Zebrafish Tg(7.2mab21l2:EGFP)ucd2 Transgenics Reveal a Unique Population of Retinal Amacrine Cells

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Purpose. Amacrine cells constitute a diverse, yet poorly characterized, cell population in the inner retina. Here, the authors sought to characterize the morphology, molecular physiology, and electrophysiology of a subpopulation of EGFP-expressing retinal amacrine cells identified in a novel zebrafish transgenic line.

Methods. After 7.2 kb of the zebrafish mab21l2 promoter was cloned upstream of EGFP, it was used to create the Tg(7.2mab21l2:EGFP)ucd2 transgenic line. Transgenic EGFP expression was analyzed by fluorescence microscopy in whole mount embryos, followed by detailed analysis of EGFP-expressing amacrine cells using fluorescence microscopy, immunohistochemistry, and electrophysiology.

Results. A 7.2-kb fragment of the mab21l2 promoter region is sufficient to drive transgene expression in the developing lens and tectum. Intriguingly, EGFP was also observed in differentiated amacrine cells. EGFP-labeled amacrine cells in Tg(7.2mab21l2:EGFP)ucd2 constitute a novel GABA- and glycine-negative amacrine subpopulation. Morphologically, EGFP-expressing cells stratify in sublamina 1 to 2 (type 1 OFF) or sublamina 3 to 4 (type 1 ON) or branch diffusely (type 2). Electrophysiologically, these cells segregate into amacrine cells with somas in the vitreal part of the INL and linear responses to current injection or, alternatively, amacrine cells with somas proximal to the IPL and active oscillatory voltage signals.

Conclusions. The novel transgenic line Tg(7.2mab21l2:EGFP)ucd2 uncovers a unique subpopulation of retinal amacrine cells. (Invest Ophthalmol Vis Sci. 2011;52:1613–1621) DOI: 10.1167/iovs.10-5376

Amacrine cells constitute approximately 40% of all neurons in the inner nuclear layer (INL).1 They are retinal interneurons, predominantly located in the INL, that synapse in the adjacent inner plexiform layer (IPL). In birds and mammals, displaced amacrine cells are also found in the ganglion cell layer (GCL). In general, amacrine cells function in retinal circuitry, mediating horizontal processing of neuronal signals derived from bipolar to cells that spike and cells that transmit rod signals to cone bipolar cells.3–5

The amacrine subtypes are classified based on morphology, physiology, and molecular markers.6–7 Approximately 24, 28, and 28 morphologic subtypes are distinguished in human, rabbit, and zebrafish retinas, respectively8–11 (Connaughton VP, et al. IOVS 2007;48:ARVO E-Abstract 5945). Morphologic distinctions are based on soma size, number of dendritic stratifications (mono-, bi-, or tri-stratified or diffuse), the size of dendritic fields (narrow-, medium-, and wide-field), and the location of dendritic stratifications within the IPL (sublamina s1–s5).8–10,12 This diversity may restrict visual signaling by limiting the synaptic interactions of specific subtypes or may reflect the dedication of subtypes to specific tasks.2,13 Physiologically, amacrine cells segregate into two groups based on only graded changes in potential.13 Based on dendritic tree stratifications, amacrine cells can also be classified as OFF and ON subtypes. These stratify within sublamina s1–2 or s3–5 of the IPL, respectively. However, many narrow- and medium-field amacrine cells synapse in both layers.9,10 Finally, amacrine cells can be subdivided based on the expression of molecular markers. Known neurotransmitters include γ-aminobutyric acid (GABA), glycine, acetylcholine, serotonin, and dopamine.14,15 GABA and glycine are the main inhibitory neurotransmitters in amacrine cells. For example, in zebrafish, the relative proportion of GABAergic to glycinergic amacrine cells is 64:35, with a small percentage negative for both.14 Other molecular markers include the calcium-binding proteins parvalbumin and calretinin, glutamate vesicular transporter 3, and aquaporin 1 and 9.14–17

Vertebrate mab21-like genes (mab21l1 and mab21l2) are expressed in the eye primordia, midbrain, branchial arches, neural tube, and limb buds during development.18–22 The function of vertebrate Mab21-like genes is largely unknown, but loss-of-function studies in mice and zebrafish suggest a role in cell proliferation.18,22,23 Both murine Mab21l1 and Mab21l2 have essential, but distinct, developmental roles—particularly in eye development. Mab21l2 mouse knockouts are embryonic lethal and have severely underdeveloped retinas.18 In contrast, Mab21l1 mouse knockouts survive to adulthood but fail to develop lenses.22 Here we isolated a 7.2-kb fragment of the zebrafish mab21l2 promoter region and used it to generate a novel transgenic zebrafish line expressing EGFP. Tg(7.2mab21l2:EGFP)ucd2 zebrafish discriminate a unique GABA/glycine-negative subpopulation of EGFP-positive amacrine cells with distinct morphology and electrophysiol-
ogy. This was unexpected because mab21l2 is not known to be expressed in retinal amacrine cells, and 99% of all amacrine cells express either GABA or glycine.14

METHODS

Creation of the mab21l2 Promoter/EGFP Construct

A 7.2 kb fragment of the zebrafish mab21l2 promoter region was PCR amplified from BAC clone zk257N17 (Imagenes, Nottingham, UK) using a proofreading polymerase (forward primer, mc065 5′-AGG TCG ACA TTC ACA CTG TAT GCC-3′; reverse primer, mc052 5′-TGG GCA CAG ATC CGG ACT GTA GAC-3′). PCR products were digested with SalI and BamHI and were subcloned into the pT2KXIGA ToI2 transposon vector digested with XhoI and BamHI generating the Tg(7.2mab21l2:EGFP) transgene.51,52 The integrity of the PCR insert in the recombinant vector was confirmed by DNA sequencing.

Generation and Analysis of Tg(7.2mab21l2:EGFP)ucd2

Tg(7.2mab21l2:EGFP) was injected into zebrafish embryos at the single-cell stage with 2.5 ng/μl ToI2 transposase mRNA added to the injection mix. The transgenic line was created by injecting the Tg(7.2mab21l2:EGFP) transgene and using the ToI2 transposon system. Transposase mRNA was synthesized using a kit (mMESSAGE mMACHINE; Ambion, Austin, TX) according to the manufacturer's instructions using NorI-digested pCST-TP vector as template. The final concentration of synthesized RNA was adjusted to 100 ng/μl. After each injection day, approximately five embryos were removed to confirm excision of the mab21l2 promoter fragment by the transposase.60 Sixty to 100 offspring from nine putative founders were screened under a fluorescence microscope at approximately 24 hpf, and a carrier was identified that transmits the transgene to approximately one-third of its offspring. The EGFP expression pattern in the confirmed transgenic line, Tg(7.2mab21l2:EGFP)ucd2, was analyzed from larval stages to adulthood. All analyses were performed using a stereomicroscope (Lumar V12; Zeiss, Thornwood, NY) or a confocal microscope (LSM 510; Zeiss).

Immunohistochemistry

Adult eyes from Tg(7.2mab21l2:EGFP)ucd2 were fixed for 30 minutes in 4% paraformaldehyde (PFA) at room temperature. The front of the eye was removed and the eyes were left in 4% PFA at 4°C overnight before infiltration with 20% sucrose and OCT embedding medium. Embryos at 5 days postfertilization (dpf) were fixed in 4% paraformaldehyde (PFA) at room temperature. The embryos were washed in PBS, dehydrated in PBS for 15 minutes before incubation in blocking buffer (5% goat serum, 0.5% Tween-20, 0.5% Triton X-100 in PBS), and before blocking solution was added, antibodies in blocking buffer overnight at 4°C. Sections were incubated in primary antibodies overnight before OCT embedding. Blocks were sectioned at 12 μm. Embryos at 5 days postfertilization (dpf) were fixed in 4% PFA at 4°C overnight before antigen retrieval.27 Sections were incubated in primary and secondary antibodies in blocking buffer overnight at 4°C. The following antibodies and dilutions were used: anti-S6 (1:100; a gift from James Fadool, Florida State University), anti-GAD65/67 (1:800; Abcam, Cambridge, MA), anti-calretinin (1:5000; a gift from Marius Aderems, Biosciences, Piscataway, NJ) according to the manufacturer’s instructions using NorI-digested pCST-TP vector as template. The final concentration of synthesized RNA was adjusted to 100 ng/μl. After each injection day, approximately five embryos were removed to confirm excision of the mab21l2 promoter fragment by the transposase.60 Sixty to 100 offspring from nine putative founders were screened under a fluorescence microscope at approximately 24 hpf, and a carrier was identified that transmits the transgene to approximately one-third of its offspring. The EGFP expression pattern in the confirmed transgenic line, Tg(7.2mab21l2:EGFP)ucd2, was analyzed from larval stages to adulthood. All analyses were performed using a stereomicroscope (Lumar V12; Zeiss, Thornwood, NY) or a confocal microscope (LSM 510; Zeiss).

Cell Morphology Analyses

Adult whole mount retinas were dissected and fixed in 4% PFA at 4°C overnight before being placed on depression slides. Adult Tg(7.2mab21l2:EGFP)ucd2 retinal sections were prepared as for the immunohistochemistry analysis. Mosaic larvae were generated by injecting the Tg(7.2mab21l2:EGFP) construct as described, but without transposase mRNA. Larvae 5 dpf were processed as described for immunohistochemistry and sectioned at 40 μm. All samples were analyzed with a confocal microscope (LSM 510; Zeiss). For IMARIS analysis, confocal z-stacks were imported into IMARIS 7.2, and 3D reconstructions of cell dendrites were performed using the filament tracing module.

Single-Cell Electrophysiology and Imaging

Fish were dark adapted for at least 20 minutes, anesthetized in a 0.02% tricaine solution until gill movements stopped, and then decapitated. Retinas were removed from the eyes. For whole-cell voltage-gated recordings, retinas were treated with hyaluronidase in Ringers for 20 minutes before being placed vitreal-side down on a filter paper. For whole-cell current clamp recordings, retinas were placed directly vitreal-side down on filter paper. Filter with retina was mounted in the recording chamber between two petroleum jelly (Vaseline; Unilever, London, UK) strips and submerged in the standard extracellular (Ring- ers) solution. The filter with retina was then cut into 100-μm sections. Each section was rotated 90° and viewed in cross-section.28 Retinal slices were perfused with extracellular Ringers supplemented with 2.5 CaCl2 at 0.5 mL/min and visualized under oblique illumination through a 60× objective on an upright microscope (Ex51WI; Olympus, Melville, NY) for current clamp recordings or a 40× water immersion lens and microscope (BX50WI; Olympus) for voltage clamp recordings. Whole-cell current clamp recordings were obtained from EGFP-positive somata using 8 to 12 MΩ patch electrodes pulled from borosilicate glass (GC120F-10; Harvard Apparatus, Kent, UK). The intracellular solution contained 104 mM K-glucuronate, 8 mM KCl, 2 mM MgCl2, 0.5 mM HEPES, 0.5 mM EGTA, 2 mM MgATP, 1 mM NaGTP, 1 mM NaGMP (pH 7.4–7.5 using KOH). Signals were recorded using an amplifier (Axopatch 200B; Molecular Devices, Sunnyvale, CA) with an ITCL-16 interface (HEKA, Lambrecht, Germany) and digitized at 20 kHz in Pulse Control (developed by Richard Brockman) under graphing and data analysis software (Igor-Pro 6.1; Waveformetrics, Lake Oswego, OR). A water-cooled EM-CCD camera (ImageM; Hamamatsu, Iwata City, Japan) was used to record fluorescence. A 1-A 470 nm light-emitting diode (LED) and a 500-mA 590 nm LED (K2; Luxeon, San Jose, CA) served as light sources for GFP and Alexa 594, respectively.

Whole-cell voltage-gated currents were recorded in response to voltage steps from a holding potential of −60 mV (−80 to +60 mV, 10-mV increments). Recordings were made using a standard extracellular Ringers solution, and a K-based pipette solution (12 mM KCl, 104 mM K-glucuronate, 1 mM EGTA, 4 mM HEPES, and 100 μM CaCl2, to pH 7.4–7.5 using KOH). Alexa Red was present in the patch pipette to label recorded neurons. Labeled cells were photographed using a camera (Oly-150; Olympus) and video frame-grabber software (Flash- Bus; Integral Technologies, Indianapolis, IN). Patch electrodes were made of thin-walled borosilicate glass pulled to 1-μm tip diameter. Recordings were made using a patch clamp amplifier (Axiopatch 1D; Molecular Devices) and software (pCLAMP, version 9.0; Molecular Devices) software. Traces were analyzed (pCLAMP, version 9.0; Molecular Devices); graphs were made with statistical software (SigmaPlot, version 6; Sigma, St. Louis, MO).
Animal Use

All procedures involving animals were carried out in accordance with the ARVO Statement for Use of Animals in Ophthalmic and Vision Research and were approved by the University College Dublin (Dublin, Ireland) Animal Research Ethics Committee, the American University (Washington, DC) Animal Care and Use Committee, and the MRC Laboratory of Molecular Biology (Cambridge, UK) Ethical Review Committee.

RESULTS

Tg(7.2mab2l2:EGFP)ucd2 Drives EGFP Expression in mab2l2 Expression Domains

An approximately 7.2 kb fragment of the zebrafish mab2l2 promoter region was cloned upstream of EGFP. A stable transgenic line, Tg(7.2mab2l2:EGFP)ucd2, was generated using this construct to characterize the expression patterns directed by the

FIGURE 1. EGFP expression in the stable transgenic line Tg(7.2mab2l2:EGFP)ucd2. Epifluorescent images of whole mount transgenic larvae (A–L). At approximately 13 somites, EGFP expression is observed prominently in the optic tectum and weakly in the lens and is missing in the retinal primordia (A–C). At approximately 28 hpf, EGFP expression remains strong in the tectum (D, inset), has increased in the central lens (E), and is initiated in olfactory bulbs (F). At approximately 3 to 5 dpf, strong EGFP expression is observed in the branchial arches, pectoral fins, eye, and optic tectum (G–L). An optical section through the eye at approximately 5 dpf identifies EGFP-expressing cells in the INL, subsequently identified as amacrine cells (K). NT, neural tube; AC, amacrine cell; BA, branchial arch; OB, olfactory bulb. Yellow arrowhead: tectum. (A, C, inset in D, I, K, L) Dorsal views. (F) Front view. (B, D, E, G, H, J) Lateral views.
promoter fragment (Fig. 1). During development, *Tg(7.2mab2l2:EGFP)ucd2* larvae exhibited transgene expression in known *mab2l2* expression domains, including the midbrain/tectum starting at approximately 13 somites (~14 hpf), the neural tube starting at approximately 24 hpf, and branchial arches starting at approximately 48 hpf (Figs. 1A, 1C, 1D, 1G, 1I, 1J, 1L). Unexpectedly, *Tg(7.2mab2l2:EGFP)ucd2* larvae do not direct EGFP expression in the primitive retina at approximately 14 hpf, a stage at

![FIGURE 2. *Tg(7.2mab2l2:EGFP)*-labeled amacrine cells constitute a unique subpopulation. Confocal images of transgenic adult (A–D) and 5 dpf larvae (E–H) retinal sections. Most EGFP-expressing cells co-label with anti-parvalbumin (A) and anti-calretinin (B). The *Tg(7.2mab2l2:EGFP)*-labeled amacrine cells do not colocalize with dopaminergic (anti-TH) (C), glycinergic (anti-Gly) (D), serotoninergic (anti-5HT) (E), cholinergic (anti-ChAt) (F), GABAergic (anti-GAD65/67) (G), or 5E11-positive amacrine cells (anti-5E11) (H). Arrowheads: colocalization. Scale bar, 50 μm. (D) Lower magnification than for other adult retinas.](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/932971/)
which endogenous mab2l2 is strongly expressed in this tissue (Figs. 1A–C).\textsuperscript{21} Other unanticipated results were that Tg(7.2mab2l2:EGFP) directs expression in the developing lens and olfactory bulbs starting at approximately 24 hpf (Figs. 1E, 1F) and, of most relevance here, directs robust reporter expression in a subset of inner retinal neurons at 3 to 5 dpf and in adult retinas (Figs. 1H, 1K, 2, 3). These are not known expression domains of mab2l2 and likely reflect the activity of the promoter fragment in isolation.

**FIGURE 3.** Morphologic characterization of the EGFP-positive amacrine cells. (A) Confocal image of a flat mounted retina from an adult Tg(7.2mab2l2:EGFP)ucd2 shows a random distribution of EGFP-labeled amacrine cells across the retina. (B) 3D reconstruction of a portion of the flat mounted retina showing that the EGFP-labeled amacrine cells send processes throughout the retina. (C) Confocal Z-stack of a section through the retina of a Tg(7.2mab2l2:EGFP)ucd2 adult. Type 1 EGFP-labeled amacrine cells have cell somas more distal from the IPL than type 2 amacrine cells. Computerized tracing of the dendritic trees identified EGFP cells stratifying in sublamina 1 to 2 (type 1 OFF) or sublamina 3 to 4 (type 1 ON) of the IPL and cells with a diffuse branching pattern (type 2). Scale bars: 50 μm (A); 20 μm (C).

**Tg(7.2mab2l2:EGFP)-Labeled Amacrine Cells Colocalize with Calretinin and Parvalbumin**

Confocal microscopy of retinal sections from 5 dpf Tg(7.2mab2l2:EGFP)ucd2 zebrafish demonstrated that the EGFP-positive cells in the INL had dendrites primarily localizing to two bands within the IPL (Fig. 1K), suggesting they were amacrine cells; this was subsequently confirmed (Figs. 2–4). To characterize these cells, Tg(7.2mab2l2:EGFP)ucd2 retinal sections were labeled with antibodies that distinguish amacrine subtypes. EGFP-positive soma do not colocalize with GABAergic (anti-GAD65/67), glycnergic (anti-Gly), dopaminergic (anti-TH), serotonergic (anti-5HT), or cholinergic (anti-ChAT)–positive amacrine cell soma or with anti-5E11, an unknown epitope expressed by most amacrine cells (Figs. 2C–H; Table 1). However, the calcium transporters calretinin and parvalbumin do colocalize with approximately 76% and approximately 70% of EGFP-positive soma, respectively (Figs. 2A, 2B; Table 1). Less than 10% of the calretinin or parvalbumin positive cells coexpressed EGFP.

**EGFP-Expressing Amacrine Cells Can Be Subclassified Based on Morphology and Electrophysiology**

To further characterize the EGFP-positive amacrine cells, morphologic analyses were performed by confocal microscopy and 3D dendrite tracing. Flat mount images of adult Tg(7.2mab2l2:EGFP)ucd2 retinas indicated that the EGFP-positive cells were evenly distributed across the retina and accounted for <5% of INL cells (Fig. 3A). In the retinal flat mounts, 3D reconstruction of dendritic morphology showed that the EGFP-positive amacrine cells contained processes that collectively spanned the length and width of the area of retina examined (Fig. 3B). Confocal images of retinal sections from Tg(7.2mab2l2:EGFP)ucd2 adults identified three characteristic morphologies of the EGFP-expressing amacrine cells. Their dendrites projected only from the soma in the INL toward the synaptic layers in the IPL, typical of amacrine cells. Two morphologic subtypes were distinguished based on location of the EGFP-labeled cell soma (Figs. 3C, 4K). Type 1 cells had somas in the middle of the INL, and type 2 cells had somas in proximity to the IPL (Figs. 3C, 4K). Type 1 amacrines could be further subtyped into type 1 OFF cells, which primarily stratified in sublamina 1 to 2, and type 1 ON cells, which primarily stratified in sublamina 3 to 4 (Fig. 3C). Type 2 cells are diffuse amacrine cells with dendrites throughout the IPL (Fig. 3C). The somas of EGFP-labeled amacrine cells have an average soma length of ~6.4 μm (6.0–6.7 μm) and an average soma width of approximately 5.0 μm (4.6–5.4 μm). Compared with the stratification pattern for ChAT, the main EGFP-positive stratifications are located at the same level as the upper ChAT-positive band and just above the lower second band (Figs. 4A–C). It is likely that type 1 ON cells corresponded to cells coexpressing EGFP and calretinin, with somas in the mid-INL and monostratified in sublamina 3 to 4 (Fig. 4K).

To analyze the morphology of individual EGFP-expressing amacrine cells, embryos were injected with the Tg(7.2mab2l2:EGFP) transgene. At 5 dpf, retinal sections from the corresponding mosaics were analyzed by confocal microscopy and 3D dendrite tracing (Figs. 4D–J). Although soma location could not be used to predict cell morphology, stratification patterns corresponding to the adult type 1 OFF (Figs. 4D, 4E, 4G, 4I). Supplementary Movie S1, http://www.iovs.org/lookup/suppl/doi:10.1167/iovs.53576/-/DCSupplemental), type 1 ON (Figs. 4D, 4E, 4H, 4J, Supplementary Movie S2, http://www.iovs.org/lookup/suppl/doi:
EGFP-positive amacrine cells were observed in the mosaic larval retinas. These analyses confirmed that this labeled subset of amacrine cells have either medium-field stratifications (type 1) or narrow-field stratifications (type 2; Figs. 4G, 4H, Supplementary Movies S1–S3, http://www.iovs.org/lookup/suppl/doi:10.1167/iovs.10-5376/-/DCSupplemental). An intriguing morphology is revealed for one type 1 ON cell that largely
stratifies in the INL but then takes an acute turn through a gap in the ganglion cell layer that opens onto the lens (Fig. 4E).

Electrophysiological recordings of EGFP-positive amacrine cells in adult Tg(7.2mab21l2:EGFP)ucd2 zebrafish indicate distinct physiological properties of type 1 and type 2 cells (Figs. 5A, 5B). Type 1 cells have a resting membrane potential of approximately −40 mV and respond linearly to depolarizing current injection in current clamp mode (data not shown). Voltage clamp recordings from five type 1 cells identify two depolarization-elicited outward currents: slowly activating, sustained currents (I_A) and rapidly activating, transient currents (I_I) (Fig. 5A). In contrast, current clamp recordings of seven type 2 cells reveal active voltage signals. These cells have a resting membrane potential of approximately −70 mV and exhibit fast (100–150 Hz), large (≤30 mV), and regular membrane potential oscillations on depolarizing current injection (Fig. 5B). Overall, the morphologic and physiological analyses of the EGFP-positive amacrine cells indicate that they are composed of three unique amacrine subtypes.

**DISCUSSION**

Our results identify a mab21l2 promoter fragment that distinguishes a unique subpopulation of retinal amacrine cells. Amacrine cells are a diverse and poorly understood cell population in the retina. Most zebrafish amacrine cells express GABA or glycine neurotransmitters, though dopaminergic interplexiform cells are a known exception.14 Interestingly, the EGFP-positive amacrine cells in Tg(7.2mab21l2:EGFP)ucd2 do not coexpress GABA, glycine, or dopamine, indicating they are a unique subtype. GABA- and glycine-negative amacrine cells are present in other vertebrate retinas, but their function is unclear and their characterization limited.29,30 Here, we characterize the molecular biology, morphology, and electrophysiology of the GABA- and glycine-negative amacrine subpopulation labeled in Tg(7.2mab21l2:EGFP)ucd2.

**Table 1.** Colocalization of Tg(mab21l2:EGFP) Amacrine Cells with Known Amacrine Cell Markers

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<td>7 (70)</td>
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<td>Anti-calretinin (adult)</td>
<td>25</td>
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<td>Anti-SE11 (adult)</td>
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Zebrafish amacrine cells have been classified based on molecular markers, morphology, and electrophysiology. However, in general, these studies are performed in isolation, and it is difficult to correlate morphologic and molecular subclasses of amacrine cells with physiological properties. Molecularly, the Tg(7.2mab21l2:EGFP)-labeled amacrine cells described here co-label with calretinin and parvalbumin but not GABA or glycine. Morphologically, these EGFP-expressing amacrine cells can be divided into medium-field, monostratified type 1 cells and narrow-field, diffuse type 2 cells. Type 1 amacrine cells can be further divided into subtypes that predominantly stratify in either sublamina 1 to 2 (type 1 OFF) or in sublamina 3 to 4 (type 1 ON). Type 1 ON amacrine cells have a morphology similar to that of the previously described A_on-s4 zebrafish amacrine cell.15 This cell is monostratified in sublamina 3 to 4, though the soma appears to be located closer to the IPL.12 Type 1 ON cells also have a morphology similar to that of the previously described pyriform, calretinin-positive amacrine cell that monostratifies in sublamina 3 to 4 and whose somas are in the vitreal aspect of the zebrafish INL.15 Type 2 cells potentially correspond to the previously described diffuse A_diffuse-1 to 2 cells.12 As with type 2 cells, their somas are located proximal to the IPL. A recent morphologic study of zebrafish amacrine cells revealed 28 inhibitory cell types.11 Several of these have somas either in the middle INL or proximal to the IPL and dendrites branching in soma 1 to 2 or 3 to 4. Further characterization will be required to reveal which, if any, of these correspond to the EGFP-expressing cells described here.11 Similarly, parvalbumin-expressing amacrine cells have been described in the zebrafish retina and appear to stratify mainly in either sublamina 3 or 4 to 5 of the IPL.31 Although approximately 70% of the EGFP-positive amacrine cells in Tg(7.2mab21l2:EGFP)ucd2 zebrafish coexpress parvalbumin, we find no evidence that the parvalbumin-positive, EGFP-positive cells correspond to any of these described populations. In summary, we define molecular markers and cell morphologies associated with the poorly characterized GABA- and glycine-negative subpopulation of amacrine cells.

Electrophysiologically, type 1 cells with somas in the INL respond linearly to current injection, whereas type 2 cells with somas in proximal INL generate active voltage oscillations. I_A is a delayed rectifying potassium current found in type 1 amacrine cells. It is a slowly activating current that is sustained. The transient I_I current found in type 1 cells is a rapidly activating and inactivating outward potassium current. Both currents have been identified in zebrafish bipolar cells.32 There are no previous reports of zebrafish amacrine cell recordings matching those of type 1 or 2 cells. However, outward K+ currents have been identified in mouse, rat, and salamander amacrine cells.33–35 In particular, mouse cholinergic amacrine cells express either I_A or I_I currents,36 similar to our findings here. Voltage oscillations similar to those ex-
hibited by type 2 cells have been recorded in wide-field amacrine cells in the bass retina. In GABA- and glycine-negative amacrine cells, labeled in Tg(7.2mab21l2:EGFP)ucd2 zebrafish, have distinct electrophysiological properties that correlate with previous recordings of amacrine cell subtypes.

Several transgenic zebrafish lines with reporter gene expression in amacrine cells have been created. The ptf1a:GFP transgenic line, in which GFP replaces pancreas transcription factor 1a (ptf1a) in a genomic clone, expresses GFP in most amacrine cells. Tg(eno2:GFP), under control of an approximately 12 kb promoter fragment of the enolase-2 gene, expresses GFP in many central nervous system cells, including retinal ganglion cells, amacrine cells, and rod photoreceptors. Some of the GFP-expressing amacrine cells coexpress tyrosine hydroxylase. Tg(−12th:MmGFP), under control of an approximately 12 kb promoter fragment of the tyrosine hydroxylase, expresses GFP in two cell subpopulations in the INL, of which approximately 30% are dopaminergic neurons. Pax6-DF4:mGFP transgenic zebras have distinct electrophysiological properties that correlate with previous recordings of amacrine cell subtypes.

In summary, this study describes a new zebrafish transgenic line, Tg(7.2mab21l2:EGFP)ucd2, within which the morphology, molecular biology, and electrophysiology of a novel subpopulation of GABA- and glycine-negative amacrine cells was characterized.

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