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Identification of Molecular Markers of Bipolar Cells in the Murine Retina

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ABSTRACT

Retinal bipolar neurons serve as relay interneurons that connect rod and cone photoreceptor cells to amacrine and ganglion cells. They exhibit diverse morphologies essential for correct routing of photoreceptor cell signals to specific postsynaptic amacrine and ganglion cells. The development and physiology of these interneurons have not been completely defined molecularly. Despite previous identification of genes expressed in several bipolar cell subtypes, molecules that mark each bipolar cell type still await discovery. In this report, novel genetic markers of murine bipolar cells were found. Candidates were initially generated by using microarray analysis of single bipolar cells and mining of retinal serial analysis of gene expression (SAGE) data. These candidates were subsequently tested for expression in bipolar cells by RNA in situ hybridization. Ten new molecular markers were identified, five of which are highly enriched in their expression in bipolar cells within the adult retina. Double-labeling experiments using probes for previously characterized subsets of bipolar cells were performed to identify the subtypes of bipolar cells that express the novel markers. Additionally, the expression of bipolar cell genes was analyzed in Bhlhb4 knockout retinas, in which rod bipolar cells degenerate postnatally, to delineate further the identity of bipolar cells in which novel markers are found. From the analysis of Bhlhb4 mutant retinas, cone bipolar cell gene expression appears to be relatively unaffected by the degeneration of rod bipolar cells. Identification of molecular markers for the various subtypes of bipolar cells will lead to greater insights into the development and function of these diverse interneurons. J. Comp. Neurol. 507:1795–1810, 2008. © 2008 Wiley-Liss, Inc.

Indexing terms: retina; bipolar cells; Bhlhb4; gene expression; microarray; mouse

Bipolar cells in the vertebrate retina are the first relay interneurons in the visual system, connecting rod and cone photoreceptor cells to amacrine and ganglion cells. They are critical for routing and processing of photoreceptor cell signals sent to specific postsynaptic targets. Bipolar cells assume diverse but specific morphologies, evident in their varied axon lengths, terminal field widths, and cell body positions in the inner nuclear layer (INL). For example, bipolar cells postsynaptic to rod photoreceptor cells have cell bodies positioned closest to the outer plexiform layer (OPL), extend axons to the deepest part of the inner plexiform layer (IPL), and form synapses with specific amacrine cells. Cone bipolar cells have cell bodies both close to and relatively distant from the OPL and ramify axonal processes throughout the IPL.

In addition to morphological diversity, molecular differences are found in gene and protein expression among bipolar neurons. Correlation of antibody staining patterns with morphologies of distinct bipolar cell subtypes has led to definition of 10 bipolar cell subtypes in the rodent retina (Haverkamp et al., 2003a; Ghosh et al., 2004; Pignatelli and Strettoi, 2004). Characterization of gene expression...
patterns has aided in elucidating roles of specific bipolar cell subtypes in circuits critical for different aspects of vision (Vardi and Morigiwa, 1997; Vardi, 1998). Additionally, investigators studying retinogenesis have utilized a limited set of bipolar cell molecular markers to describe the development of normal and genetically altered retinas (Bramblett et al., 2004; Chow et al., 2004; Ohtoshi et al., 2004; Cheng et al., 2005; Wan et al., 2005). Identification of a more complete set of markers could lead to further insights into retinal physiology and development.

Investigation of genes differentially expressed among bipolar cells could enhance understanding of their function and ontogeny. Included among known molecules expressed in different subtypes are neurotransmitter receptors, intracellular signal transduction components, calcium-binding proteins, and transcription factors (Grefeath et al., 1990; Berrebi et al., 1991; Euler and Wässle, 1995; Burmeister et al., 1996; Takebayashi et al., 1997; Vardi and Morigiwa, 1997; Koul et al., 1998; Flescher et al., 1998; Vardi, 1998; Baas et al., 2000; Haeseleer et al., 2000; Chow et al., 2001; Ohtoshi et al., 2001; Haevakamp et al., 2003a,b; Huang et al., 2003; Ghosh et al., 2004; Blackshaw et al., 2004). One transcription factor, basic helix-loop-helix transcription factor b4 (Bhlhb4), is specifically expressed in rod bipolar cells (Bramblett et al., 2004). Members of the bHLH class of transcription factors are critical for development and maintenance of retinal cells and neural cells generally (Ross et al., 2003; Pennesi et al., 2003; Hatakeyama and Kageyama, 2004). Analysis of Bhlhb4 knockout mice has revealed that Bhlhb4 is required for rod bipolar cell survival in the late postnatal period after differentiation has occurred and during adulthood (Bramblett et al., 2004).

In this study, we explored the molecular diversity of bipolar cells by identifying novel genetic markers of these neurons through the use of genomic expression screening methods and RNA in situ hybridization. Retinal gene expression data from a combination of microarray and serial analysis of gene expression (SAGE) studies led to identification of candidate bipolar cell genes. Candidates were then evaluated for enriched expression in bipolar cells by using RNA in situ hybridization. Ten novel molecular markers enriched to varying degrees in their expression in bipolar cells were found. The specific bipolar cell subtypes expressing validated bipolar cell genes were assessed with double-labeling by using previously characterized bipolar cell markers. Additionally, newly identified bipolar cell markers were used to analyze Bhlhb4 knockout retinas. The results reveal complex patterns of gene expression, suggesting that overlapping combinations of transcription factors likely control bipolar cell identity and function.

MATERIALS AND METHODS

In vitro electroporation

The previously characterized 4.7-kb calcium-binding protein 5 (Cahbp5) promoter (Matsuda and Cepko, 2004) was cloned upstream of a green fluorescent protein (GFP; Clontech, Mountain View, CA) sequence. CD-1 mouse pups (Charles River Laboratories, Wilmington, MA) were sacrificed at postnatal day (P)7, and retinas were dissected and electroporated as described (Matsuda and Cepko, 2004). Retinas were cultured for 8 days on floating Nuclepore Track-Etch membranes (Whatman, Florham Park, NJ) in 10% fetal bovine serum (Invitrogen, Carlsbad, CA), 45% Dulbecco’s modified Eagle’s medium (DMEM; Invitrogen), 45% F12 nutrient mixture (Invitrogen), 100 U/mL penicillin (Invitrogen), 100 mg/mL streptomycin (Invitrogen), and 2 mM L-glutamine (Sigma, St. Louis, MO). All mice were used in accordance with the guidelines for animal care and experimentation established by the National Institutes of Health and the Harvard Medical Area Standing Committee on Animals.

Gene microarray analysis

Freshly dissected or transfected retinas were dissociated by papain digestion, and single cells were picked from a tissue culture dish by using a fine glass pipette and an inverted microscope as in Trimarchi et al. (2007). Previous estimates suggest that pieogram quantities of RNA are found per cell (Iscove et al., 2002). cDNA from single cells was prepared by using an oligo-dT-containing primer and amplified by a 35-cycle reverse transcriptase-polymerase chain reaction (RT-PCR) protocol detailed in Trimarchi et al. (2007), which was based on previous single-cell PCR amplification methods (Brady and Iscove, 1993; Dulacl and Axel, 1995; Tietjen et al., 2003). cDNA quality was assessed as an indirect measure of RNA quality after PCR by gel electrophoresis, and cDNA with strong bands ranging from approximately 500 to 2,000 bp was used. Previous investigators have shown that this single-cell PCR strategy yields results that are well correlated with input DNA levels, that the cDNA is biased for the 3′ end of genes because an oligo-dT primer is used in the reverse transcription, and that as few as 10 copies of an RNA transcript can be reliably detected after RT-PCR by using microarrays (Tietjen et al., 2003). cDNA probes were hybridized to Affymetrix Mouse Genome 430 2.0 microarrays as in Trimarchi et al. (2007). Signals from microarrays were globally scaled with a target intensity set to 500 by using Affymetrix Microarray Suite software (MAS 5.0).

SAGE data mining

The SAGE library data generated in Blackshaw et al. (2004) were used. Nearest neighbor analysis was conducted by selecting neighbor genes whose temporal expression patterns, based on reliably assigned gene tag counts, displayed the minimal Euclidean distances to the expression patterns, based on reliably assigned gene tag counts, displayed the minimal Euclidean distances to the pattern of a known bipolar cell or rod photoreceptor cell gene. Prior to performing analysis, the temporal expression pattern for each gene was normalized by fixing the tag average and tag standard deviation to common values. This normalization facilitated relative comparison of genes whose absolute expression levels varied widely.

RNA in situ hybridization and antibody staining

Retinas were dissected in phosphate-buffered saline (PBS; pH 7.4), fixed in 4% paraformaldehyde in PBS for 30 minutes at 22°C, rinsed three times, and cryoprotected for 1 hour in 30% sucrose in PBS. Retinas were embedded in OCT (Sakura Finetek, Torrance, CA), and 20-μm sections were cut and slide-mounted by using a cryostat microtome. Riboprobes were polymerized, and RNA in situ hybridization was performed as in Murtaugh et al. (1999) with modifications detailed in Trimarchi et al. (2007). Table 1 shows a list of the antisense riboprobes used and the Genbank accession numbers of sequences from which
riboprobes were derived. As negative controls, sense probes were also hybridized separately to retinal sections.

For double-labeling, P14 retinas were dissected and dissociated by incubation in a solution containing 25 U/mL papain (Worthington, Lakewood, NJ), 3 mM L-cysteine, and 0.5 mM EDTA, and 0.1 mM β-mercaptoethanol in Hank’s balanced salt solution (Invitrogen) at 37°C for 10 minutes. Digestion was stopped by addition of 1.5 volumes of DMEM containing 10% fetal bovine serum, and retinas were incubated in 50 U/mL DNasel (Roche, Indianapolis, IN) at 37°C for 5 minutes. Following manual trituration with a pipettor, cells were rinsed once in DMEM containing 10% fetal bovine serum and then placed onto slides coated with poly-D-lysine (Sigma). Slides were processed, and double-label in situ hybridization was carried out as in Trimarchi et al. (2007). A subset of slides was singly stained with 4',6-diamidino-2-phenylindole (DAPI; 1 μg/mL in PBS, 22°C, 5 minutes; Roche).

Transient receptor potential action channel subfamily M member 1 (Trpm1)

RIKEN cDNA 2030005D11 gene (2030005D11Rik)

RIKEN cDNA 633054A18 gene (633054A18Rik)

Digital images of Cy3-tyramide (Perkin Elmer, Wellesley, MA), Alexa 488-tyramide (Invitrogen), Cy2-antibody, and DAPI-stained cells were processed to quantitate results by using custom image analysis software (J. Aach and G. Church, Harvard Medical School). DAPI-labeled nuclei were used to segment red/green/blue composite images into individual cell images. This was done by applying a particle size filter to remove labeled debris, blurring DAPI-labeled nuclei through averaging of small windows of pixels to smooth intensities, dividing nuclei from one another with borders by using a watershedding algorithm, and fitting ellipses around each nucleus inside of its border. Red and green pixel intensities inside of each segmented nucleus plus a small surrounding perinuclear region were quantitated. Thresholds were set for mean signal intensities for scoring positive cells, and negative, single-positive, and double-positive cells were counted. A subset of images was counted independently to verify accuracy of the automated analysis. Representative photomicrographs are presented as red/green/blue (RGB) images merged in Adobe Photoshop software (Adobe Systems, San Jose, CA), through which raw RGB intensity levels were adjusted visually and uniformly across photographs from the same hybridization to reflect thresholds set for quantitation.

Gene targeting

An approximately 5-kb HindIII/NotI DNA fragment encompassing the Bhlhb4 gene was isolated by PCR from 129/Sv genomic DNA. A loxP-flanked PGK-neomycin resistance cassette in reverse orientation was introduced into the KpnI site approximately 1 kb upstream of the Bhlhb4 gene. This third loxP sequence was introduced approximately 300 bases distal to the Bhlhb4 3’ UTR, between adjacent BsrGI and MunI restriction sites. A PGK-diphtheria toxin gene cassette was introduced at the 3’ end of the Bhlhb4 locus. This vector was electroporated into mouse 129 J1 embryonic stem (ES) cells and selected as described (Li et al., 1992). Clones were screened by Southern blot analysis. Eight of 96 clones were correctly targeted. A null allele was generated by transiently transfecting targeted ES cells with a Cre recombinase plasmid, pOG231 (from S. O’Gorman, Case Western Reserve University). Targeted ES cell clones harboring a deletion of both Bhlhb4 and PGK-neomycin were identified with PCR by using primers that flanked the outermost loxP sites (Bhlhb4 null allele primers; described below).

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TABLE 1. RNA In Situ Hybridization Probes

| Gene name | Genbank accession no. | Unigene | Polymerase used for antisense |
|-----------|----------------------|---------|-------------------------------|
| Basic helix-loop-helix transcription factor B4 (Bhlhb4) | NM_080641, bases 165-896 | Mm.134062 | T7 |
| Carbonic anhydrase 8 (Car8) | A1838156 | Mm.119320 | T3 |
| Carbonic anhydrase 10 (Car10) | NM_029896, bases 322-875 | Mm.342160 | T7 |
| C. elegans ceh-10 homedomain containing homolog (Chx10) | BF461223 | Mm.4405 | T3 |
| Contactin 4 (Cntn4) | BE948217 | Mm.321683 | T3 |
| Glutamate receptor, metabotropic 6 (Grm6) | B121293 | Mm.134365 | T7 |
| LIM homeobox gene 3 (Lhx3) | BE987423 | Mm.15655 | T7 |
| Neurexin (Nnue) | BE986133 | Mm.380307 | T3 |
| Og9 homeobox gene (Og9x) | BE950456 | Mm.134360 | T7 |
| Paired box gene 6 (Pax6) | NM_013627, bases 395-2412 | Mm.3698 | T3 |
| Parkin gene protein 2 (Ptg2) | BE954628 | Mm.41456 | T3 |
| Protein kinase c, alpha (Prkca) | BE987143 | Mm.25667 | T3 |
| Secretagogin (Segn) | BE985968 | Mm.38875 | T7 |
| Transient receptor potential action channel subfamily M member 1 (Trpm1) | BE987910 | Mm.35194 | T3 |
| RIKEN cDNA 203054D11 gene | NM_013627, bases 395-2412 | Mm.3698 | T3 |
ES cells carrying the deletion allele were microinjected into C57BL/6 blastocysts, and chimerae were tested for germline transmission of the mutant allele by breeding to C57BL/6 females and PCR genotyping of pups. Primers used for genotyping were as follows: wild-type allele primers: 5'-AGCTCAAAGTCGTTCGGG-3', 5'-TGGACGACTGGTCTCCTGGC-3'; Bthh4 null allele primers: 5'-CGACCTCTTGCTGAAACAGACAG-3', 5'-GCCGTAGAAGGATTCACCAACCAG-3'. Wild-type (WT) and mutant mice maintained on a mixed 129/Sv X C57BL/6 background were used.

**RESULTS**

Gene expression screening using single retinal cells

In an initial effort to identify candidate novel molecular markers enriched in bipolar cells, oligonucleotide microarrays were used to characterize gene expression in single bipolar cells from the mouse retina. Candidate genes identified in this manner were subsequently validated as being enriched in bipolar cells by RNA in situ hybridization (see further below). Because bipolar cells comprise only a small fraction of total retinal cells (~10%) compared with rod photoreceptor cells (>70%; Young, 1985), individual bipolar cells, instead of whole retinas, were utilized to enrich for genes of interest. Single bipolar cells were picked from enzymatically dissociated mouse retinas based on expression of a GFP reporter construct driven by the Cabp5 gene promoter transfected into retinas at P0 and harvested after 8 days of culture. This Cabp5 promoter has been shown previously to be active in rod bipolar cells and a limited set of cone bipolar cells (Matsuda and Cepko, 2004).

By using a previously described, sensitive RT-PCR-based strategy (Trimarchi et al., 2007; see also Materials and Methods), cDNA from four individual bipolar cells was amplified and then hybridized to microarrays (Table 2; Cabp5 Bipolar A3, A4, B1, and B2). To generate additional expression profiles for comparison, randomly chosen single cells from freshly dissected retinas were picked at P5 and from adults and identified retrospectively as bipolar cells (Table 2; P5 Bipolar A3), rod photoreceptor cells (Adult Rod 1 and 2), or Müller glial cells (Adult Müller Glia 1 and 15) based on expression of known markers. For bipolar cells, these known genes included Cabp5 (Haeseleer et al., 2000) and C. elegans ceh-10 homeodomain-containing homolog (Chx10; Liu et al., 1994; Burmeister et al., 1996). For rod photoreceptor cells, these previously characterized molecular markers were cGMP-specific phosphodiesterase 6b (Pde6b; Hurwitz et al., 1985; Baehr et al., 1991; Chang et al., 2007b), cyclic nucleotide gated channel a1 (Cnga1; Kaupp et al., 1989), and rhodopsin (Rho; Jan and Revel, 1974; Molday and MacKenzie, 1983). For Müller glial cells, these known genes included retinaldehyde binding protein 1 (Rihp1; Bunt-Milam and Saari, 1983) and glutamate-ammonia ligase (Glul; Riepe and Norenburg, 1977).

The fluorescence signal intensity levels from the microarrays of five bipolar cells were compared with those from two rod photoreceptor cells and two Müller glial cells. This comparison was done to enrich for genes expressed relatively specifically in bipolar cells and to filter out more widely expressed genes in at least some other retinal cell types. Table 2 shows the intensity levels for selected gene sequences from the single cells. The signal intensities for several previously characterized bipolar cell genes, including Cabp5, Purkinje cell protein 2 (Pcp2; Berrebi et al., 1991), protein kinase C α (Prkca; Greferath et al., 1990), and Chx10, were enriched between 8- and 156-fold when the average signal intensities for bipolar cells were compared with those for rod photoreceptor and Müller glial cells, confirming the utility of this method in identifying genes enriched in their expression in bipolar cells.

For each of these genes, the average signal intensity for the bipolar cells was significantly greater than the average signal intensity for the rod photoreceptor and Müller glial cells (P < 0.05, one-tailed Student's t-test, Table 2). Table 2 also includes signal intensities for several selected genes that were significantly enriched in the single bipolar cells and whose retinal expression has not been previously characterized. These genes, which exhibited some of the highest signal intensity ratios when comparing bipolar cells with other cells in the filtered results, were of particular interest because the possibility that they could be new bipolar cell-enriched molecular markers was substantially given that known bipolar cell genes were similarly enriched. The novel candidate bipolar cell genes were enriched between 8- and 81-fold and included contactin 4 (Cntn4), carbonic anhydrase 8 (Car8), RIKEN cDNA 2300002D11 gene (2300002D11Rik), Og9 homeobox gene (Og9x), carboxic anhydrase 10 (Car10), and neurofascin (Nfasc). For each of these genes, the average signal intensity for the bipolar cells was significantly greater than the average signal intensity for the rod photoreceptor and Müller glial cells (P < 0.05, one-tailed Student's t-test, Table 2). For comparison, signal intensities for a subset of known rod photoreceptor (Pde6b, Cnga1, Rho) and Müller glial cell genes (Rihp1, Glul) are shown in Table 2.

As expected for these rod photoreceptor and Müller glial cell genes, the signal intensity ratios for the bipolar cells to the rod photoreceptor and Müller glial cells were low, ranging from 0.004 to 0.051. These six candidate bipolar cell genes were demonstrated to be expressed in an enriched manner in bipolar cells, as assessed by RNA in situ hybridization (see further below). This limited set of single cells, while insufficient to provide the statistical power for identification of all bipolar cell-enriched genes, or to compare different cell types quantitatively, was sufficient for the purpose of screening for candidate novel bipolar cell molecular markers. Other genes exhibited high signal intensities in single bipolar cells and low signal intensities in rod photoreceptor and Müller glial cells, but these genes were not expressed in an enriched manner in bipolar cells as assessed by RNA in situ hybridization and so were not pursued further (data not shown).

**Identification of bipolar cell candidate genes by using SAGE**

In an additional effort to identify candidate novel bipolar cell molecular markers, retinal SAGE data were also examined (Blackshaw et al., 2004). A previous analysis of gene expression during mouse development was carried out with SAGE by using 10 retinal cDNA libraries generated at various stages between embryonic day (E)12.5 and adulthood. Bipolar cell-enriched molecular markers were previously identified based on large-scale RNA in situ hybridization studies of genes shown to have dynamic temporal expression patterns within the SAGE data.
| Probe set ID | Unigene | Gene name | Fluorescence signal intensities | Ratio of signal intensities of bipolar cells to rod photoreceptor + Müller glial cells | P value |
|-------------|---------|-----------|---------------------------------|-----------------------------------------------|---------|
| 1451826_at | Mm.109669 | Calcium binding protein 5 (Cabp5) | P5 bipolar A3: 7.274; Cabp5 bipolar A3: 21.964; Cabp5 bipolar A4: 18.135 | 155.6 | 0.0042 |
| 1424944_at | Mm.41456 | Purkinje cell protein 2 (Pcp2) | P5 bipolar A3: 3.742; Cabp5 bipolar A3: 4.364 | 4.3 | 0.0406 |
| 1450945_at | Mm.222178 | Protein kinase C alpha (Prkca) | P5 bipolar A3: 1.43; Cabp5 bipolar A3: 3.273; Cabp5 bipolar A4: 7.272 | 40.9 | 0.0243 |
| 14190628_at | Mm.4405 | C. elegans ceh-10 homeodomain-containing homolog (Ceh-10) | P5 bipolar A3: 4.718; Cabp5 bipolar A3: 24.762; Cabp5 bipolar A4: 22.820 | 7.6 | 0.0543 |
| 1448782_at | Mm.321683 | Contactin 4 (Cntn4) | P5 bipolar A3: 3.0; Cabp5 bipolar A3: 6.773 | 80.6 | 0.0240 |
| 1427462_a_at | Mm.119220 | Carbonyl synthase 8 (Carb8) | P5 bipolar A3: 96.7; Cabp5 bipolar A3: 6.773 | 63.0 | 0.0174 |
| 14520508_at | Mm.151594 | RIKEN cDNA 2300002D11 gene (2300002D11Rik) | P5 bipolar A3: 14.214; Carbop5 bipolar A3: 25.518; Carbop5 bipolar A4: 23.537 | 47.0 | 0.0002 |
| 1457946_at | Mm.143460 | Oph1 homeobox gene (Oph1) | P5 bipolar A3: 191.0; Carbop5 bipolar A3: 6.683; Cabp5 bipolar A4: 9.945 | 41.0 | 0.0165 |
| 1424547_at | Mm.342160 | Carbonyl synthase 10 (Carb10) | P5 bipolar A3: 106.0; Carbop5 bipolar A3: 9.109; Cabp5 bipolar A4: 3.104 | 20.2 | 0.0471 |
| 1433505_at | Mm.38037 | Neurod2 (Neurod2) | P5 bipolar A3: 221.0; Carbop5 bipolar A3: 8.476; Cabp5 bipolar A4: 9.099 | 17.2 | 0.0180 |
| 1425041_at | Mm.15655 | LIM homeobox protein 3 (Lhx3) | P5 bipolar A3: 10.281; Carbop5 bipolar A3: 56.0; Cabp5 bipolar A4: 42.0 | 8.3 | 0.2271 |
| 1419740_at | Mm.1372 | Phosphodiesterase 6b, cGMP, rod receptor, beta polypeptide (Pde6b) | P5 bipolar A3: 21.0; Carbop5 bipolar A3: 7.981; Cabp5 bipolar A4: 38.0 | 0.010 | 0.0786 |
| 1451763_at | Mm.23703 | Cyclic nucleotide gated channel 1 (Cngal1) | P5 bipolar A3: 22.0; Carbop5 bipolar A3: 1.979; Cabp5 bipolar A4: 7.0 | 2.995 | 0.005 | 0.0443 |
| 1451617_at | Mm.2965 | Rhodopsin (Rho) | P5 bipolar A3: 9.55; Carbop5 bipolar A3: 26.0; Cabp5 bipolar A4: 26.0 | 12.406 | 0.004 | 0.0667 |
| 1418310_a_at | Mm.41653 | Retinaldehyde binding protein 1 (Rhbp1) | P5 bipolar A3: 5.0; Carbop5 bipolar A3: 4.521; Cabp5 bipolar A4: 26.0 | 109.338 | 0.051 | 0.0586 |
| 1428296_a_at | Mm.210745 | Glutamate-aminomutase ligase (GlaA) | P5 bipolar A3: 41.0; Carbop5 bipolar A3: 3.798; Cabp5 bipolar A4: 13.0 | 89.714 | 0.011 | 0.0684 |

**Table 2. Scaled Fluorescence Signal Intensity Levels from Microarrays of Single Mouse Retinal Cells**

**Notes:** 1. Signals are shown from a P5 bipolar cell (column d), four bipolar cells transfected with a Cabp5::GFP reporter construct at P0 and picked from retinas after 8 days in culture (columns e–h), two adult rod photoreceptor cells (columns i–j), and two adult Müller glial cells (column k). For each gene, the ratio of the average signal of bipolar cells to the average signal of all other cells is shown (column n). The average bipolar signal was compared with the average signal of all other cells by one-tailed Student’s t-test, and resulting P values are shown (column n). Candidate and known bipolar cell-enriched genes had ratios greater than 7.6, whereas known rod photoreceptor and Müller glial cell-enriched genes had ratios less than 0.051.
To mine the SAGE data further for additional genes enriched in bipolar cell expression, a nearest neighbor method was applied. Because bipolar cells are born in a discrete developmental period and differentiate relatively late (Young, 1985), genes with late onset of expression might be novel bipolar cell genes. A search was carried out by using nearest neighbor analysis and known bipolar cell genes that have late onset of expression. Candidate genes with temporal gene expression patterns that displayed minimal Euclidean distances to patterns for known bipolar cell genes were selected for further analysis by RNA in situ hybridization (see further below).

The temporal expression patterns for the known bipolar cell gene Cabp5 (Haeseleer et al., 2000) and eight genes with similar profiles are shown in Figure 1. The onset of expression for these genes was from P0 to P6.5, and the relative expression levels peaked between P6.5 and adulthood. This set included genes previously shown to be expressed in bipolar cells, such as metabotropic glutamate receptor 6 (Grm6; Nakajima et al., 1993; Vardi and Morigiwa, 1997), γ-aminobutyric acid (GABA)-C receptor rho subunit 1 (Gabrr1; Koulen et al., 1998), visual system homeobox 1 homolog (Vsx1; Chow et al., 2001, 2004; Ohotoshi et al., 2001, 2004), and G protein β3 (Gnb3; Huang et al., 2003), confirming the utility of this method in identifying genes enriched in their expression in bipolar cells. Also included was 2300002D11Rik, a gene identified as a candidate bipolar cell molecular marker from the microarray screening.

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libraries were demonstrated to be expressed in a highly enriched manner in bipolar cells as assessed by RNA in situ hybridization (see further below). Other genes exhibited temporal expression pattern similar to the profile of Cabp5, but these genes were not expressed in an enriched manner in bipolar cells as assessed by RNA in situ hybridization and were not pursued further (data not shown).

**RNA in situ hybridization analysis**

RNA in situ hybridization analysis in P21 mouse retinal sections was carried out to evaluate expression of the candidate bipolar cell genes identified as described above. This validation process revealed that five of the candidate bipolar cell genes appeared to have highly enriched expression in bipolar cells, whereas five candidate bipolar cell genes exhibited enriched expression in bipolar cells and some expression in additional retinal cell types, as detailed below. For reference, the pattern for Chx10, a transcription factor gene expressed in all bipolar cells and a subset of Müller glial cells, is shown (Liu et al., 1994; Burmeister et al., 1996; Rowan and Cepko, 2004). Chx10 expression was observed in cells on the outer (scleral) side of the INL where bipolar neuron cell bodies are located (Fig. 2A). Expression of the cell adhesion gene Cntn4 was found in a subset of bipolar cells, when compared with the Chx10 expression pattern, and weakly in a subset of amacrine cells, found in the inner (vitreal) part of the INL (Fig. 2B). Car8 expression was seen in a subset of bipolar cells (Fig. 2C). The uncharacterized cDNA 230002D11Rik was expressed strongly in bipolar cells and weakly in the ganglion cell layer (Fig. 2D). The homeobox transcription factor gene Og9x was expressed in a subset of bipolar cells (Fig. 2E).

Car10 expression was observed in a subset of bipolar cells and weakly in amacrine cells and the ganglion cell layer (Fig. 2F). Expression of the cell adhesion molecule Nfasc was found in a subset of bipolar cells and weakly in amacrine cells, photoreceptor cells, and the ganglion cell layer (Fig. 2G). The calcium-binding protein gene Sgcn was expressed strongly in a subset of bipolar cells (Fig. 2H). Tprm1 expression was seen in a subset of bipolar cells (Fig. 2I). The uncharacterized cDNA with homology to POLO-like kinase genes, 6330514A18Rik, was expressed strongly in a subset of bipolar cells and weakly in the ONL (Fig. 2J). Lhx3 was enriched in its expression eightfold in bipolar cells compared with rod photoreceptor and Müller glial cells in the microarray analysis, but the difference in expression levels was not significant (Table 2), perhaps because Lhx3 is only expressed in a limited subset of bipolar cell types represented in the microarray data set. Consistent with this notion, expression of Lhx3 was observed in a small subset of bipolar cells (Fig. 2K).

Thus, the RNA in situ hybridization study results using retinal sections validated the utility of the microarray and SAGE screening. These screening methods were effective in identifying genes expressed in an enriched manner in bipolar cells.

To evaluate which types of bipolar cells express the newly identified genes, double-label expression studies were carried out by using fluorescent riboprobes hybridized to dissociated cells from P14 retinas. Probes for novel bipolar cell-enriched markers were labeled with a red fluorophore, and co-expression with a rod bipolar cell-enriched gene, Pcp2 (Berrebi et al., 1991), an ON bipolar cell-specific gene, Grm6 (Nakajima et al., 1993; Vardi and Morigiwa, 1997), or a pan-bipolar cell gene, Chx10 (Liu et al., 1994; Burmeister et al., 1996), each labeled by a green fluorescent probe, was assessed. Examples of double labeling are shown in Figure 3, and quantitation of the results by using computer-based image analysis is shown in Table 3. Bipolar cells are a relatively rare class of neurons in the mouse retina (~10%) compared with rod photoreceptor cells (~70%; Young, 1985), and so the majority of dissociated cells were unlabeled by the known bipolar cell markers. Nonetheless, Og9x-positive cells were mostly also positive for Pcp2, Grm6, and Chx10, suggesting that Og9x is a rod bipolar cell-specific gene (Fig. 3A–C). The percentages of Og9x-positive cells that were also positive for Pcp2, Grm6, and Chx10 were 69.8%, 83.7%, and 98.8%, respectively (Table 3; Og9x row; columns i, j, k). Rod bipolar cells are only a fraction of ON bipolar cells and bipolar cells in general (Euler and Wässle, 1995; Ueda et al., 1997), and consistent with the suggestion that Og9x is a rod bipolar cell-specific gene, only a fraction of Grm6-positive cells and Chx10-positive cells were also Og9x positive (Table 3; Og9x row; columns g, h).

In contrast, Sgcn-positive cells were almost all Pcp2-negative, even though the majority was Chx10 positive, suggesting that Sgcn is expressed in cone bipolar cells (Fig. 3G; Table 3; Sgcn row; columns i, j, k). Sgcn-positive cells were both Grm6 positive and Grm6 negative (Fig. 3H; Table 3; Sgcn row; column j), suggesting that Sgcn is expressed in both ON and OFF cone bipolar cells. Data for Car10 and Lhx3 are not shown because the fluorescent in situ hybridization signals for these genes were too weak to detect in dissociated cells. Cntn4 is expressed in bipolar cells and amacrine cells, and from the double-labeling experiments, it was found in at least some Pcp2-positive cells and Grm6-positive cells. The majority of Car8-positive cells were also positive for Pcp2, Grm6, and Chx10, suggesting that Car8 is a rod bipolar cell-specific gene. 230002D11Rik is expressed in bipolar cells and the ganglion cell layer, and from the double-labeling studies, it was observed in at least some Pcp2-positive cells and Grm6-positive cells.

Nfasc is expressed in bipolar cells and the amacrine and the ganglion cell layer, and it was detected in dissociated cells in at least some Pcp2-positive cells and a small fraction of Grm6-positive cells. Tprm1-positive cells were almost all labeled with the Chx10 probe, but only a minority of cells was positive for Pcp2 or Grm6, suggesting that Tprm1 is expressed in cone OFF bipolar cells and in a small number of cone ON bipolar cells and rod bipolar cells. 6330514A18Rik is expressed in bipolar cells and photoreceptor cells, and from the double-labeling experiments, it was found in a small minority of Pcp2-positive cells and in at least some Grm6-positive cells. Thus, the novel bipolar cell-enriched genes were expressed in a variety of different subtypes of bipolar cells.

Mouse retina bipolar cell bodies appear intermingled in sections in the INL with horizontal cell and Müller glial cell bodies. Double-labeling experiments in dissociated retinal cells were conducted by using probes against novel bipolar cell-enriched genes and antibodies against calbindin (Calb), a protein expressed abundantly in horizontal cells and weakly in a subset of amacrine cells (Hamano et al., 1990; Elshatory et al., 2007), and Glu, a Müller glial cell marker (Riepe and Norenburg, 1977), to determine whether the novel molecular markers are found in these cell types. Additionally, the possibility that novel bipolar...
cell-enriched genes are expressed in amacrine cells was addressed by double-labeling dissociated cells using a Pax6 riboprobe, which marks amacrine, horizontal, and ganglion cells (de Melo et al., 2003). Cells positive for Calb expression were negative for Og9x (0/11), Scgn (0/15), Cntn4 (0/15), Car8 (0/15), 2300002D11Rik (0/14), and Trpm1 (0/16) expression (Fig. 3, Supplementary Fig. 1). However, Nfasc- and 6330514A18Rik-positive cells overlapped with strongly labeled Calb-positive cells (15/16 and 6/6, respectively), suggesting that these two genes are also found in horizontal cells or amacrine cells. Horizontal cells are so rare in the retina (<1%; Jeon et al., 1998) that
Fig. 3. Characterization of novel bipolar cell-enriched genes by double-labeling with markers of bipolar cell subtypes and other retinal cells. Fluorescent RNA in situ hybridization and antibody staining images from representative fields of dissociated P14 mouse retinal cells. A–F: Og9x hybridization signal is shown in red. G–L: Scgn hybridization signal is shown in red. A,G: Pcp2 hybridization signal is shown in green. B,H: Grm6 signal is shown in green. C,I: Chx10 signal is shown in green. D,J: Glul antibody staining signal is shown in green. E,K: Pax6 signal is shown in green. F,L–R: Calb antibody staining signal is shown in green. M: Ctn4 hybridization signal is shown in red. N: Car8 hybridization signal is shown in red. O: 230002D11Rik hybridization signal is shown in red. P: Nfasc hybridization signal is shown in red. Q: Trpm1 hybridization signal is shown in red. R: 633061A18Rik hybridization signal is shown in red. Arrows, double-positive cells. Nuclei were stained blue with DAPI. Scale bar = 10 μm in A–R.
TABLE 3. Quantitation of Dissociated P14 Mouse Retinal Cells Double-Labeled with Fluorescent Riboprobes for Novel and Known Bipolar Cell-Enriched Markers1

| Experimental probe | Grm6 | Chx10 | Pcp2 | Trpm1 | Car8 | Scgn | Og9x | Nfasc | 2300002D11Rik | 6330514A18Rik |
|--------------------|------|-------|------|-------|------|------|------|-------|--------------|---------------|
| Omp                | 5.8 ± 0.3 | 5.9 ± 0.3 | 1.2 ± 0.6 | 4.9 ± 0.4 | 6.2 ± 0.6 | 7.0 ± 0.8 | 5.6 ± 0.2 | 9.5 ± 0.4 | 5.2 ± 0.2 | 7.7 ± 0.2 |
| Car8               | 5.8 ± 0.3 | 5.9 ± 0.3 | 1.2 ± 0.6 | 4.9 ± 0.4 | 6.2 ± 0.6 | 7.0 ± 0.8 | 5.6 ± 0.2 | 9.5 ± 0.4 | 5.2 ± 0.2 | 7.7 ± 0.2 |
| Car8               | 5.8 ± 0.3 | 5.9 ± 0.3 | 1.2 ± 0.6 | 4.9 ± 0.4 | 6.2 ± 0.6 | 7.0 ± 0.8 | 5.6 ± 0.2 | 9.5 ± 0.4 | 5.2 ± 0.2 | 7.7 ± 0.2 |
| Car8               | 5.8 ± 0.3 | 5.9 ± 0.3 | 1.2 ± 0.6 | 4.9 ± 0.4 | 6.2 ± 0.6 | 7.0 ± 0.8 | 5.6 ± 0.2 | 9.5 ± 0.4 | 5.2 ± 0.2 | 7.7 ± 0.2 |

1. Percentages of cells labeled with various experimental probes, a probe for the rod bipolar cell-enriched gene *Pcp2*, and a probe for the pan-bipolar cell gene *Grm6*, are shown. Columns b–e list the percentage of cells labeled with probes out of the total number of cells. Columns f–h list the percentages of cells doubly labeled with a probe for an experimental and a known gene out of the number of cells singly labeled with a probe for a known gene. These percentages are the fraction of cells positive for a known gene that are also positive for an experimental gene. Columns i–k list the percentages of cells doubly labeled with a probe for an experimental and a known gene out of the number of cells singly labeled with a probe for an experimental gene. These percentages were obtained by examining thin sections of retinas stained with probes for known and experimental genes and counting labeled cells in each section. The percentage of cells labeled with probes for known genes was approximately 75% in WT retinas, and the percentage of cells labeled with probes for novel genes was approximately 25% in WT retinas. The percentage of cells doubly labeled with probes for known and novel genes was approximately 15% in WT retinas. The percentage of cells labeled with probes for known genes was approximately 50% in KO retinas, and the percentage of cells labeled with probes for novel genes was approximately 30% in KO retinas. The percentage of cells doubly labeled with probes for known and novel genes was approximately 10% in KO retinas. The percentage of cells labeled with probes for known genes was approximately 75% in WT retinas, and the percentage of cells labeled with probes for novel genes was approximately 25% in WT retinas. The percentage of cells doubly labeled with probes for known and novel genes was approximately 15% in WT retinas.

Bipolar cell gene expression in Bhlhb4−/− retinas

To assess further the identity of bipolar cells in which the novel markers are expressed, in situ hybridization studies were conducted in retinas from P21 WT and Bhlhb4-deficient mice in which rod bipolar cells have previously been shown to die from P8 to P12 (Bramblett et al., 2004). A null mutation at the Bhlhb4 gene locus was introduced by gene targeting and Cre/loxP-mediated recombination in ES cells, as shown in Figure 4. Bhlhb4-null mice were completely absent in retinas of homozygous null mice as assessed by in situ hybridization (Fig. 4D). The specific loss of rod bipolar cells in Bhlhb4 mutants was confirmed by examining Prkea expression, a known rod bipolar cell gene (Grefeff et al., 1990). Whereas WT retinas displayed robust expression of Prkea in bipolar cell bodies closely apposed to the OPL and in a subset of amacrine cells, bipolar cells expressing Prkea were completely absent from the Bhlhb4-null retina; amacrine cell expression was maintained, however (Fig. 5A,B).
Fig. 4. Mutagenesis of the mouse Bhlhb4 gene. A: Gene targeting strategy showing partial restriction map of WT Bhlhb4 allele, the targeting vector, the targeted ES cell allele, and the Bhlhb4 null allele. The Bhlhb4 gene (which is a single exon gene), the PGK-neomycin cassette, and the PGK-diphtheria toxin cassette are represented by rectangles; the arrows represent open reading frames, and the triangles represent loxP sites. Thin lines show the positions of 5’ and 3’ probes used in Southern blotting analysis. BsmI restriction sites (B), used for screening from the 5’ side of the gene, and NheI restriction sites (N), used for screening from the 3’ side, are indicated. B: Southern blot analysis of ES cells. Genomic DNA was digested with either BsmI or NheI, and Southern blots were analyzed by using either the 5’ or the 3’ probe, respectively. Fragment sizes for WT (+/+) and targeted (−/−) DNA are indicated. C: PCR genotyping from mouse tail DNA from WT (+/+), heterozygous (+/−), and Bhlhb4-null (−/−) animals. WT allele, 216 bp; Bhlhb4-null allele, 299 bp. D: RNA in situ hybridization for Bhlhb4 RNA. Retinal sections from P21 WT (+/+) and Bhlhb4-null (−/−) mice are shown. Scale bar = 100 μm in D.
Fig. 5. Bipolar cell gene expression in the Bhlhb4-deficient retina. RNA in situ hybridization patterns from representative sections of P21 mouse retinas. A,C,E,G,I,K,M,O,Q,S,U,W,Y,A' : WT retinal sections. B,D,F,H,J,L,N,P,R,T,V,X,Z,B' : Bhlhb4-deficient retinal sections. A,B: Prkca. C,D: Pcp2. E,F: Grm6. G,H: Chx10. J,L: Og9x. K,L: Car8. M,N: Nfasc. O,P: Ctnn4. Q,R: 2300002D11Rik. S,T: Trpm1. U,V: Scgn. W,X: 6330514A18Rik. Y,Z: Car10. A',B' : Lhx3. Scale bar = 100 μm in M (applies to A–Z,A',B').
Additionally, bipolar cells expressing 6330514A18Rik (Fig. 5W,X), Car10 (Fig. 5Y,Z), and Lhx3 (Fig. 5A,’B’) appeared unchanged in mutant retinas, indicating that these genes are expressed predominantly in cone bipolar cells. Supplementary Figure 2 shows the results of sense riboprobe hybridizations as negative controls. Table 4 lists the identities of the cells in which novel bipolar cell markers are expressed. Many of the known and novel bipolar cell molecular markers are also expressed outside the eye. These genes are represented in cDNA libraries from different tissue types in the Unigene database (http://www.ncbi.nlm.nih.gov/sites/entrez?db=unigene; Supplementary Table 3), and some genes are found to be expressed in various brain regions (Allen Brain Atlas, Lein et al., 2007; Supplementary Table 3).

**DISCUSSION**

This study has revealed more of the complexity of gene expression of retinal bipolar cells and added a substantial number of bipolar cell-enriched molecular markers to those previously described. By using gene microarrays and SAGE data, genes were identified as candidates for novel bipolar cell molecular markers. RNA in situ hybridization studies showed the enriched expression to varying degrees in 10 genes in bipolar cells. These genes will prove useful in characterizing diverse bipolar cell types, understanding bipolar cell physiology, and elucidating bipolar cell development. This report complements studies that used genomic techniques to characterize retinal gene expression in general or to describe expression of a limited set of genes in bipolar cells (Huang et al., 2003; Blackshaw et al., 2004; Hackam et al., 2004; Dorrell et al., 2004; Zhang et al., 2005; Trimarchi et al., 2007). The use of single bipolar cell cDNA as microarray probes and clustering of temporal expression patterns around that of a known bipolar cell gene by using SAGE data made a directed search for bipolar cell markers possible. In contrast to these methods, other investigators have identified genes fortuitously or by screening through molecules in families for which a member was already known to be expressed in bipolar cells. Another approach has been to find novel markers in the central nervous system (CNS) by undertaking comprehensive RNA in situ hybridization studies on a genome-wide scale (Lein et al., 2007). All these genomic techniques will prove generally useful in dissecting the complexity of gene expression in the nervous system.

In this study, not all previously identified bipolar cell markers were found. Notable missing genes were Bhlhb4 and Irx5, transcription factor genes required for bipolar cell development or maintenance (Bramblett et al., 2004; Cheng et al., 2005), and Gli5, Lhx4, and Zf, bipolar cell molecular markers identified in a previous SAGE study (Blackshaw et al., 2004). Various factors underlie the relative sensitivity of the genomic screening approaches used here. These factors include lack of representation of some bipolar cell gene sequences on microarrays (e.g., Grm6), excessively low expression of bipolar cell genes on a cell-by-cell basis, temporal expression of bipolar cell genes outside the period of bipolar cell differentiation in which strongest SAGE clustering was found, and high expression of a given marker but only in a relatively rare bipolar cell type. With regard to this last factor, and most of the single bipolar cells examined in this study were picked based on expression of a transfected Cabp5-GFP reporter construct; Cabp5 is only expressed in a subset of bipolar cells (rod bipolar cells, type 3, and type 5 cone bipolar cells; Ghosh et al., 2004). In retrospect, all these Cabp5-expressing cells appeared to be rod bipolar cells, based on high expression of the rod bipolar cell markers Prkca (GrefeFath et al., 1990) and Og9x. Consequently, many bipolar cell genes identified were rod bipolar cell-specific (e.g., Og9x, Car8) or at least were expressed in rod bipolar cells but were also found in cone bipolar cells (e.g., Cntn4, 2300092D11Rik, Trpm1). More markers for cone bipolar cells, rather than rod bipolar cells, could be obtained by picking bipolar cells identified by using novel cone bipolar cell markers found in this study. Examining more single bipolar cells in general would also allow for quantitative comparisons of different cell types based on microarray signal intensities alone by increasing statistical power, but in this study, microarray data were used solely as a screening method and bipolar cell expression was ultimately evaluated by RNA in situ hybridization.

Evaluating expression of bipolar cell genes by RNA in situ hybridization was informative for understanding bipolar cell diversity. From double-labeling experiments, it was possible to estimate proportions of various bipolar cell types. For bipolar cells in general, the percentage of cells positive for the pan-bipolar cell marker Chx10 was −14% (Table 3, column e), similar to other estimates of the bipolar cell percentage of 10−16% from comprehensive morphological studies (Young, 1985; Jeon et al., 1998). For ON bipolar cells, dividing the percentage of Grm6-positive cells (−10%, Table 3, column d) by the percentage of Chx10-positive cells (−14%, Table 3, column e), an estimate of the fraction of ON bipolar cells out of the total population of bipolar cells is obtained as −72%. Because Chx10 is also expressed in a subset of Müller glial cells (Liu et al., 1994; Burmeister et al., 1996; Rowan and Cepko, 2004), the estimate of the fraction of bipolar cells

**TABLE 4. Summary of Expression of Novel Bipolar Cell-Enriched Markers**

| Gene name | Bipolar cell expression | Other retinal cell expression |
|-----------|-------------------------|------------------------------|
| 2300092D11Rik | Rod bipolar cells, subset of cone ON and OFF bipolar cells | Ganglion cell layer |
| 6330514A18Rik | Subset of cone ON and OFF bipolar cells | Photoreceptor cells, horizontal cells, Müller glial cells, amacrine cells |
| Car10 | Rod bipolar cells | Amacline cells, ganglion cell layer |
| Cntn4 | Subset of cone bipolar cells | Amacline cells, ganglion cell layer |
| Lhx3 | Rod bipolar cells, subset of cone ON and OFF bipolar cells | Photoreceptor cells, horizontal cells, amacrine cells, ganglion cell layer |
| Nfatc | Subset of rod bipolar cells | |
| Og9x | Rod bipolar cells | |
| Segn | Subset of cone ON and OFF bipolar cells | |
| Trpm1 | Subset of rod bipolar cells, subset of cone ON and OFF bipolar cells | |
out of the total population using Chx10 is likely slightly overestimated, and the estimate of ON bipolar cells using Grm6 and Chx10 is likely underestimated. Previous studies using adult rat retina suggested that at least 50% of bipolar cells are rod bipolar cells based on antibody staining for protein kinase C α and Purkinje cell protein 2 (Euler and Wässle, 1995). Based on the fraction of cells expressing the rod bipolar cell-specific markers Og9x and Car8 out of the population of Chx10-positive cells, rod bipolar cells comprise 34–48% of all bipolar cells (Table 3, column b, Og9x and Car8 rows). In this study, estimates were made by using P14 mouse retina. Differences in species, time points examined, and detection sensitivities could account for differences with previous figures. Some apoptosis of developing bipolar cells occurs in the mouse retina from P5 to P18, but the peak of death is evident at P8–P11, and only a few cells die thereafter (Young, 1984). Thus, the quantities of bipolar cells counted at P14 likely reflect the mature state. Additionally, Nfasc and Trpm1 are expressed in a minority of cells expressing the rod bipolar cell-enriched gene Pcp2, which could reflect gene expression heterogeneity in these cells. Molecular differences among rod bipolar cells have not been explored and need to be confirmed by additional methods. Whereas this study has characterized overlap of gene transcripts with markers of different bipolar and INL cell subtypes, more sensitive methods for assessing gene or protein expression in the future could reveal that the novel markers are found in additional retinal cell types.

Expression in additional cell types does not necessarily exclude use of a marker. For example, Chx10, which is used as a pan-bipolar cell marker, is also expressed in Müller glial cells (Liu et al., 1994; Burmeister et al., 1996; Rowan and Cepko, 2004). In addition to the sensitivity of a detection method, other variables such as cell morphology can influence results. Double-labeling with the novel bipolar cell gene riboprobes and the Glul antibody showed expression of bipolar genes in a small percentage of Müller glial cells. These cells have long processes that can surround other cells even after dissociation, which can give a false impression of expression in Müller glial cells. Additionally, outside of the eye, cDNAs for novel and known bipolar cell-enriched molecular markers are represented in libraries made from several nervous system tissues, including brain, dorsal root ganglion, sympathetic ganglion, and spinal cord, as well as in non-nervous system tissues (see Supplementary Table 3). Many genes are also shown to be expressed in various brain regions when gene expression atlas data are examined (see Supplementary Table 3).

The expression studies using Bhlhb4-deficient retinas were revealing with regard to rod bipolar cells. Persistence of some Pcp2-positive cells in this mutant in which rod bipolar cells die and the rod bipolar cell component of the electroretinographic response is completely absent (Bramblett et al., 2004) suggests that Pcp2 is expressed in some cone bipolar cells. Previous investigators concluded that Pcp2 is a rod bipolar cell marker, based on immunostaining of cells extending axons to the deepest part of the IPL (Berrebi et al., 1991). Visualization of Pcp2-positive cell bodies in the Bhlhb4 mutant retina by in situ hybridization thus complemented immunohistochemical approaches investigating in which cell types this gene is expressed. It is possible that cone bipolar cells express Pcp2 aberrantly as a consequence of rod bipolar cell loss. However, the remaining Pcp2-positive cells in the mutant retina were located relatively distant from the OPL and were expressed weakly. Similar Pcp2-positive cells were also seen in the WT retina, suggesting that Pcp2 is normally expressed in a subset of cone bipolar cells. Given this indication that Pcp2 is enriched in its expression in rod bipolar cells but is also found in a subset of cone bipolar cells, figures for the percentage likelihood that a novel marker is expressed in rod bipolar cells using Pcp2 are likely underestimates. Furthermore, the analysis of the Bhlhb4 mutants suggests that cone bipolar cell gene expression is unaffected by the absence of rod bipolar cells. Expression of the cone bipolar cell genes Scgn and 6330514A18Rik was not changed in the mutant retina. In the absence of rod bipolar cells, the remaining cone bipolar cells appear unable to compensate for the loss, at least in terms of gene expression. Moreover, unlike cone photoreceptor cells, which undergo cell death after rod photoreceptor cells die in various forms of retinal degeneration, cone bipolar cells can persist even after rod bipolar cells are eliminated (Carter-Dawson et al., 1978; Bramblett et al., 2004). Understanding the causes of selective rod bipolar cell degeneration in Bhlhb4-deficient mice will require exploration of gene expression changes before and during the period of cell death (P8–P12). Bhlhb4 could regulate expression of trophic factor or trophic signal transduction genes that promote rod bipolar cell survival specifically. Alternatively, it might modulate expression of genes involved in rod bipolar neuronal activity, and rod bipolar cells could die as a consequence of abnormal physiological activity.

Exploration of the role of the novel bipolar cell genes could reveal more about bipolar cell development and function. Cntn4 and Nfasc are both immunoglobulin domain-containing adhesion molecule genes (Volkmer et al., 1992; Yoshihara et al., 1995). Contactin protein family members participate in axon guidance and shaping dendritic projections, and Nfasc has been implicated in mediating specific neuron-neuron interactions (Falk et al., 2002). There is some evidence that contactin and neurofascin proteins can physically interact. Thus, it is possible that Cntn4 and Nfasc function in the formation of bipolar cell axon structure and contacts. Additionally, the homeodomain-containing transcription factor genes Og9x and Lhx3 are specifically expressed in bipolar cell subsets. Several homeodomain-containing transcription factors have been shown to be required for bipolar cell fate determination and differentiation (Burmeister et al., 1996; Chow et al., 2004; Ohtoshi et al., 2004; Cheng et al., 2005). The possibility that Og9x and Lhx3 regulate bipolar cell development will be addressed in future gain- and loss-of-function experiments. Transcription factors that control bipolar cell gene expression and development could be investigated by examining common transcriptional regulatory elements of bipolar cell genes identified here and elsewhere, as has been done for photoreceptor cell genes (Qian et al., 2005; Hsiung et al., 2007). Thus, the identification of bipolar cell genes by genomic expression screening will reveal more about how development and diversification of these relay interneurons are regulated.

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LITERATURE CITED

Basa D, Bunstedt KM, Martinez JA, Vaccarino FM, Wikler KC. Barnstable CJ. 2000. The subcellular localization of Otx2 is cell-type specific and developmentally regulated in the mouse retina. Brain Res Mol Brain Res 78:26–37.

Baehr W, Champagne MS, Lee AK, Pittler SJ. 1991. Complete cDNA sequences of mouse rod photoreceptor G3MP phosphodiesterase alpha- and beta-subunits, and identification of beta-, a putative beta-subunit, as produced by alternative splicing of the beta-subunit gene. FEBS Lett 278:107–114.

Bascom RA, Manara S, Collins L, Molday RS, Kalnins VI, Mclnnes RR. 1992. Cloning of the cDNA for a novel photoreceptor membrane protein (opsin1) identifies a disk rim protein family implicated in human retinopathies. Nature 357:1117–1184.

Berrebi AS, Oberdick J, Sangamweswaran L, Christakos S, Morgan JI, Mughnani E. 1991. Cerebellar Purkinje cell markers are expressed in retinal bipolar neurons. J Comp Neurol 308:630–649.

Blackshaw S, Harpavat S, Trimmer J, Cai L, Huang H, Kuo WP, Weber CM, Le K, Pfauw R, Chukov JM, Jastreboff A, Ohno-Machado L, Wong WH, Cepko CL. 2004. Genomic analysis of mouse retinal development. PLoS Biol 2:E247.

Brady G, Iscove NN. 1993. Construction of cDNA libraries from single cells. Methods Enzymol 225:611–623.

Bramblett DE, Pennesi ME, Wu SM, Tsai MJ. 2004. The transcription factor Brhl2 is required for rod bipolar cell maturation. Neuron 47:73–79.

Bunt-Milam AH, Saari JC. 1983. Immunocytochemical localization of two retinoid-binding proteins in vertebrate retina. J Cell Biol 97:703–712.

Burmeister M, Novak J, Liang MY, Basu S, Ploder L, Hawes NL, Vidgen D, Hoover F, Goldman D, Kalnins VI, Roderick TH, Taylor BA, Hankin MH, McLnnes RR. 1996. Ocular retardation mouse caused by Chx10 homeobox null allele: impaired retinal progenitor proliferation and bipolar cellular differentiation. Nat Genet 12:376–384.

Carter-Dawson LD, LaVail MM, Sidman RL. 2004. The transcription factor Brn3b, and Chx10 homeobox gene expression defines the retinal ganglion and inner nuclear layers of the developing and adult mouse retina. J Comp Neurol 461:187–204.

Chang ML, Wu CH, Jiang-Shieh YF, Shieh JY, Wen CY. 2007a. Reactive changes of retinal astrocytes and Muller glial cells in kainate-induced neuroexocytosis. J Anat 210:54–65.

Chang B, Hawes NL, Pardue MT, German AM, Hurd RE, Davison MT, Nasrinwitz S, Rengarajan K, Boyd AP, Sidney SS, Phillips MJ, Stewart R, Frangis R, Nickerson JM, Heckenlively JR, Bostrigt JH. 2007b. Two mouse retinal bipolar cell generations caused by missense mutations in the beta-subunit of rod G3MP phosphodiesterase gene. Vision Res 47:824–833.

Cheng CW, Chow RL, Lebel M, Sakuma R, Cheung HO, Thanabalasingham V, Zheng SX, Hui CC, Mclnnes RR, Chng SH. 2005. The Iroquois homeobox gene, Irx1, is required for retinal bipolar cell development. Dev Biol 287:48–60.

Chow RL, Snow B, Novak J, Looser J, Freund C, Vidges D, Ploder L, Mclnnes RR. 2001. Vsx1, a rapidly evolving paired-like homeobox gene expressed in cone bipolar cells. Mech Dev 109:315–322.

Chow RL, Volgyi B, Szilard RK, Ng D, McKerlie C, Bloomfield SA, Birch DG, Mclnnes RR. 2004. Control of late off-center cone bipolar cell differentiation and visual signaling by the homeobox gene Vsx1. Proc Natl Acad Sci U S A 101:1754–1759.

de Melo J, Qiu X, Du G, Cristante L, Eisenstat DD. 2003. Dlx1, Dlx2, Pax6, Brn3b, and Chx10 homeobox gene expression defines the retinal ganglion and inner nuclear layers of the developing and adult mouse retina. J Comp Neurol 461:187–204.

Dorrell MI, Aguilar E, Weber C, Friedlander M. 2004. Global gene expression analysis of the developing postnatal mouse retina. Invest Ophthalmol Vis Sci 45:1009–1019.

Dulaic C, Axell R. 1995. A novel family of genes encoding putative pheromone receptors in mammals. Cell 83:195–206.

Elshatory Y, Deng M, Xie X, Gan L. 2007. Expression of the LIM-domain protein Isl1 in the developing and mature mouse retina. J Comp Neurol 503:182–197.

Euler T, Wäsche H. 1995. Immunocytochemical identification of cone bipolar cells in the rat retina. J Comp Neurol 361:461–478.

Falk J, Boncon C, Girault JA, Faivre-Sarrailh C. 2002. F3‘contacin, a neuronal cell adhesion molecule implicated in axogenesis and myelination. Biol Cell 94:327–334.

Fletcher EL, Koulou P, Wäsche H. 1998. GABAA and GABAC receptors on mammalian rod bipolar cells. J Comp Neurol 396:351–365.

Ghosh KK, Bujan S, Haverkamp S, Feiogenspan A, Wäsche H. 2004. Types of bipolar cells in the mouse retina. J Comp Neurol 470:70–82.

Grefrath U, Grünert U, Wäsche H. 1990. Rod bipolar cells in the mammalian retina show protein kinase C-like immunoreactivity. J Comp Neurol 302:417–424.

Hatakeyama J, Kageyama R. 2004. Retinal cell fate determination and bHLH factors. Semin Cell Dev Biol 15:85–89.

Haverkamp S, Ghosh KK, Hirano AA, Wäsche H. 2003a. Immunocytochemical description of five bipolar cell types of the mouse retina. J Comp Neurol 455:463–476.

Haverkamp S, Haseeeler F, Hendrickson A. 2003b. A comparison of immunocytochemical markers to identify bipolar cell types in human and monkey retina. Vis Neurosci 20:589–600.

Howes K, Bronson JD, Dang YL, Li N, Zhang K, Ruiz C, Helekar B, Lee M, Subbaraya I, Kolb H, Chen J, Baehr W. 1998. Gene array and expression of mouse retina guanylate cyclase activating proteins 1 and 2. Invest Ophthalmol Vis Sci 39:867–875.

Hsiau TH, Diaconu CM, Myers CA, Lee J, Cepko CL, Corbo JC. 2007. The cis-regulatory logic of the mammalian photoreceptor transcriptional network. PLoS ONE 2:e643.

Huang I, Max M, Margolskee RF, Su H, Masland RH, Euler T. 2003. G protein subunit G gamma 13 is coexpressed with G alpha o, G beta 3, and G beta 4 in retinal ON bipolar cells. J Comp Neurol 455:1–10.

Huwitz RL, Bund-Milam AH, Chang ML, Beavo JA. 1985. GMP phosphodiesterase in rod and cone outer segments of the retina. J Biol Chem 260:588–573.

Iscove NN, Barbara M, Gu M, Gibson M, Modoi C, Winegard N. 2002. Representation is faithfulness preserved in global cdNA amplified exponentially from sub-picogram quantities of mRNA. Nat Biotechnol 20:940–945.

Jan LY, Revel JP. 1974. Ultrastructural localization of rhodopsin in the vertebrate retina. J Cell Biol 62:257–273.

Jean CJ, Streitii E, Masland RH. 1998. The major cell populations of the retina. J Neurosci 18:8906–8946.

Kaufp DJ, Niidome T, Tanaka A, Terada S, Bönigk W, Stühmer W, Cook NJ, Kangawa K, Matsu H, Hirose T, Miyata T, Numa S. 1989. Primary structure and functional expression from complementary DNA of the rod photoreceptor cyclic GMP-gated channel. Nature 342:762–766.

Koulou P, Brandstätter JH, Enz R, Bormann J, Wäsche H. 1998. Synaptic clustering of GABA/C receptor rho-subunits in the rat retina. Eur J Neurosci 10:115–127.

Lee Ed, Mann LB, Rickman DW, Lim Ed, Chun MH, Grzywacz NM. 2006. All amacrine cells in the distal inner nuclear layer of the mouse retina. J Comp Neurol 494:651–662.

Lein ES et al. 2007. Genome-wide atlas of gene expression in the adult mouse brain. Nature 445:185–176.

Lerea CL, Somers DE, Hurley JB, Klock IB, Bund-Milam AH. 1986. Identification of specific transducin alpha subunits in retinal rod and cone photoreceptors. Science 234:77–80.

Li E, Bestor TH, Jaenisch R. 1992. Targeted mutation of the DNA methyltransferase gene results in embryonic lethality. Cell 69:915–926.

Lee Ed, Chen JD, Ploder L, Vidges D, van der Koos D, Kalnins VI, McLnnes RR. 1994. Developmental expression of a novel murine homeobox gene (Chx10): evidence for roles in determination of the neuroretina and inner nuclear layer. Neuro 13:377–393.

Matsuda T, Cepko CL. 2004. Electroporation and RNA interference in the rodent retina in vivo and in vitro. Proc Natl Acad Sci U S A 101:16–22.

Molday RS, MacKenzie D. 1983. Monoclonal antibodies to rhodopsin: characterization, cross-reactivity, and application as structural probes. Biochemistry 22:653–660.

Murtough LC, Chyung JH, Lassar AB. 1999. Sonic hedgehog promotes...
somitic chondrogenesis by altering the cellular response to BMP signaling. Genes Dev 13:225–237.

Nakajima Y, Iwakabe H, Akazawa C, Nawa H, Shigemoto R, Mizuno N, Nakanishi S. 1993. Molecular characterization of a novel retinal metabotropic glutamate receptor mGluR6 with a high agonist selectivity for L-2-amino-4-phosphonobutyrate. J Biol Chem 268:11868–11873.

Ohtoshi A, Justice MJ, Behringer RR. 2001. Isolation and characterization of Vex1, a novel mouse CVC paired-like homeobox gene expressed during embryogenesis and in the retina. Biochem Biophys Res Commun 286:133–140.

Ohtoshi A, Wang SW, Maeda H, Saszick SM, Frishman LJ, Klein WH, Behringer RR. 2004. Regulation of retinal cone bipolar cell differentiation and photopic vision by the CVC homeobox gene Vex1. Curr Biol 14:530–536.

Peng YW, Rohishaw JD, Levine MA, Yau KW. 1992. Retinal rods and cones have distinct G protein beta and gamma subunits. Proc Natl Acad Sci U S A 89:10882–10886.

Pennesi ME, Cho JH, Yang Z, Wu SH, Zhang J, Wu SM, Tsai M. 2003. BETA2/NeuroD1 null mice: a new model for transcription factor-dependent photoreceptor degeneration. J Neurosci 23:453–461.

Pignatelli V, Strettoi E. 2004. Bipolar cells of the mouse retina: a gene gun, morphological study. J Comp Neurol 476:254–266.

Qian J, Esumi N, Chen Y, Wang Q, Chowers I, Zack DJ. 2005. Identification of regulatory targets of tissue-specific transcription factors: application to retina-specific gene regulation. Nucleic Acids Res 33:3479–3491.

Rhee KD, Ruiz A, Duncan JL, Hauswirth WW, Lavail MM, Bok D, Yang XJ. 2007. Molecular and cellular alterations induced by sustained expression of ciliary neurotrophic factor in a mouse model of retinitis pigmentosa. Invest Ophthalmol Vis Sci 48:1389–1400.

Riepe RE, Norenburg MD. 1977. Muller cell localization of glutamine synthetase in rat retina. Nature 268:654–655.

Ross SE, Greenberg ME, Stiles CD. 2003. Basic helix-loop-helix factors in cortical development. Neuron 39:13–25.

Rowan S, Cepko CL. 2004. Genetic analysis of the homeodomain transcription factor Chx10 in the retina using a novel multifunctional BAC transgenic mouse reporter. Dev Biol 271:388–402.

Subbaraya I, Ruiz CC, Helekar BS, Zhao X, Gerczay WA, Pettenati MJ, Rao PN, Palczewski K, Ehrhr W. 1994. Molecular characterization of human and mouse photoreceptor guanylate cyclase-activating protein (GCAP) and chromosomal localization of the human gene. J Biol Chem 269:31080–31089.

Takabayashi K, Takahashi S, Yokota C, Tsuda H, Nakanishi S, Asashima M, Kageyama R. 1997. Conversion of ectoderm into a neural fate by ATH-3, a vertebrate basic helix-loop-helix gene homologous to Drosofha proneural gene atonal. EMBO J 16:384–395.

Tietjen I, Ruhl JM, Cao Y, Koentges G, Zakhary L, Dulac C. 2003. Single-cell transcriptional analysis of neuronal progenitors. Neuron 38:161–175.

Trimarchi JM, Studler MB, Roska B, Billings N, Sun B, Barch B, Cepko CL. 2007. Molecular heterogeneity of developing retinal ganglion and amacrine cells revealed through single cell gene expression profiling. J Comp Neurol 502:1047–1065.

Tuteja N, Farber DB. 1988. Gamma-subunit of mouse retinal cyclic-GMP phosphodiesterase: cDNA and corresponding amino acid sequence. FEBS Lett 232:182–186.

Ueda Y, Iwakabe H, Masu M, Suzuki M, Nakanishi S. 1997. The mGluR6 5' upstream transgene sequence directs a cell-specific and developmentally regulated expression in retinal rod and ON-type cone bipolar cells. J Neurosci 17:3014–3023.

van der Spuy J, Chapple JP, Clark BJ, Luthert PJ, Sethi CS, Cheetham ME. 2002. The Leber congenital amaurosis gene product AIPL1 is localized exclusively in rod photoreceptors of the adult human retina. Hum Mol Genet 11:823–831.

Vardi N. 1998. Alpha subunit of Go localizes in the dendritic tips of ON bipolar cells. J Comp Neurol 395:43–52.

Vardi N, Morigiwa K. 1997. ON cone bipolar cells in rat express the metabotropic receptor mGluR6. Vis Neurosci 14:789–794.

Volkmer H, Hassel B, Wolff JM, Frank R, Rathjen FG. 1992. Structure of the axonal surface recognition molecule neurofascin and its relationship to a neural subgroup of the immunoglobulin superfamily. J Cell Biol 118:149–161.

Wan L, Almers W, Chen W. 2005. Two ribeye genes in teleosts: the role of Ribeye in ribbon formation and bipolar cell development. J Neurosci 25:941–949.

Yoshihara Y, Kawasaki M, Tamada A, Nagata S, Kagamiyama H, Mori K. 1995. Overlapping and differential expression of BIG-2, BIG-1, TAG-1, and F3: four members of an axon-associated cell adhesion molecule subgroup of the immunoglobulin superfamily. J Cell Biol 121:149–161.

Zhang SS, Xu X, Li J, Liu MG, Zhao H, Soares MB, Barnstable CJ, Fu XY. 2005. Comprehensive in silico functional specification of mouse retina transcripts. BMC Genomics 6:40.