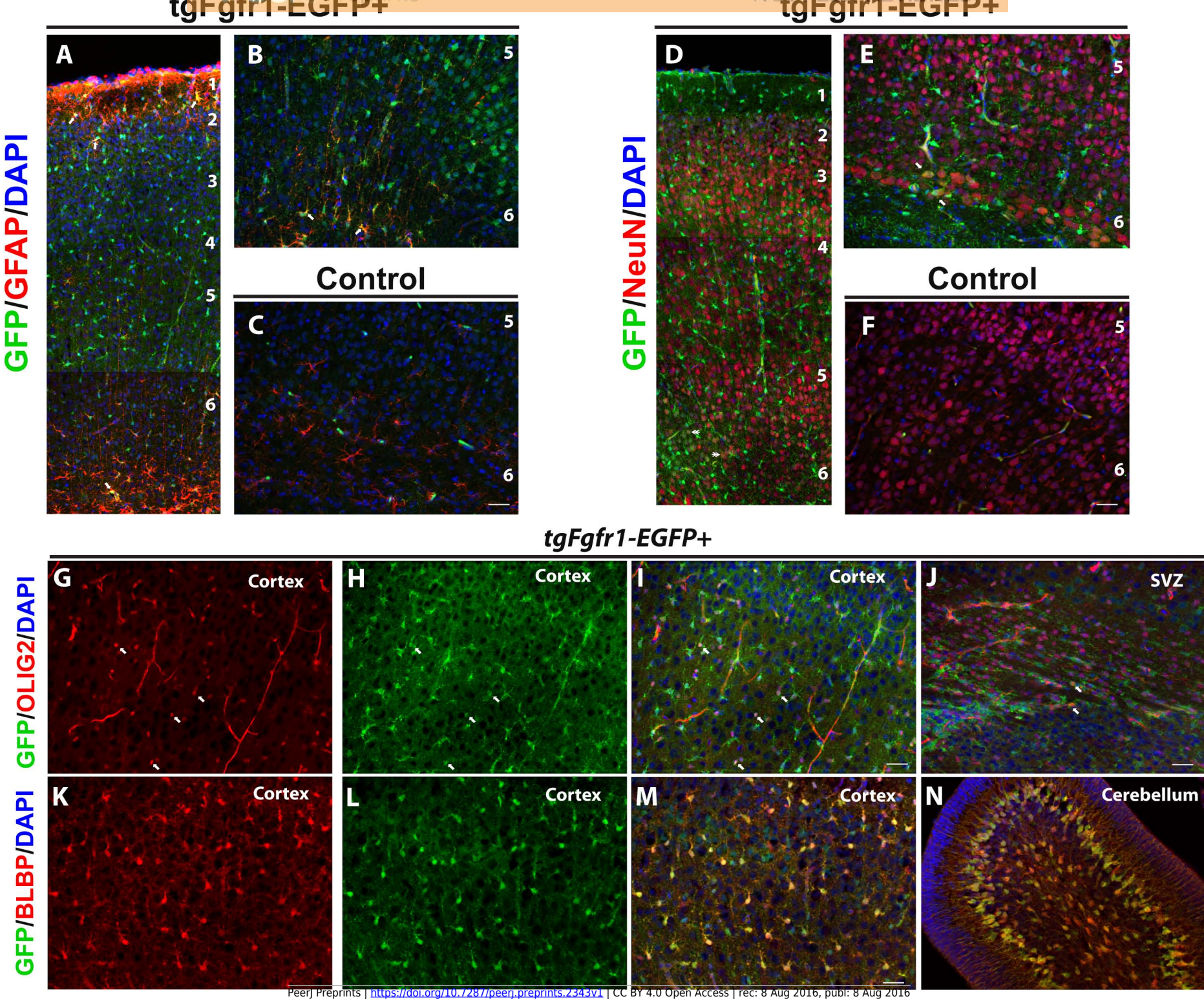

Figure 5. *Fgfr1* expression in the dentate gyrus and CA of 1-month mice. A majority of SOX2+ cells (**A**, **C**) in the DG of *tgfgfr1-EGFP*+ mice colocalize with GFP (**B**, **C**) compared to GFP- controls (**D**). Counts of SOX2+ and GFP+ cells were made directly from Z stack images (19μm thick, 1 μm steps, from Z stack images using StereoInvestigator software from MBF). The relative proportions of single, and double-labeled cells in the DG were quantified (**E**), with 71% of SOX2 positive cells expressing GFP. A majority of DCX+ (**F**, **H**) cells in the DG also express GFP (**G**, **H**) compared to GFP- controls (**I**). Counts for DCX+ and GFP+ were performed on 10μm thick, 1μM step size, Z stack images using Image J (n=3) of the dentate gyrus. The relative proportions of single, and double-labeled cells in the DG were quantified (**J**) with 85% of DCX+ cells expressing GFP. GFAP (Red), NeuN (Blue), and GFP triple immunolabeling was perfumed on 1-month old mice. We observed GFAP and GFP colabeling in both the SGZ of the DG (**K**-**N**), as well as in the CA region (**O**-**R**) where most GFAP+ cells are present in the stratum oriens or stratum radiatum. NeuN+/GFP+ double positive cells were primarily observed in the stratum pyramidale (SP) of the CA region in the hippocampus. These cells were quantified by unbiased stereology with the StereoInvestigator (Table 3). Scale bar in **I** is 25 μm for images **A-D** and **F-I**, Scale bar in **R** is 50 μm for images **K**-**R**.

Figure 5

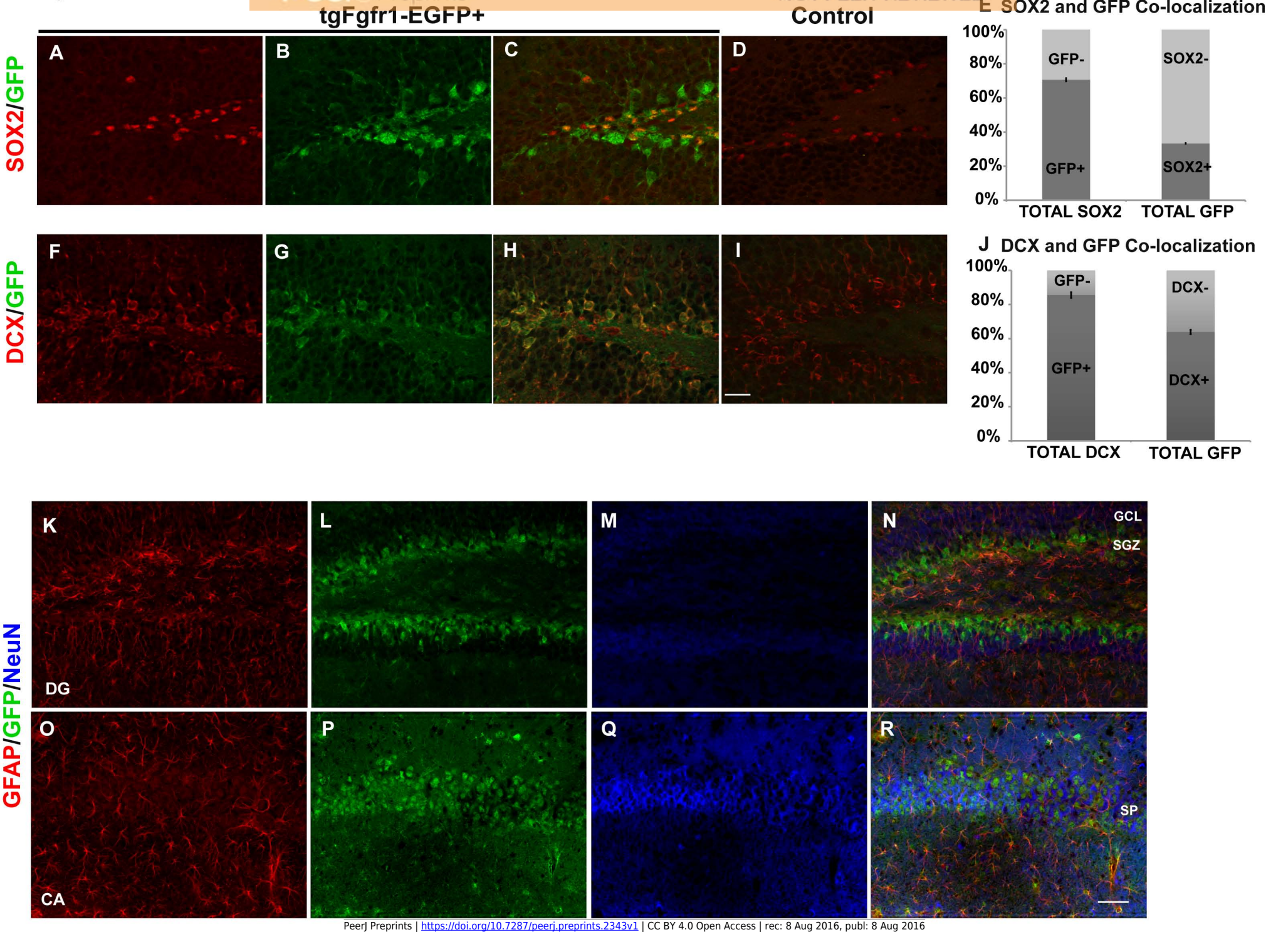

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Figure 6. *Fgfr1* expression in the SVZ and rostral migratory stream of 1-month mice. GFP (**A**,**E**), GFAP (**B**,**F**), NeuN (**C**), immunostaining of the SVZ in 1-month *tgfgfr1-EGFP*+ mice (**A-H,** n=3). GFP+ cells of the SVZ colocalized with GFAP + cells (**D**, high magnification in **G** and **H**. Arrowheads in **E-H**=GFAP/GFP+ cells) and GFAP+ fibers. GFP (**I**) and SOX2 (**J**) staining demonstrated that many, but not all SOX2+ cells also colabel with GFP+ (**K** and **L**, DAPI staining included in **L**). In contrast, DCX+ neuroblasts in the SVZ and rostral migratory stream did not colabel with GFP (**L-O**). Scale bar is 50μm in **A-D** and **M-P** and 25μm in **E-L**.

Figure 6

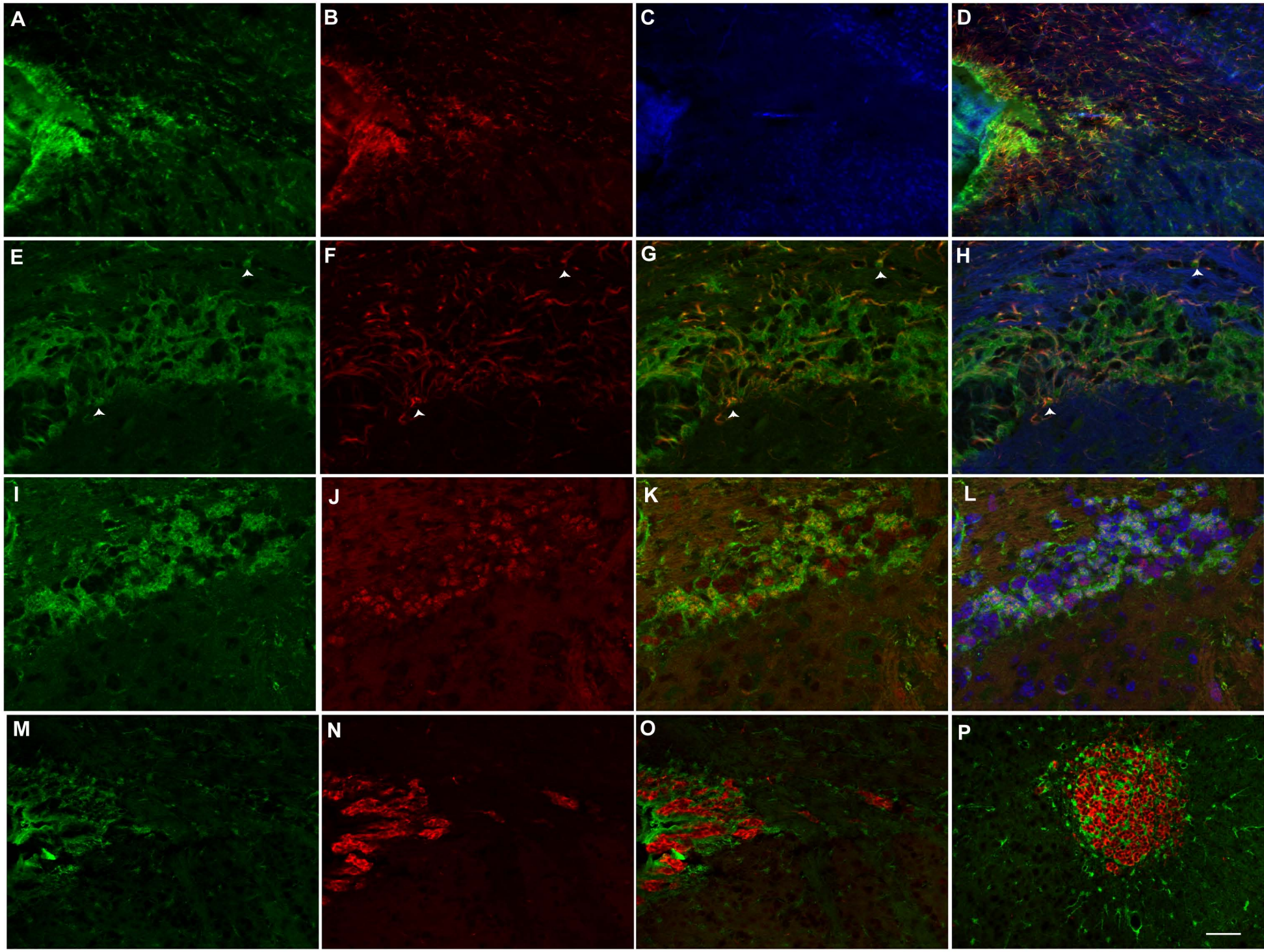

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Figure 7. *Fgfr1* expression in the cortex of 1-month mice. Cortical GFAP (Red), NeuN (Blue), and GFP immunostaining in 1-month *tgfgfr1-EGFP*+ mice (**A-E,** n=3) and *tgfgfr1-EGF*- mice (**F,** n=3). GFP+ cells colocalized with GFAP+ (arrows) (**A**, **B**, merged in **D**, low magnification in **E**), and some NeuN+ (double arrows) (**B, C,** merged in **D, lower** magnification in **E**). Immunostaining for Olig2+ in *tgfgfr1-EGFP*+ mice (**G**, **H**) compared to *tgfgfr1-EGF*- mice (**I**) demonstrated that many Olig2+ cells colocalized with GFP. Scale bars are 50μm.

Figure 7

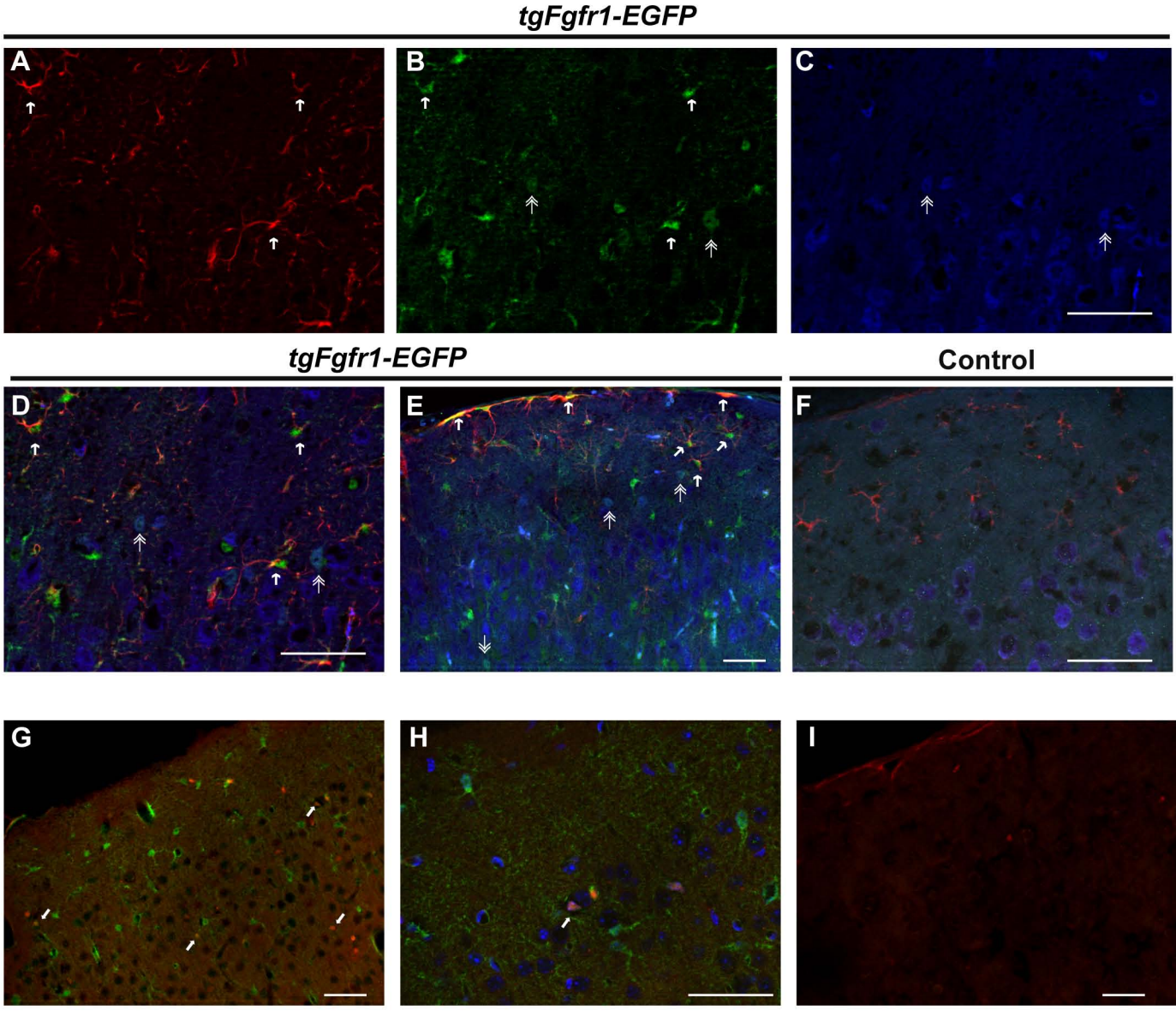

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Figure 8. *Fgfr1* expression in the hypothalamus. Sox2+ positive cells were observed along the third ventricle of *tgfgfr1-EGF*- control mice (**A-C**) and *tgfgfr1-EGF*+ mice (**D-I**). These SOX2+ cells also express GFP under the Fgfr1 promoter (**D-I**). GFAP+ tanacytes along the third ventricle and arcuate nucleus also colocalize with GFP, as do GFAP+ cells within the hypothalamus (**J-L**). NeuN+ cells in the hypothalamus do not colocalize with GFP (**M-O**). **A-L,** 1 month; **M-O**, P7. Scale bar is 50μm.

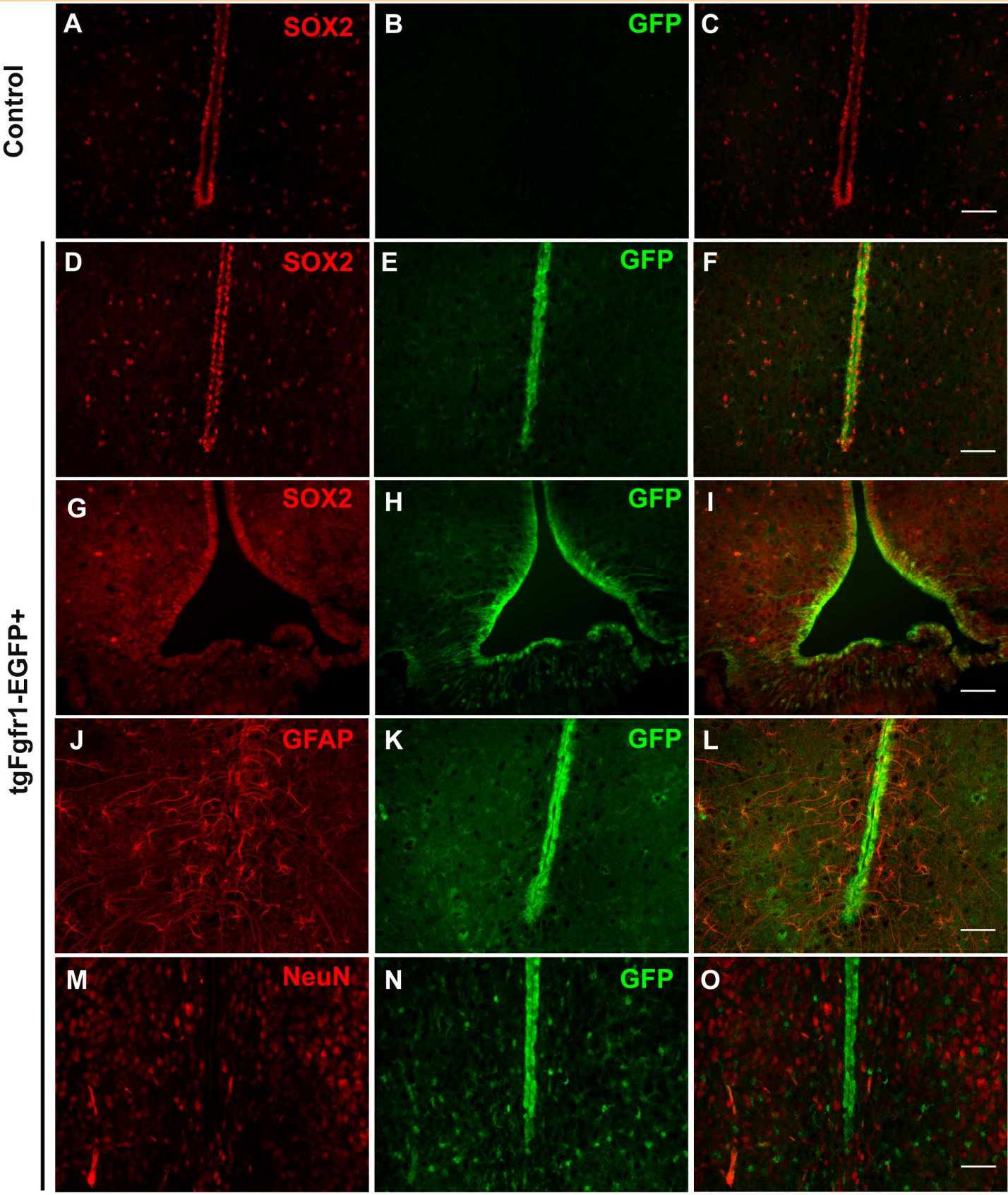

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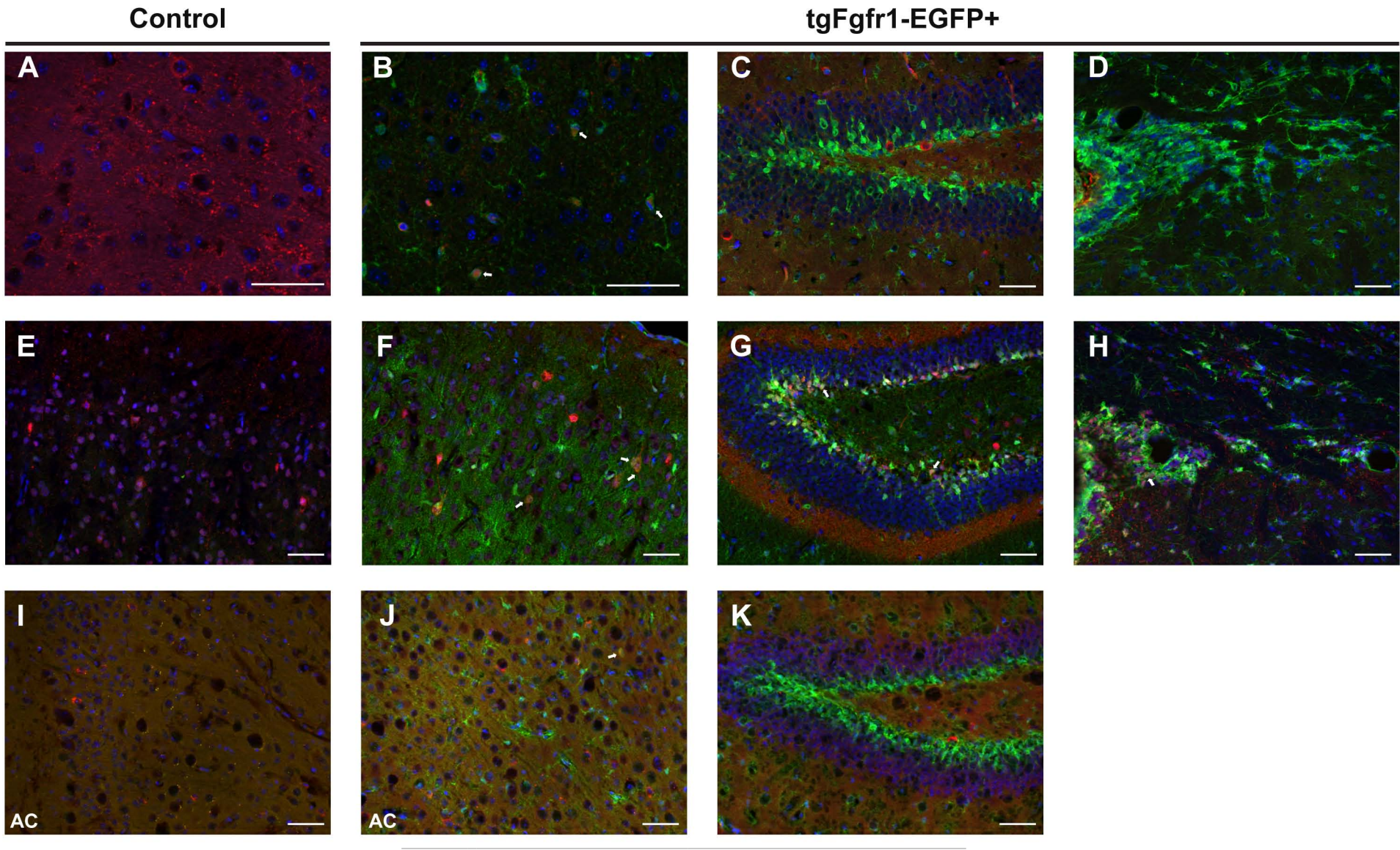
Figure 9. *Fgfr1* expression in the 1-month interneurons. GAD67, CR, SST, and GFP immunostaining of the cortex, DG, and SVZ in one-month old *tgfgfr1-EGFP*- controls (**A, E, I,** n=2 SST, n=3 GAD67, CR) and *tgfgfr1-EGFP*+ mice (**B-D, F-H, J, K,** n=2 SST, n=3 GAD67, CR). GFP+ cells colocalized with GAD67+ cells in the cortex (**B**), but not in the DG (**C**) and SVZ (**D**). Some CR+ cells express GFP in the cortex (**F**), DG (**G**) and SVZ (**H**). Some SST+ cells express GFP in the anterior cingulate of the cortex (**J**), but not in the DG (**K**). Scale bars are 50μm. AC = anterior cingulate.

Figure 9



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