Genome-wide chromatin accessibility analyses provide a map for enhancing optic nerve regeneration

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Retinal Ganglion Cells (RGCs) lose their ability to grow axons during development. Adult RGCs thus fail to regenerate their axons after injury, leading to vision loss. To uncover mechanisms that promote regeneration of RGC axons, we identified transcription factors (TF) and open chromatin regions that are enriched in rat embryonic RGCs (high axon growth capacity) compared to postnatal RGCs (low axon growth capacity). We found that developmental stage-specific gene expression changes correlated with changes in promoter chromatin accessibility. Binding motifs for TFs such as CREB, CTCF, JUN and YY1 were enriched in the regions of the chromatin that were more accessible in embryonic RGCs. Proteomic analysis of purified rat RGC nuclei confirmed the expression of TFs with potential role in axon growth such as CREB, CTCF, YY1, and JUND. The CREB/ATF binding motif was widespread at the open chromatin region of known pro-regenerative TFs, supporting a role of CREB in regulating axon regeneration. Consistently, overexpression of CREB fused to the VP64 transactivation domain in mouse RGCs promoted axon regeneration after optic nerve injury. Our study provides a map of the chromatin accessibility during RGC development and highlights that TF associated with developmental axon growth can stimulate axon regeneration in mature RGC.

Retinal Ganglion Cells (RGCs) in the retina receive visual information from bipolar cells and transmit it to several regions in the brain via axons projecting into the optic nerve. RGCs originate from retinal precursor cells and most of them are born between E11 and E20. Transcription factors (TFs) such as Pax6, Math5, Pou42, form a hierarchical network that regulates RGC differentiation from retinal precursors in space and time. Once differentiated, RGCs grow their axons towards the brain through the optic nerve. Early born RGCs (born before E16) arrive at the superior colliculus before birth while late born RGCs (born after E16) arrive at the superior colliculus at P4/P5. Right before eye-opening (P12), all RGCs have formed stable synapses with their brain targets, providing a functional visual system. The maturation of the visual system correlates with a decrease in the regenerative capacity of RGCs. Therefore, RGC injury in adult mammals is followed by axon regeneration failure and a degeneration process that leads to cell death. As a result, diseases that cause optic nerve damage such as traumatic optic neuropathy, glaucoma, or optic nerve ischemia result in an irreversible loss of vision. Identifying molecular and cellular mechanisms that increase survival and regeneration of RGC may offer new treatment strategies for patients with glaucoma or other types of optic neuropathies.

RGCs lose their capacity to grow axons after birth3,4. Axon growth capacity in rat RGCs peak at embryonic day 21 (E21), and start declining after birth reaching their minimum growth potential at postnatal day 11 (P11), right before eye-opening suggesting that the axon growth program is substituted by a synapse function program. Isolation of RGCs by immunopanning, laser microdissection, and cell sorting has enabled the identification of gene expression changes between these developmental stages and the differences in axon growth capacity between RGC subtypes. Multiple TFs that promote axon growth, such as CREB, SOX11 and KLF7 are downregulated during RGCs development. Other TFs that inhibit axon growth such as KLF4 and KLF9 are upregulated during development. Overexpressing KLF7 and Sox11, or deleting KLF4 and KLF9 promotes axon regeneration after...
Results

Genetic programs that control axon growth are downregulated during RGC development. To determine the transcriptional changes that occur between embryonic 21 days (E21) and postnatal 11 days (P11) RGCs, RNA was extracted from immunopanned RGCs and sequenced in four independent replicates. We identified 3,646 genes differentially regulated (log2 fold change >1 and Benjamini–Hochberg corrected p value <0.01) between E21 and P11 RGCs (Fig. 1A, Supplementary Fig. 1A, and Supplementary File 1). There were 1,116 genes differentially upregulated and 2,530 genes downregulated at E21 (Supplementary Fig. 1B). RNA expression analysis showed that RGC marker genes such as Pou4f1 and RBPMS were highly enriched compared to markers of microglia, astrocyte, Muller cells, photoreceptor, bipolar, and amacrine cells (Supplementary Fig. 1C), as expected from previous publications reporting 99% purity of RGCs derived from this immunopanning technique. We also observed that many of the marker genes for RGC subtypes identified by single cell sequencing, such as Nefh (intrinsically photosensitive RGCs, ipRGCs), Opn4 (on/off direction sensitive RGCs, oDSGCs), and Cartpt (ON–OFF directional sensitive RGCs, oDSGCs), were expressed at lower levels at E21 and were significantly upregulated at P11 (Supplementary Fig. 1C). This suggests that E21 RGCs are not fully differentiated and that RGCs lose their capacity to grow axons during their differentiation into different subtypes. Interestingly, some RGC subtypes such as ipRGCs and, especially, αRGCs retain some axon growth capacity while others such as oDSGCs do not.

Gene Ontology (GO) analysis revealed that Biological Processes (BP) related to axon guidance and axonogenesis are enriched at E21 (Fig. 1B, Supplementary File 2), including genes whose protein products are localized in RGC growth cones such as CRMP1, STBN1, GAP43, and β-tubulins, aligning with an essential role in axon growth and pathfinding in E21 RGCs (Fig. 1F). GO Molecular Function revealed enrichment at P11 of genes related to voltage-gated channels, including the L-type calcium channel Cav1.4 subunit (Cacna1f) (Fig. 1C, Supplementary File 2) aligning with their role in synapse function and neuronal activity at P11. It is noteworthy that prior studies have shown that voltage gated ion channels, specifically L-type calcium channels, suppress axon regeneration in sensory neurons25. GO analysis for Molecular Function also showed an enrichment of genes related to transcription factors at both E21 and P11 (Fig. 1C, Supplementary File 2). We observed E21 upregulation of TF genes with known role in optic nerve axon regeneration such as Sox11, Klf6, Myc, and Klf7, and other TFs such as Dlx2, Runx1, Foxd1, Zic3, and Isl1 with described role in axon growth development. Interestingly, αRGCs have higher levels of Myc in postnatal stages compared to other subtypes25, suggesting high Myc expression levels in αRGCs may partially explain their higher axon growth capacity. We did not observe major changes in genes related to epigenetic regulation, with few exceptions such as HDAC10, which is upregulated at E21 and HDAC11, which is downregulated at E21. We also observed postnatal upregulation of the MEF2 family of TFs, which are known to work together with class IIa HDACs such as HDAC524. Whereas HDAC5 promotes optic nerve regeneration23, deleting MEF2 members promotes RGC survival but not axon regeneration after optic nerve injury25. The Molecular Function GO analysis also showed enrichment of genes related to growth factor binding. We observed some key growth factor receptors genes upregulated in E21 such as Insr, Lgfl1r and
Figure 1. RNA-seq analysis of E21 and P11 purified RGCs. (A) Differentially expressed genes (DEGs) between E21 and P11. The cut off for DEGs displayed in the figure was log2 fold change > 1 and false discovery rate (FDR) adjusted p values < 0.01, which includes a Benjamini–Hochberg correction. Red represents gene expression above average expression level across all samples. Blue represents gene expression below average expression level across all samples. A total of 3,646 genes were differentially expressed, 1116 upregulated and 2530 downregulated in E21. (B–D) Gene ontology (GO) analysis of the DEGs. A subset of the most significantly enriched GO terms in (B) biological processes (BP), (C) molecular functions (MF) and (D) cellular component (CC) are represented. GO terms with a FDR corrected p value < 0.05 were considered as significant. (E) KEGG pathways analysis of DEGs. A subset of the twelve most significantly enriched pathways are represented. (F) Gene expression change between E21 and P11 of key individual genes from the most relevant pathways to axon growth in (B–D).
that pathways related to ribosome function and axon guidance are enriched in E21, whereas neurophysiological analysis reveals that, as expected, E21 RGCs are in an active axon growth stage, whereas P11 RGCs have established synapses and downregulated the axon growth program. MMP9 (inhibitor of axon growth). P11 RGCs upregulate matrix metalloproteinase 9 (MMP9) which is known to regulate cell death in these cells.

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Changes in gene expression correlate with changes in chromatin accessibility at the promoter regions during RGC development. To ensure robust results in downstream analyses, we only used OCRs that were identified in both biological replicates for each developmental stage. A total of 116,417 OCRs were shared by both E21 samples, and 131,806 OCRs shared by both P11 samples (Fig. 2B). These OCRs, at either E21 or P11, were used to determine whether mRNA expression levels correlate with chromatin accessibility at promoter region (<3 kb from TSS), genic region (intron and exon), and distal region (>3 kb but <100 kb from TSS) at each developmental stage. The value for chromatin accessibility for each gene was defined as the sum of the average normalized peak counts of all the OCRs associated with a gene at each studied region. The chromatin accessibility of the promoter region moderately correlated with the RNA expression at each stage (Fig. 2C, D). Also, the changes in chromatin accessibility at the promoter region between E21 and P11 moderately correlated with the changes in RNA expression between E21 and P11 (Fig. 2E). In contrast, the chromatin accessibility at the genic and distal region correlated very weakly to RNA expression (Supplementary Fig. 2D–I). OCR visualization of selected RAGs, which were differentially expressed and downregulated, was performed near the TSS of representative genes Smad1 (promoter of axon growth) and Klf9 (inhibitor of axon growth). DORs are represented in blue accordingly to the developmental stage where this region is more accessible.

Ngfr, which may contribute to a higher activation of PI3K/mTOR pathway at this stage providing a higher axon growth potential. Surprisingly, we did not observe a differential expression of genes related to lipid metabolism such as protrudin-1 (Zfyve27) suggesting that these changes may happen later during development. Cellular components (CC) enriched at E21 are predominantly related to ribosomes suggesting active cell growth at this stage (Fig. 1D, Supplementary File 2). A decline in ribosome gene expression has been observed during neuronal development and has been related to the loss of axon growth capacity. Multiple ribosome genes are downregulated in P11 including Rpl24 and Rpl26, which have been previously implicated in axon growth decline during development. Genes related to extracellular matrix were also enriched at P11 (Fig. 1D, Supplementary File 2) suggesting that RGCs regulate their surrounding extracellular matrix during development. We observed that P11 RGCs upregulate matrix metalloproteinase 9 (MMP9) which is known to regulate cell death in these cells. Whether the interplay between RGCs and surrounding cells during development affects axon growth capacity is unknown.

Box plot representing chromatin accessibility of E21 and P11 replicates near the TSS of representative associated genes Smad1 (promoter of axon growth) and Klf9 (inhibitor of axon growth). DORs are in an active axon growth stage, whereas P11 RGCs have established synapses and downregulated the axon growth program.
Figure 3. Differentially open regions (DORs) are preferentially located at the promoter region of E21 genes and correlate with RNA gene expression changes. (A) The number of OCRs that were present in both samples of each developmental stage and the number of DORs (cross-hatched area) obtained using DESeq269 implemented in the ATAC-seq Integrative Analysis Package (AIAP) package with default parameters. (B) Distribution of DORs with respect the closest gene TSS. (C) Read count frequency of DORs with respect to TSS. (D) Distribution of DORs in the different regions of the genome. (E) Number of DORs at the promoter region (<3 kb from TSS), distal region (>3 kb but <100 kb from TSS), and genic (intron + exon) region. (F) Genes associated with DORs present at the promoter, distal, and genic region. (G) RNA expression changes at E21 and P11 in relation to the presence of DORs at the promoter region. Each row represents a gene that is associated with only E21 DORs (green), only P11 DORs (red), or both E21 and P11 DORs (purple). (H) Pearson correlation coefficient (p < 0.01) of log2 fold changes in gene expression between E21 and P11 and log2 fold changes in peak signal of DORs that are located in the promoter regions.
at TSS compared to P11 DORs (Fig. 3B,C). More E21 DORs were located within promoters whereas P11 DORs were more prominent in introns compared to E21 (Fig. 3D). As a result, we identified 1,583 E21 DORs and 747 P11 DORs in the promoter region (< 3 kb from TSS) (Fig. 3E). Genes associated with these DORs were identified, resulting in 1,427 genes associated with E21 DORs (Fig. 3F) including RAGs such as Smad1, Tubb3, Jun, and Myc (Fig. 2F and Supplementary Fig. 4). We found 689 genes that were associated with P11 DORs (Fig. 3F) including RAGs such as Klf9 and Klf2 (Fig. 2F and Supplementary Fig. 4). Only 29 genes were associated with both E21 and P11 DORs in the promoter region, with chromatin openness changing in opposite directions during development (Fig. 3F). Interestingly, The E21 DOR- associated genes had fewer OCRs at P11 and those OCRs were evenly dispersed across the 3 kb regions surrounding the TSS (Supplementary Fig. 3B). The P11 DOR-associated genes had also fewer OCRs at E21. However, those OCRs were enriched in the TSS regions (Supplementary Fig. 2E). These results demonstrate that the E21 and P11 DOR associated-genes have distinct chromatin accessibility between these two developmental stages.

Next we investigated the relationship between changes of chromatin openness at the DORs and changes in mRNA expression of the DOR-associated genes between E21 and P11. The stage-specific increase of RNA expression levels of the DOR-associated gene is associated with the presence of stage-specific DORs at the promoter region (Fig. 3G) but not DORs at the genic or distal regions (Supplementary Fig. 3C,E). The changes in mRNA expression of the DOR-associated genes and the changes in chromatin accessibility of the DORs have a moderate but significant correlation at the promoter region (Fig. 3G,H). In contrast, we observed a very weak correlation at the genic region and no significant correlation at the distal region (Supplementary Fig. 3C-F).

**TF binding sites (TFBSs) are enriched in developmental stage-specific DORs.** To identity potential TFs regulating the transcriptional change between E21 and P11, we performed TF binding motif enrichment analysis to identify TFBSs that were enriched in the DORs of either E21 or P11, located in the promoters, since these regions significantly correlated with mRNA expression (Fig. 3G). Overrepresentation index (ORI), which takes into account the frequency and the density of a particular binding motif in a set of target sequences, was calculated to measure how much more probable it is to find a particular TF binding motif in stage specific DORs than in a random background set in the genome. We identified six binding motifs that were exclusively enriched (false discovery rate (FDR) adjusted p values < 0.01) at E21 DORs but not at P11 DORs (Fig. 4A and Supplementary File 3). The TFs associated with these binding motifs include CREB/ATF, E74A (mammalian ortholog: ELF), bZIP911, v-Jun, ACAAT, and CCAAT. However, these last 4 binding motifs appear in less than 5% of the DORs underlining a widespread role regulating the E21 transcriptome. In contrast CREB/ATF and E74A appeared in more than 50% of the DORs supporting an important role in regulating E21 genes (Supplementary File 3). We also found 78 binding motifs that were exclusively enriched in P11 DORs but not in E21 (Supplementary File 3) including MEF2, BACH, and RAR-related orphan receptors (Fig. 4B). Binding motifs of certain TFs were found to be enriched in both E21 and P11 DORs suggesting that they control different genes depending on the cellular context. Some of these binding motifs were more predominant in one particular stage as shown by the ORI ratio (Log2 E21 ORI/P11 ORI; Supplementary Fig. 5 and Supplementary File 3). These TFs include TAX/CREB, NRF-1, E2F, MYC, HIF1, and c-JUN in E21, and LXR in P11. Some of them has been shown to have a role in axon growth such as MYC45, HIF146, c-Jun47 and NRF-148. This suggests that their activity or the number of genes they regulate may vary during development.

We additionally performed TFBS enrichment analysis using HOMER software49 (Supplementary File 4). In this case, the percentage of DORs containing the TF motif is calculated for E21 and P11 DORs and compared to a random background sequence obtained from the complementary regions of the OCRs to calculate statistical differences. Therefore, TF binding motifs that appeared significantly more in DORs than in a background sequence were considered to be enriched (Supplementary File 4). Twenty-three and seven TF motifs for E21 and P11, respectively, were significantly enriched (Benjamini adjusted p values < 0.01) for at least two folds in the DORs compared to the background set (Fig. 4C,D and Supplementary File 4) and appeared in more than 5% of DORs at the specific developmental stage. Interestingly, these TF binding motifs are uniquely enriched in one of the developmental stages which supports their role in controlling programs at a specific developmental stage. We found binding motifs being enriched exclusively in E21 DORs such as CREB, c-MYC, CTFC, YY1, RFX, JUND, NRF1, ELF1, and E2F (Fig. 4C) and other set of binding motifs being enriched exclusively in P11 DORs, such as MEF-2, BACH2, and ROR receptors (Fig. 4D). Other TFs that have been described as pro-regenerative in the literature such as SOX449, HIF146 and STAT350 were also significantly enriched in E21 DORs with frequencies 1.6 to 1.9 times higher than the background set (Supplementary File 4), although is lower than the stringent cutoff we set in Fig. 4C. Interestingly, CREB and MEF2 motifs were found to be uniquely enriched in E21 and P11 respectively, by both methods which utilize different TFBS motif database and very different statistical frameworks. Many TFBS motifs found to be more highly enriched in E21 than P11 by ORI ratio were found to be uniquely enriched in E21 by HOMER, e.g. MYC, JUND, NRF1 and E2F, demonstrating consistent high activity of those TFs in E21. The mRNA expression levels of most TFs correlated with their binding motif enrichment at their given developmental stage (Fig. 4E) supporting the role of TFs, such as CREB, c-MYC, JUND, NRF1, CTFC, E2F7, RFX, YY1 and MEF2 in regulating RGC transcriptional change during development.

**Proteomic analysis of RGC nuclear fractions confirms the presence of TFs regulating transcriptional change.** Since the presence of an mRNA does not always guarantee the presence of its corresponding protein, we performed a proteomic analysis of isolated nuclei from E21 and P11 RGCs to identify TFs that are expressed in RGC nuclei at the protein level. A total of six E21 samples and five P11 samples were analyzed by LC–MS (Supplementary File 5). We identified 1192 proteins present in RGC nuclei. GO enrichment analysis showed that these proteins were enriched for nuclear function-related terms (Fig. 4F), confirming that nuclei
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A: E21 enriched motifs (ORI)

B: P11 enriched motifs (ORI)

C: E21 enriched motifs (HOMER)

D: P11 enriched motifs (HOMER)

E: RNA expression and HOMER value of selected TFs

F: Proteomic analysis of isolated RGC nuclei

G: TF protein expression in isolated RGC nuclei
CREB binding domain motifs are widespread at the promoter region of E21 DEGs. Since we detected the presence of CREB and ATF2 at the protein level in RGC nuclei (Fig. 4G) and the CREB/ATF binding motif is enriched at E21 DOGs in our binding motif analysis (Fig. 5A), we focused on this binding motif to identify the specific pathways regulated by CREB in E21 RGCs. From the 766 DEGs that have at least one OCR in their promoter, CREB/ATF binding motif appeared in 498 of them. We performed Biological Processes GO analysis for the group of genes with CREB/ATF binding motifs and found that these genes predominantly regulate neuron differentiation, axonogenesis and cytoplasmic translation (Fig. 5B). We next performed Molecular Function GO analysis and found that CREB/ATF binding motif predominantly appears in the promoter of genes that have DNA binding transcription factor activity including regenerative TFs such as SMAD1, KLF7, MYC, or SOX11, and also ribosome genes (Fig. 5C). GO Cellular Component analysis confirmed that many of the genes with CREB/ATF binding motif at their promoter region are ribosomal (Fig. 5D). Altogether, these analyses suggest that CREB occupies a high rank in the hierarchical order of regenerative TFs and also plays an important role regulating ribosome biogenesis.

CREB-VP64 overexpression promotes optic nerve regeneration. Our ORI and HOMER analysis revealed that CREB binding motifs are enriched in E21 DOGs, suggesting that during development, CREB target gene regulation decreases as axon growth capacity declines. Therefore, we tested if overexpressing an active form of CREB would promote axon regeneration. To achieve this, we fused CREB to the VP64 transactivation domain, a tetramer of the 11 amino acids minimal activation domain of VP16, which significantly increases the recruitment of transcriptional machinery and increases activation compared to VP1651. Previous studies have demonstrated that the addition of VP16 on pro-regenerative transcription factors increases their ability to drive regeneration in vivo5,14,32. We performed intravitreal injections of AAV-CREB-VP64 fusion, or AAV-GFP as a control, as described previously15. This procedure achieves expression of the transgene in ~70% of RBPMS positive RGCs (Supplemental File 6). Fourteen days after viral injection, we performed optic nerve crush injury. After another fourteen days, retina were dissected to quantify cell survival or the fluorescently labeled cholera toxin b was injected to track regenerating axons. We found that overexpression of CREB-VP64 did not significantly increase RGC survival two weeks post optic nerve injury compared to GFP control (Fig. 6A,B). However, overexpression of CREB-VP64 significantly promoted optic nerve regeneration compared to GFP control, tripling the number of regenerating axons (Fig. 6C,D). The extent of axon regeneration we observed two weeks after optic nerve injury is similar to what has been reported by manipulating SOX11, c-Myc or SOCS33,27,45 or by expressing the combination of the transcription factors Oct4-Sox2-Klf441. These results indicate that CREB-VP64 promote RGC axon regeneration, supporting a key role for the CREB-dependent transcription program in the axon growth capacity of RGCs. Further studies will be needed to test if CREB overexpression synergizes with other TFs like ATF2 or other strategies targeting the mTOR signaling pathways22,29,31,53 or DNA methylation patterns41.

Discussion
In the present study, we used RNA-seq, ATAC-seq, and proteomics analyses to identify the key TFs regulating RGC axon growth capacity during development. We have shown that the RNA expression of genes that control axon growth and ribosome biogenesis are downregulated during RGC development, and that the mRNA expression changes correlate with chromatin accessibility changes at the promoter region. We found that binding motifs...
of several TFs that are present at the protein level such as CREB, JUND, CTCF and YY1 are enriched at these chromatin regions. The CREB/ATF motif is especially prevalent, and is enriched at the promoter regions of other regenerative TFs, suggesting a high rank of CREB in the hierarchical order of TFs regulating axon growth. In accordance with this role, overexpressing CREB fused to the VP64 transactivation domain in RGCs promotes...
optic nerve regeneration to a similar extent as targeting the mTOR pathway\textsuperscript{23,29,31,33} and DNA methylation\textsuperscript{11} or expressing the transcription factors Sox11, c-Myc or SOCS\textsuperscript{38,27,45} or protrudin\textsuperscript{26}, partially reverting the poor regenerative capacity of adult RGCs. Our analysis provides a map of the chromatin accessibility in acutely purified retinal ganglion cells at two different stages of development. Immunopanning enabled us to obtain a sufficient number of cells with purity close to 99% and with good RNA and DNA integrity. A downside is that it takes a few hours to dissociate and isolate the RGCs, which may result in gene expression changes. However, previous studies have shown that those changes are small\textsuperscript{54} and limited to immediate early genes\textsuperscript{7} and thus do not preclude obtaining reliable gene expression data. Since RGCs represent less than 0.5% of all the cells in the retina, our study provides more specific information of the TFs regulating axon growth than studies analyzing whole retina tissue\textsuperscript{30,55}. Specifically, we found that the downregulation of genes in postnatal stages, such as axon growth genes and ribosomal genes, correlates with specific promoter regions becoming less accessible. In contrast, genes that regulate synapse function are upregulated during development and their promoter regions become more accessible. Our results are consistent with the observation that in the cortex, there is a developmental change in promoter accessibility that correlates with gene expression\textsuperscript{56}. Venkatesh et al. study demonstrates that the target genes of the key RAGs STAT3 and JUN, but not SOX11 and KLF6, become less accessible in the adult stage\textsuperscript{56}. This study was however limited by using a heterogenous population of cortical cells, whose proportions are dynamically changing during development. Another advantage of our study is that we complemented our TF binding motif analysis with proteomic analysis of RGC nuclei. This allowed us to confirm the presence at the protein level of several of the TFs whose binding motifs were enriched at DORs such as CREB, JUND, CTCF, YY1, and ATF2. We also observed TFs whose target regions are becoming less accessible during RGC development including TFs with known roles in axon regeneration, such as CREB, JUN, SOX4, c-MYC, CTCF and HIF1\textsuperscript{15,8,14,20,45–47}, as well as other TFs whose roles in axon regeneration have not been thoroughly studied such as YY1, NRF1 and RFX. Interestingly, KLF's motifs were not found to be predominantly enriched at any stage. KLF6 and KLF7 are highly expressed in embryonic stage, whereas KLF2 and KLF9 are highly expressed in postnatal stage\textsuperscript{5}, and these TFs

Figure 6. Overexpressing CREB-VP64 promotes optic nerve regeneration. (A) Representative images of retinal wholemounts stained for RBPMS (white) to label RGCs in the uninjured and injured condition 2 weeks after optic nerve crush. Scale bars = 50 µm. (B) Quantification of RGC survival 2 weeks post crush. Eyes injected with AAV2-CREB-VP64 (n = 7 animals) showed a trend towards increased survival compared to eyes injected with AAV2-GFP that was not significant (unpaired T-test. p = 0.1308). Error bars represent mean ± SEM. (C) Representative images of optic nerves sections showing regenerative fibers of mice intravitreally injected with either AAV2-CREB-VP64 or AAV2-GFP. Scale bar = 250 µm. (D) Number of regenerative fibers at various distances. Multiple t-test analysis with Holm-Sidak correction. * p adj < 0.05. n = 6 optic nerves per treatment. Four optic nerve sections were used to calculate the average for each nerve. Box-Whiskers plot was used where the box represents the 25th and 75th percentiles, the inside line represents the median, and the whiskers represents the largest and smallest values.
have opposing effects in axon growth. Since TFs of the same family bind to similar motifs, it is possible that we were not able to distinguish whether the binding motif present at the DOR is from an axon growth promoting (KLF6 and KLF7) or axon growth inhibitory KLF (KLF9 and KLF2). We also found that the promoter regions of regenerative RAGs such as SMAD1, MYC and TUBB3 were less accessible in P11 RGCs compared to E21. In Zebrafish, a species that can successfully regenerate axons in the optic nerve, chromatin accessibility does not significantly change between non injured RGCs and regenerating RGCs. This suggests that in zebrafish, the chromatin remains fairly open at the target genes of regenerative TFs, whereas in mammals, the chromatin closes during development, limiting the access of regenerative TFs to activate the expression of RAGs after optic nerve injury. Altogether, these results supports the notion that in mammals, axon growth decline might be explained by the limited accessibility of TFs to certain regions of the chromatin.

Our chromatin analysis also showed that the DORS at the promoter of postnatal genes are enriched for certain TF binding motifs, including MEF2. Interestingly, MEF2 isoforms were upregulated in postnatal stage in our RNA-seq data, and MEF2A and MEF2D were also identified at the protein level in postnatal RGC nuclei. This suggests that MEF2 might have an important role in regulating RGC maturation and potentially axon growth inhibition. However, it has been recently shown that deleting MEF2 or overexpressing a MEF2 dominant negative isoform promote RGC survival but not optic nerve regeneration.

It is noteworthy that the expression levels of CREB do not change between E21 and P11 according to our RNA-seq and proteomics data. This contrasts with prior studies showing that CREB is higher in actively growing RGCs compared to those that have already reached their targets. Our approach does not allow us to differentiate between those two developmental states, which may explain why the higher expression at E21 in our data is unable to reach statistical significance. Another possibility is that differences in axon growth capacity between the two stages may be not entirely relate to a higher expression of CREB but also to a higher activation state of CREB in RGCs. Our chromatin accessibility analysis suggesting that this TF is regulating transcriptional changes in embryonic stage. CREB activity is regulated by cAMP levels and previous studies have shown that the levels of cAMP drop after birth during CNS and PNS neuron development. In rat RGC, cAMP levels are three times higher in E18 compared to P5. This suggests that CREB is activated and regulating axon growth genes in embryonic RGCs. After birth, cAMP levels drop and therefore transcription of axon growth genes by CREB ceases. Interestingly, activating CREB by increasing cAMP levels in vivo has shown controversial results. Some studies reported modest increase in optic nerve regeneration, whereas others showed that increasing cAMP alone was not sufficient to promote optic nerve regeneration, but could when combined with other stimuli such as providing neurotrophic factors, oncomodulin or PTEN deletion. In addition, elevating cAMP in cultured RGCs by adding forskolin does not fully revert the axon growth decline observed in postnatal RGC. We observed that the chromatin in the promoter region of axon growth promoting genes is less accessible in postnatal RGCs, suggesting that endogenous CREB activated by cAMP may be unable to effectively access these chromatin sites to promote regeneration in adult RGCs. We demonstrate that expression of CREB fused to the transactivation domain VP64 in adult RGCs promotes optic nerve regeneration. Therefore, CREB-VP64, but not endogenous CREB activated by cAMP, might be able to open the chromatin of pro-regenerative CREB target genes to induce optic nerve regeneration. Transactivation domains such as VP16 and VP64 are well-known chromatin-modifying agents that open chromatin and greatly activate transcription. However, it is possible that other TFs in combination with CREB-VP64 could further increase the number of regenerating RGC and the distance at which they regenerate. Combining CREB-VP64 with other TFs or treatments targeting the neurotrophic factor CNTF, mTOR or DNA methylation might provide a synergistic effect in optic nerve regeneration.

**Methods**

**Retinal Ganglion cell immunopanning purification.** All animal protocols were approved by the Washington University School of Medicine Institutional Animal Care and Use Committee (IACUC) under protocol A3381-01. All experiments were performed in accordance with the relevant guidelines and regulations. All experimental protocols involving rats and mice were approved by Washington University School of Medicine (protocol #20180128). Mice and rats were housed and cared for in the Washington University School of Medicine Animal Care facility. This facility is accredited by the Association for Assessment & Accreditation of Laboratory Animal Care (AAALAC) and conforms to the PHS guidelines for Animal Care. Accreditation—7/18/97, USDA Accreditation: Registration # 43-R-008. The study was carried out in compliance with the ARRIVE guidelines.

The isolation of RGCs was performed by using a slightly modified version of the immunopanning procedure originally established in Barres laboratory. For embryonic RGCs, E21 day pregnant Sprague Dawley rats were euthanized by CO2 and embryos were transferred to a plate with DPBS where retinas were dissected out and cleaned. For postnatal RGCs, P11 Sprague Dawley pups were euthanized by CO2 and eyes were transferred to DPBS medium where retinas were dissected. Next, RGCs were isolated as previously described. Briefly, retinas were transferred to a filtered solution of papain in DPBS containing 2 mg of L-Cysteine and 2000 units of DNase. For E21 retina, 140 units of papain were added. For P11, 200 units were added. After 30 min, enzymatic solution was removed and retinas were triturated to obtain a single cell solution. RGCs were isolated by immunopanning. First, negative selection using an anti-macrophage antibody and then positive selection using anti-thyl antibody. RGCs attached to the plate were trypsinized, counted in a Neubauer, and centrifuged for subsequent processing. The procedure of dissociating and panning cells, which lasts 3–4 h, may result in gene expression changes. However, previous studies have shown that gene expression changes during tissue dissociation are small and limited to immediate early genes. Therefore this technique is suitable for comparing the transcriptome of the purified cells in two different developmental stages.
RNA sequencing and analysis. Total RNA from 700,000 to 1.25 million RGCs from four independent rat litters per developmental stage was isolated using the Qiagen RNAeasy kit from Qiagen, which included a 15 min On-column DNase step. RNA was stored at −80 °C and sent to Genome Technology Access Center at Washington University for library preparation and sequencing. RNA quality was assessed using an Agilent Bioanalyzer (RIN > 9.5). Samples were subjected to DNase treatment. rRNA depletion was achieved with the Riboprobe rRNA removal kit. Library preparation was performed using the SMARTer kit (Clontech), and sequencing was performed on an Illumina HiSeq3000. Basecalls and demultiplexing were performed with Illumina’s bcl2fastq software and a custom python demultiplexing program with a maximum of one mismatch in the indexing read. Sequences were adapter-Trimmed using Cutadapt 1.168 and subjected to quality control using PRINSEQ 0.20.466 and aligned to Rat (Rattus norvegicus) annotations based on genome assembly RNOR6 using STAR 2.5.3a.67. Reads in features were counted using HTseq 0.6.1.18. Genes differentially expressed between conditions were identified using DESeq250 with log2FC > 1.0 and a false discovery rate (FDR) adjusted p values < 0.01, which includes a Benjamini–Hochberg correction96. Variance stabilizing transformation (VST) normalized counts were calculated using DESeq2, and normalized gene counts were converted to Z scores for plotting. Heatmaps were generated using ComplexHeatmap R package70. Sequencing performance was assessed for total number of aligned reads, total number of uniquely aligned reads, genes and transcripts detected, ribosomal fraction, known junction saturation, and reads distribution over known gene models with RSeqC 2.6.241. R package clusterProfiler72 was used for GO and KEGG pathway enrichment analysis and plotting. GO and KEGG pathway terms with FDR corrected p value < 0.05 were considered as significant. R version 4.0.4 was used for statistical analysis and plotting.

R (citation: R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/).

ATAC-seq and data analysis. After isolation, 300,000 RGCs from two independent rat litters per developmental stage were centrifuged and resuspended in Neurobasal/B27 + medium and 10% DMSO, to quick freeze at −80 °C. Samples were processed by UCSD Center of Epigenomic Technologies using their proprietary assay for Transposase-Accessible Chromatin coupled with high-throughput sequencing (ATAC-seq). ATAC-seq Integrative Analysis Package (AIAP) was used for sequence quality assurance, mapping, open chromatin region (OCR) calling42. We used DESeq250 implemented in the ATAC-seq Integrative Analysis Package for downstream differential open chromatin region identification. Those OCsR that have FDR adjusted p value < 0.01 and log twofold change > 1 were considered DORs (differentially open regions). Following data quality control analyses were performed for each sample and across the projects: (1) Reads under peak percentage ranged 31.6–39.3%. (2) Signal enrichments around the TSS relative to genome wide average, a metric which identifies datasets with high signal to noise ratios, ranged 10.8–14.4%. (3) Pearson correlation coefficient between the two replicates were calculated to measure the concordance between the two biological replicates. To ensure the robustness of our analysis we used only OCsR that were present in both biological replicates of either stage for downstream analyses. This ensures that only the most robust peaks were included in the analyses.

Transcription factor binding motif enrichment analysis and CREB target analysis. To identify candidate transcription factors that regulate differentially expressed genes, the HOMER49 and motif over-representation index (Motif-ORI)44 algorithms were used to identify transcription factor binding sites enriched in the differentially open region. Genomic regions complementary to the region of all the called OCsR (considered as all of the non-open regions in the genome) were obtained and were provided as the background set sequence for HOMER analysis. This non-open region set was used as input to perform random sampling of genomic regions to obtain a set of genomic regions with the same number and length distribution as a set of query sequences. This random sampled genomic region set was provided as the background set sequence for Motif-ORI analysis and this analysis is repeated 100 times and statistical significance was calculated using a Student’s t-test with the NULL hypothesis that ORI is not significantly larger than 1.2, a stringent cutoff determined in previous publication44 to distinguish enriched motifs. A motif with Benjamini–Hochberg procedure corrected p value < 0.05 were considered as significant. The TF logo image was generated using enoLOGOS97.

To identify targets of CREB, sequence of OCR peaks were retrieved using BEDTools81 and was scanned using Patser to identify CREB binding sites. The Patser program calculates the probability of observing a sequence with a particular score or greater75,76 for the given matrix and determines the default cutoff score based on that p-value. Any gene with at least one CREB binding site in one of the gene-associated OCR peaks was counted as target gene.

RGC nuclei proteome characterization by LC–MS. Nuclei from 700,000–1.25 million RGCs from 6 E21 and 5 P11 independent rat litters were isolated using the Thermo Scientific NE-PER Nuclear and Cytoplasmic Extraction Kit. Next, trypsin digestion was perform by adding a buffer containing 100 mM ammonium bicarbonate, 10 mM TCEP and 25 mM iodoacetamide followed by digestion with trypsin at 37 °C overnight. The digested sample was acidified with 1% TFA then cleaned up with C18 tip. The extracted peptides were dried down. Proteomic samples were fractionated in a StageTip casted with four SDB-RPS disks (3 M Empore SPE disks). Peptides were sequentially eluted with four buffers of increasing salt content. The four fractions were dried under vacuum and dissolved with 0.1% formic acid for LC–MS analysis. Fractions of each sample were analyzed by LC–MS with a Dionex RSLnano HPLC coupled to an Orbitrap Fusion Lumos (Thermo Scientific) mass spectrometer using a 2 h gradient. Peptides were resolved using 75 μm × 50 cm PepMap C18 column (Thermo Scientific). Sequence mapping and label-free quantification were achieved using MaxQuant (version 1.6.1). MaxQuant was set up to search Human reference proteome (Uniprot.org). The digestion enzyme was set
as trypsin. Carboxymethylation of cysteine was set as fixed modification. Oxidation of methionine and acetylation of N-terminal of protein were specified as variable modifications.

**Optic nerve regeneration assay.** All surgical procedures were performed under isoflurane anesthesia according to approved guidelines by the Washington University in St. Louis School of Medicine Institutional Animal Care and Use Committee. To generate AAV constructs, GFP or CREB (human sequence) were subcloned into an AAV transfer plasmid provided by the Washington University Viral Core which uses the CMV promoter. AAV2 viral particles were generated by Washington University Viral Core with titers for AAV2-CREB-VP64 (2.4 × 10^{13} vg/ml) and AAV2-GFP (1.7 × 10^{13} vg/ml). Five week old C57Bl/6 mice were anesthetized with isoflurane and intravitreally injected with 1.25 µl of the AAV2-CREB-VP64 or AAV2-GFP virus two weeks before optic nerve crush using a Hamilton syringe and a pulled glass attached by an adaptor. Optic nerve crush was performed by a surgeon blinded to treatment as previously described\(^2\). Mice were anesthetized by isoflurane inhalation, and optic nerve was exposed and crushed for 3 s with a 50 forceps. For analgesia, 1 mg/kg buprenorphine SR-LAB (ZooPharm) was administered subcutaneously. Two weeks after surgery, mice were intravitreally injected with 1.5 µl of 1 mg/ml fluorescent Cholera toxin B. Two days after, animals were sacrificed by CO\(_2\) inhalation and perfused with PBS followed by 4% Paraformaldehyde. Nerves were dissected out and post-fixed for 4 h, washed in PBS and incubated in 30% Sucrose solution overnight at 4 Celsius. Nerves were then dissected and sectioned at 11 µm thickness. Optic nerve sections were imaged in a fluorescent microscope. The number of axons growing at 250, 500, 750 and 1000 µm distal from the injury site were quantified by a researcher blinded to treatment. Multiple t-test analysis with Holm-Sidak correction was performed.

For RGC survival assay, eyes were dissected out of the orbit with Vanna scissors and immersed in 4% PFA overnight at 4 °C. Eyes were transferred to PBS and the cornea, iris, lens, sclera, choroid were removed and the whole retina collected in a 24-well plate under a dissection microscope as described\(^7\). Following five 5-min washes with PBS, TBST blocking buffer (10% normal donkey serum, 0.5% TritonX-100 in PBS) was applied for 3 h at room temperature with gentle rotation. This was replaced with anti-RBPM5 primary antibody (generous gift by Dr. Philip Williams, Cat# ABN1376, EMD Millipore, USA; 1:500) or anti-GFP in TBST blocking buffer at 4 °C overnight with gentle rotation. Following five further 5-min washes with PBS, retina were incubated with Alexa Fluor 594 secondary antibody (1:300) in TBST blocking buffer at room temperature for 2.5 h with gentle rotation. After five further washes with PBS, retina was flattened with four incision and mounted onto charged Superfrost microslides using ProLong Gold antifade mounting reagent (Invitrogen) and allowed to dry overnight at 4 °C. Images of flat mount retina (5 images/flat mount, 1–2 images/quadrant) were acquired using epifluorescence microscope Nikon Eclipse Ti2 with a 40 × objective. Blinded manual counting of all images was performed (100µm² area in each count and 5 count/image). Uninjured eyes were counted (n = 3–4 per group) and the averaged used to normalize the percentage RGC survival.

To count GFP positive RGC, three images of each flat mount retina were used to count GFP positive and RBPM5 positive cells and the % of GFP positive cells was calculated with respect to total RBPM5 positive cells in each image.

**Data availability**

The raw FASTQ files were deposited at the NCBI GEO database under the accession number GSE163564.

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**References**

1. Rapaport, D. H., Wong, L. L., Wood, E. D., Yasumura, D. & LaVail, M. M. Timing and topography of cell genesis in the rat retina. *J. Comp. Neurol.* 474, 304–324. https://doi.org/10.1002/cne.20134 (2004).
2. Dallimore, E. I., Cui, Q., Beazley, L. D. & Harvey, A. R. Postnatal innervation of the rat superior colliculus by axons of late-born retinal ganglion cells. *Eur. J. Neurosci.* 16, 1295–1304. https://doi.org/10.1111/1460-9558.2002.02178.x (2002).
3. Steketee, M. B. et al. Regulation of intrinsic axon growth ability at retinal ganglion cell growth cones. *Invest. Ophthalmol. Vis. Sci.* 55, 4369–4377. https://doi.org/10.1167/iovs.14-13882 (2014).
4. Goldberg, J. L., Klassen, M. F., Hua, Y. & Barres, R. A. Amacrine-signaled loss of intrinsic axon growth ability by retinal ganglion cells. *Science* 296, 1860–1864. https://doi.org/10.1126/science.1068428 (2002).
5. Moore, D. L. et al. KLF family members regulate intrinsic axon regeneration ability. *Science* 326, 298–301. https://doi.org/10.1126/science.1175737 (2009).
6. Moses, C. et al. The acquisition of target dependency by developing retinal ganglion cells. *eNeuro* 2. https://doi.org/10.1523/ENEURO.0044-14.2015 (2015).
7. Tran, N. M. et al. Single-cell profiles of retinal ganglion cells differing in resilience to injury reveal neuroprotective genes. *Neuron* 104, 1039–1055 e1012. https://doi.org/10.1016/j.neuron.2019.11.006 (2019).
8. Norsworthy, M. W. et al. Sox11 expression promotes regeneration of some retinal ganglion cell types but kills others. *Neuron* 94, 1112–1120 e1114. https://doi.org/10.1016/j.neuron.2017.05.035 (2017).
9. Blackmore, M. G. et al. Kruppel-like factor 7 engineered for transcriptional activation promotes axon regeneration in the adult corticospinal tract. *Proc. Natl. Acad. Sci. U S A* 109, 7517–7522. https://doi.org/10.1073/pnas.1120684109 (2012).
10. Apara, A. et al. KL-F9 and JNK3 interact to suppress axon regeneration in the adult CNS. *J. Neurosci.* https://doi.org/10.1523/JNEUROSCI.0643-16.2017 (2017).
11. Lu, Y. et al. Reprogramming to recover youthful epigenetic information and restore vision. *Nature* 588, 124–129. https://doi.org/10.1038/s41586-020-2973-4 (2020).
12. Hellstrom, M. & Harvey, A. R. Cyclic AMP and the regeneration of retinal ganglion cell axons. *Int. J. Biochem. Cell Biol.* 56, 66–73. https://doi.org/10.1016/j.biocel.2014.04.018 (2014).
13. Kurimoto, T. et al. Long-distance axon regeneration in the mature optic nerve: Contributions of oncomodulin, cAMP, and pten gene deletion. *J. Neurosci.* 30, 15654–15663. https://doi.org/10.1523/JNEUROSCI.4540-10.2010 (2010).
Injury-induced HDAC5 nuclear export is essential for axon regeneration. Cell 155, 894–908. https://doi.org/10.1016/j.cell.2013.10.004 (2013).

Puttagunta, R. et al. PCAF-dependent epigenetic changes promote axonal regeneration in the central nervous system. Nat. Commun. 5, 3527. https://doi.org/10.1038/ncomms4527 (2014).

Hervera, A. et al. PP4-dependent HDAC3 dephosphorylation discriminates between axonal regeneration and regenerative failure. EMBO J. 38, e101032. https://doi.org/10.15252/embj.2018101032 (2019).

Finelli, M. J., Wong, J. K. & Zou, H. Epigenetic regulation of sensory axon regeneration after spinal cord injury. J. Neurosci. 33, 19664–19676. https://doi.org/10.1523/JNEUROSCI.0589-13.2013 (2013).

Palmisano, I. et al. Epigenomic signatures underpin the axonal regenerative ability of dorsal root ganglia sensory neurons. Nat. Neurosci. https://doi.org/10.1038/s41593-019-0490-4 (2019).

Schmitt, H. M., Pelzel, H. R., Schlamp, C. L. & Nickells, R. W. Histone deacetylase 3 (HDAC3) plays an important role in retinal ganglion cell death after acute optic nerve injury. Mol. Neurodegener. 9, 39. https://doi.org/10.1186/s13024-015-0236-9 (2014).
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Additional information

The authors declare no competing interests.

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Author contributions

W.P.T. and V.C. designed research. W.P.T. performed RGC purification and optic nerve regeneration assay. A.K. performed RGC survival experiment. T.M.G. analyzed RNA sequencing data. G.Z. performed ATAC-seq and transcription factor binding site analyses. W.P.T. and G.Z. analyzed the data. W.P.T., G.Z. and V.C. wrote the manuscript. All authors approved the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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