Development/Plasticity/Repair

Synaptic Plasticity in CNGA3\(^{-/-}\) Mice: Cone Bipolar Cells React on the Missing Cone Input and Form Ectopic Synapses with Rods

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In the mammalian retina, rods and cones connect to distinct sets of bipolar cells. Rods are presynaptic to a single type of rod bipolar cell, whereas cones connect to different types of cone bipolar cells. Synaptic rewiring between cone photoreceptor terminals and rod bipolar cell dendrites has been described as a general result of photoreceptor degeneration. To investigate whether cone bipolar cells also show synaptic plasticity in the absence of cone input, we studied the connectivity of cone bipolar cell dendrites in CNGA3\(^{-/-}\) mice, a model with specific loss of cone photoreceptor function. Dendritic connections of ON and OFF cone bipolar cells were visualized using specific cell markers or by intracellular injection with fluorescent dyes. The results show that cone bipolar cells in CNGA3\(^{-/-}\) mice form ectopic synapses with rods. In contrast, cone bipolar cells do not form ectopic synapses with rods in CNGA3\(^{-/-}\) Rho\(^{-/-}\) mice, in which both types of photoreceptors are nonfunctional. In analogy with these results, we found that input-deprived rod bipolar cells form ectopic synapses with functional cones in Rho\(^{-/-}\) mice but not with inoperable cones in the CNGA3\(^{-/-}\) Rho\(^{-/-}\) mouse. Our data indicate that the formation of ectopic bipolar cell synapses in the outer plexiform layer requires a functional presynaptic photoreceptor.

Key words: retina; cones; rods; bipolar cells; dendritic plasticity; ectopic synaptogenesis
that is complete at ~3 months postnatally (Humphries et al., 1997; Jaisl et al., 2001). We used these mice, as well as mice deficient for both CNGA3 and Rhodopsin (CNGA3<sup>−/−</sup>/Rho<sup>−/−</sup>) (Claes et al., 2004), to test our hypothesis that the formation of ectopic bipolar cell synapses in the outer plexiform layer (OPL) requires a functional presynaptic photoreceptor.

**Materials and Methods**

*Animals.* The generation of CNGA3<sup>−/−</sup> mice and Rho<sup>−/−</sup> mice was described previously (Humphries et al., 1997; Briel et al., 1999). Double mutants were generated by cross-breeding CNGA3<sup>−/−</sup> with Rho<sup>−/−</sup> mice (Claes et al., 2004). The α-gustducin–green fluorescent protein (GUS–GFP) transgenic mouse line was kindly provided by R. Margolskee (Mount Sinai Medical Center, New York, NY) (Huang et al., 2003).

The electron microscopic study included eight CNGA3<sup>−/−</sup> mice of different ages (postnatal week 3, 4, 5, and 6) by preembedding immunoelectron microscopy. We did not count the number of PKC<sub>α</sub>-labeled rod bipolar cell dendrites at cone pedicles, because the penetration of the PKC<sub>α</sub>-antibody was not optimal and we only found labeling at the surface, not enough to find a sufficient number of examples for quantification.

**Light microscopic immunocytochemistry.** OFF cone bipolar cells were labeled with antibodies against the neurokinin-3 receptor (rabbit anti-NK3R; 1:500; kindly provided by R. Shigemoto, National Institute, Okazaki, Japan) and rod bipolar cells with antibodies against protein kinase Ca<sub>2+</sub> (rabbit anti-PKC<sub>α</sub>; 1:10,000; Sigma, St. Louis, MO). Synaptic ribbons were visualized with an antibody against the cytomatrix protein bassoon (mouse anti-bassoon; 1:5000; Stressgen Biotechnologies, Victoria, British Columbia, Canada) or with antibodies against the C-terminal binding protein 2 (mouse anti-CtBP2; 1:10,000; BD Transduction, Heidelberg, Germany). The Glur5 antibody (goat anti-GluR5N; 1:100; Santa Cruz Biotechnology, Heidelberg, Germany) has been used to label cone bipolar cells using the current-clamp circuit of the EPC-9 patch-clamp amplifier (HEKA Elektronik, Lambrecht, Germany). After injection, the slices were fixed in 4% paraformaldehyde for 20 min, washed in PB and applied overnight at 4°C. After several washes in distilled water, the DAB reaction product was silver-intensified by incubating the sections in a solution containing 2.6% hexamethylene tetramine, 0.2% silver nitrate, and 0.2% disodium tetraborate for 10 min at 60°C. The sections were then rinsed in distilled water and treated for 2 min with gold chloride (0.05% in distilled water). Finally, the sections were rinsed in distilled water and incubated for 2 min in sodium thiosulfate (2.5% in distilled water). The sections were then postfixed with 0.5% OsO<sub>4</sub> in cacodylate buffer for 30 min, dehydrated in a graded series of ethanol (30–100%) followed by propylene oxide, and flat-embedded in Epon 812 (Serva, Heidelberg, Germany). Serial ultrathin sections were cut, stained with uranyl acetate and lead citrate, and examined with a Zeiss EM10 electron microscope.

We used these mice, as well as mice deficient for both CNGA3 and Rhodopsin (CNGA3<sup>−/−</sup>/Rho<sup>−/−</sup> mice; postnatal week 3.2, 4.0, 5.0, 6.1, 6.6, and 7.6) to study the formation of ectopic bipolar cell synapses in the mouse retina (Tsukamoto et al., 2001) (see Fig. 5). The densely packed somas form ~10 tiers; the underlying synaptic terminals form three to four tiers. The NK3R-labeled dendrites reach the innermost tier of synaptic terminals, where cone pedicles and rod spherules intermingle (see Fig. 2B, C). Because the dendrites mostly stop there and barely penetrate the remaining tiers of rod spherules, we counted only the rod spherules in this innermost tier.

Intracellular injection of ON cone bipolar cells. For the preparation of vertical sections, the retinas of C57BL/6 wild-type and CNGA3<sup>−/−</sup> mice were removed from the eye cup and embedded in 2% agarose in Ames medium (Sigma, Deisenhofen, Germany). Arg blocks were mounted on a vibratome (Leica, Nussloch, Germany) and cut into slices of 200 μm thickness. After cutting, the slices were fixed in 4% paraformaldehyde for 10 min, washed in PB, and subsequently transferred to the stage of an upright microscope (Leica) for intracellular injections.

Intracellular injections were performed with sharp borosilicate microelectrodes (Hilgenberg, Malsfeld, Germany) filled with 10 ms Alexa Fluor 488 hydrazide (Invitrogen). Alexa 488 was injected iontophoretically (2–3 min, −1 nA) into the somata of morphologically identified bipolar cells using the current-clamp circuit of the EPC-9 patch-clamp amplifier (HEKA Elektronik, Lambrecht, Germany). After injection, slices were fixed in 4% paraformaldehyde for 20 min, washed in PB, and processed for immunocytochemistry as described below.

**Postembedding immuno electron microscopy.** Vibratome sections were incubated for 4 d at 4°C in a primary antibody solution (anti-NK3R, 1:1000; anti-PKCα, 1:20,000) containing 3% normal goat serum (NGS), 1% bovine serum albumin, and 0.05% sodium azide in PBS. Thereafter, the sections were rinsed in PBS and immunolabeling was detected with a biotinylated goat anti-rabbit IgG (1:100; Vector Laboratories, Burlingame, CA) and a peroxidase-based enzymatic detection system ( Vectastain Elite ABC kit; Vector Laboratories). After rinses in PBS and in 0.5% Tris-HCl, pH 7.6, the sections were reacted in 3,3′-diaminobenzidine (DAB; 0.05% in Tris-HCl) with 0.01% H<sub>2</sub>O<sub>2</sub> for 5–10 min. Subsequently, the sections were rinsed in Tris-HCl and then in 0.1 m cacodylate buffer, pH 7.4, postfixed in 2.5% glutaraldehyde in cacodylate buffer for 2 h at 4°C, and washed in cacodylate buffer overnight at 4°C. After several washes in distilled water, the DAB reaction product was silver-intensified by incubating the sections in a solution containing 2.6% hexamethylene tetramine, 0.2% silver nitrate, and 0.2% disodium tetraborate for 10 min at 60°C. The sections were then rinsed in distilled water and treated for 2 min with gold chloride (0.05% in distilled water). Finally, the sections were rinsed in distilled water and incubated for 2 min in sodium thiosulfate (2.5% in distilled water). The sections were then postfixed with 0.5% OsO<sub>4</sub> in cacodylate buffer for 30 min, dehydrated in a graded series of ethanol (30–100%) followed by propylene oxide, and flat-embedded in Epon 812 (Serva, Heidelberg, Germany). Serial ultrathin sections were cut, stained with uranyl acetate and lead citrate, and examined with a Zeiss EM10 electron microscope.
ments, sections were incubated in a mixture of primary antibodies, followed by a mixture of secondary antibodies.

Confocal micrographs of fluorescent specimens were taken with a Leica TCS SL confocal microscope equipped with an argon and a helium–neon laser. Scanning was performed with a 40×/1.25 Plan-Apochromat and a 63×/1.32 Plan-Apochromat objective at a resolution of 1024 × 1024 pixels (z-axis step size, 0.5 μm). Different wavelength scans were performed sequentially to rule out cross-talk between red, green, and blue channels.

**Results**

The retina of CNGA3−/− mice displays a normal general morphology and lamina (Biel et al., 1999). Only a degeneration of cones is evident over a time course of several months (Michalakis et al., 2005). To investigate the connectivity of OFF cone bipolar cells in the CNGA3−/− retina, we used a specific antibody directed against the neurokinin-3 receptor (Ding et al., 1996). NK3R labels type 1 and type 2 bipolar cells in the mouse retina but not the rod contacting type 3 cell, which can be labeled by antibodies against the calcium-binding protein 5 (CaB5) (Haverkamp et al., 2003; Ghosh et al., 2004).

NK3R immunoreactivity was present in bipolar cells with axons terminating in the outermost part of the inner plexiform layer (IPL) (Fig. 1A). The processes in the inner IPL in Figure 1A belong to NK3R-immunoreactive amacrine cells (Haverkamp et al., 2003). There was no difference between wild-type and CNGA3−/− retinas except for small NK3R-labeled dendrites extending into the outer part of the outer plexiform layer (Fig. 1A, arrows). To determine potential contact sites of these dendrites, we double labeled vibratome sections with antibodies against NK3R and the cytomatrix protein bassoon. Bassoon labels the photoreceptor ribbons in rod spherules, where they show a horseshoe-shaped structure, and in cone pedicles, where they are clustered in a row (frame). In the OPL of a wild-type mouse, bassoon labels the photoreceptor ribbons in rod spherules, where they show a horseshoe-shaped structure, and in cone pedicles, where they are clustered in a row (frame). In the OPL of a wild-type mouse, bassoon labels the photoreceptor ribbons in rod spherules, where they show a horseshoe-shaped structure, and in cone pedicles, where they are clustered in a row (frame).

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**OFF cone bipolar cells in the CNGA3−/− mouse contact rod spherules**

At the ultrastructural level, ON and OFF bipolar cells can be clearly distinguished with respect to their contacts with cone pedicles. OFF cone bipolar cells make flat contacts at the cone pedicle base, whereas ON cone bipolar cells make invaginating contacts at the ribbons (Kolb and Nelson, 1995). In the case of the NK3R-immunolabeled OFF cone bipolar cells, we found many examples of flat contacts at the cone pedicle base of CNGA3−/− mice (Fig. 2A). In addition, labeled dendrites contacting rod spherules were seen frequently (Fig. 2B, C). To demonstrate that these contacts were flat, noninvaginating synaptic contacts, we performed serial sectioning and followed the labeled dendrites in 8–10 sections (Fig. 2C, D). Altogether, eight CNGA3−/− mice of different age have been investigated, and in all cases, numerous ectopic synapses at rod spherules have been found. In contrast, almost no ectopic contacts were found in wild-type mouse retinas. For quantification, we counted the number of flat contacts at rod spherules from single sections of three CNGA3−/− and three wild-type animals (see Materials and Methods). In the case of the CNGA3−/− tissue, 207 of 1282 rod spherules made ectopic synapses with NK3R-labeled dendrites (16%); in the case of the wild-type tissue, only 6 of 867 rod spherules were possibly contacted by NK3R-labeled dendrites (0.67%).

We now asked whether the presence of these ectopic synapses depends on the activity of rod photoreceptors. To this end, we looked for ectopic synapses in retinas of CNGA3−/−/Rho−/− mice, in which both cones and rods are nonfunctional. In all double-mutant mice, we investigated (four mice between postnatal week 3.3 and 6.6), the NK3R-labeled OFF cone bipolar cells did not contact rod spherules. Apparently, cone bipolar cells form ectopic synapses with functional rods but not with rods sending no light-driven output onto second-order neurons, suggesting that the formation of ectopic synapses in the OPL requires a functional presynaptic photoreceptor.

**GluR5 expression at ectopic synapses in the CNGA3−/− mouse**

Connections between rods and OFF cone bipolar cells have been described in rodent and rabbit retina, and the synaptic nature of these contacts was confirmed by the presence of the GluR1 and GluR2 receptors (Hack et al., 1999; Li et al., 2004). To prove the functional relevance of the ectopic bipolar cell synapses in the
contacts to NK3R-immunoreactive dendrites (arrows).

We double labeled sections for GluR5 and bassoon and found a clear difference between wild-type and CNGA3<sup><s>-/-</s></sup> retina (Fig. 3). In the wild-type retina, GluR5 was exclusively aggregated in postsynaptic clusters at the cone pedicle base (Fig. 3A) [Haverkamp et al. (2003), their Fig. 8B–D]. In contrast, in the CNGA3<sup><s>-/-</s></sup> retina, clear examples of GluR5 puncta were found at the positions where OFF bipolar cell dendrites contact rod spherules (compare Figs. 3B, C, 1C–F). The localization of GluR5 puncta at ectopic contact sides strongly indicates that the rod–cone bipolar cell synapses are functional. In addition, it shows that OFF cone bipolar cells other than NK3R-positive cells are engaged in ectopic synapses with rod spherules.

### Plasticity of ON cone bipolar cells in the CNGA3<sup><s>-/-</s></sup> mouse

Direct synaptic contacts of ON cone bipolar cells with rods have not been described so far. This could be because of a technical problem, because immunocytochemical markers for specific ON cone bipolar cell types are not available, and chances of analyzing all ON types in a sufficient number by intracellular dye injection are low. Therefore, we concentrated on a transgenic mouse line with strong GFP expression in a single type of ON cone bipolar cell. GFP expression was also present in rod bipolar cells but was significantly weaker than in ON cone bipolar cells (GUS–GFP mouse) (Huang et al., 2003). The labeled ON cone bipolar cells resemble those termed type 7 by Ghosh et al. (2004). Figure 4 shows the dendritic trees of two type 7 cells double labeled with antibodies against GluR5 and GFP. It can be seen that all the bipolar dendrites terminate at clusters of GluR5 puncta, which represent individual cone pedicles; none of the dendrites terminates at a rod sphäre (Fig. 4B, D). This was the case for all type 7 cells we examined (n = 36). Their dendrites contacted all the cone pedicles (between 6 and 10 per cell) within their dendritic field. None of the cells made a potential contact with a rod spherule.

Because ON cone bipolar cells resembling type 7 in the GUS–GFP mouse are exclusively connected to cones, we injected this bipolar cell type in the CNGA3<sup><s>-/-</s></sup> mouse retina. In addition, we also studied the presynaptic contacts of type 5 ON cone bipolar cells. Figure 5A shows a projection of a type 5 ON cone bipolar cell with its axon terminating in stratum 3 of the IPL. When double-labeled with antibodies against kinesin and mGluR6, the presynaptic and postsynaptic components of the photoreceptor to bipolar cell synapse can be visualized. In single optical sections, cone pedicles can be easily identified according to the row-like clustering of the synaptic ribbon marker kinesin. As expected, all type 5 cells examined (n = 6) contacted cone pedicles (Fig. 5B). However, this cell type also extended dendrites into close proximity of rod spherules, suggesting potential synaptic contact sites (Fig. 5C). We observed putative ectopic synapses between type 5 ON cone bipolar cells and rod spherules in all cells injected (n = 6).

Injection and double-labeling of type 7 ON cone bipolar cells in the CNGA3<sup><s>-/-</s></sup> mouse retina (Fig. 5D) also provided evidence for ectopic contacts with rod spherules. Again, the clustering of...
kinesin and mGluR6 immunoreactivity is indicative for cone pedicles, and dendrites of type 7 ON cone bipolar cells clearly make synapses with cones (Fig. 5E). However, individual contact sites (in contrast to the cone pedicle clusters) suggest also putative synapses with rod spherules (Fig. 5F). Dendrites extending from type 7 ON cone bipolar cells to rod spherules were observed in six of seven injected cells (86%).

Cone contacts of rod bipolar cells in the *Rho*<sup>−/−</sup> mouse

We have shown so far that cone bipolar cells react to the loss of light-driven output by establishing synaptic contacts to rod spherules. We now asked whether rod bipolar cells do also show a corresponding behavior when the rod photoreceptor output is missing. It has been shown that rod bipolar cells form ectopic synapses with cones in diverse photoreceptor degeneration models (Peng et al., 2000, 2003), and one would expect to find the same in the *Rho*<sup>−/−</sup> mouse.

To analyze their synaptic contacts at the light microscopic level, rod bipolar cells were labeled with antibodies against PKCa (Haverkamp and Wässle, 2000) and photoreceptor ribbon synapses with antibodies against CtBP2 (tom Dieck et al., 2005) (Fig. 6). We did not find any PKCa-labeled dendrites closely associated with cone pedicles in the wild-type retina (Fig. 6B), and we found hardly any examples of rod bipolar cell dendrites making potential contact with cone pedicles in the *Rho*<sup>−/−</sup> retina (Fig. 6C).

Analyzing the contacts of rod bipolar cell dendrites at the ultrastructural level was much more promising. We found a number of examples of PKCa-labeled dendrites at cone pedicles in the *Rho*<sup>−/−</sup> mouse (Fig. 7). In the wild-type retina, rod bipolar cells make invaginating synaptic connections with rod spherules (Fig. 7A) but not with cone pedicles (Peng et al., 2000). In the *Rho*<sup>−/−</sup> mouse, most of the rod bipolar cell dendrites, which were followed through a series of sections at the cone pedicle base, made invaginating synaptic contact (Fig. 7B–E). This result is in contrast to the findings in rhodopsin transgenic pigs and RCS rats, in which nearly all of the ectopic cone–rod bipolar cell synapses had flat, noninvaginating characteristics (Peng et al., 2000, 2003).

When looking for ectopic rod bipolar cell synapses in the *CNGA3<sup>−/−</sup>Rho<sup>−/−</sup>* mouse, the success rate, again, was extremely low. We found only one positive example in three animals, indicating that rod bipolar cells form ectopic synapses with functional cones but not with those lacking cone function.

**Discussion**

In the wild-type mouse retina, most of the cone bipolar cells do not form connections with rods. We analyzed the dendritic connections made by cone bipolar cells in the retina of *CNGA3*-deficient mice, in which the cone light input is specifically switched off by genetic deletion of the A subunit of the cone CNG channel. Interestingly, we found that most of the cone bipolar cells in these mice show synaptic plasticity and form ectopic synapses with rods.

The demonstration of ectopic synapses between rod bipolar cells and cones in the OPL of RCS rats has been interpreted as a process of synaptic rewiring during retinal degeneration (Peng et al., 2003). Our results demonstrate that also cone bipolar cell dendrites have the capability to make alternative connections when the preferred contacts are out of function. Hence, the rules that govern synaptic partnering between rods and rod bipolar cells and between cones and cone bipolar cells are not absolute.

The molecular events that mediate the formation of normal rod and cone synapses during retinal development are poorly understood; however, an inherent molecular flexibility for forming synaptic connections may provide an adaptive advantage for the visual system. Molecular flexibility in forming synaptic contacts at the photoreceptor terminals have been explored in retinas in which the cones are genetically eliminated (Soucy et al., 1998) or in retinas in which the rods fail to form and all photoreceptors are cone-like (*Nrl<sup>−/−</sup>* mouse) (Strettoi et al., 2004; Daniele et al., 2005). The direct connections between rods and cone bipolar cells in the “coneless” mouse can be interpreted as a reaction caused by the genetic manipulation, such that cone bipolar cells search for and make inappropriate contacts with rods in the absence of the normal synaptic target. The same holds true for the *Nrl<sup>−/−</sup>* mouse, in which rod bipolar cells form synaptic connections with cone-like cells that presumably were supposed to further develop into rods.

Although a large number of cones in *CNGA3<sup>−/−</sup>* mice degenerate in the first postnatal months, the ultrastructure of the remaining ones appears normal (Michalakis et al., 2005). OFF cone bipolar cells make the usual flat contacts at the cone pedicle base (Fig. 2A,B); ON cone bipolar cells and horizontal cells make invaginating contacts at the ribbon synapses [Michalakis et al. (2005), their Fig. 7]. In this study, we found several clear examples of OFF cone bipolar cells making flat contacts with rod spherules. ON cone bipolar cells also made putative contact with rod spherules, but EM reconstruction will be necessary to show whether these contacts are flat or invaginating ones. Most of the ectopic rod bipolar cell contacts we found in the *Rho*<sup>−/−</sup> mouse were invaginating contacts, which shows that bipolar cells keep their synaptic features at ectopic synapses in the *CNGA3<sup>−/−</sup>* and *Rho*<sup>−/−</sup>* mouse.

We have no explanation for the contrary findings of Peng and his colleagues (2000, 2003). They showed in different retinal degeneration models that most of the ectopic cone–rod bipolar cell synapses had flat, noninvaginating characteristics.

Interestingly, we found no evidence of cone bipolar cell sprouting into the ONL (NK3R immunostaining in *CNGA3<sup>−/−</sup>* and *CNGA3<sup>−/−</sup>Rho<sup>−/−</sup>* mice; data not shown), whereas rod bipolar cell and horizontal cell sprouting has been demonstrated in several animal models. Horizontal and rod bipolar cell processes
Double-labeling immunocytochemistry with antibodies against mGluR6 (red) and kinesin (blue) reveals a contact site with a cone interference contrast image of the corresponding vertical section. The horizontal lines indicate strata S1 through S5 in the IPL. A type 5 ON cone bipolar cell as visualized by projecting a morphology of a type 7 ON cone bipolar cell. Double-labeling immunocytochemistry same as in structure) but not to the labeled ribbons of the two cone pedicles. PKC-labeled dendrites are in close proximity to CtBP2-labeled ribbons in rod spherules (horseshoe-shaped structure) but not to the labeled ribbons of the two cone pedicles. Overall morphology of a type 7 ON cone bipolar cell. In a single optical section, a dendrite of this bipolar cells makes synaptic contacts with two cone pedicles (circles). Overall morphology of a type 7 ON cone bipolar cell. In a different optical section, a putative synapse with a rod spherule (RS; circle) is visible. In a different section, three contact sites with rod spherules (circles) are clearly visible. Double-labeling immunocytochemistry same as in A and B. Scale bars: (in A) A, 20 μm; B, C, 12 μm; E, F, 10 μm.

Figure 5. Confocal images of type 5 and type 7 ON cone bipolar cells in the CNGA3−/− mouse retina. A, Overall morphology of a type 5 ON cone bipolar cell as visualized by projecting a z-stack of optical images and superimposed onto the differential interference contrast image of the corresponding vertical section. The horizontal lines indicate strata S1 through S5 in the IPL. B, Double-labeling immunocytochemistry with antibodies against mGluR6 (red) and kinesin (blue) reveals a contact site with a cone pedicle (CP; circle). C, In a different optical section, a putative synapse with a rod spherule (RS; circle) is visible. D, Overall morphology of a type 7 ON cone bipolar cell. E, In a single optical section, a dendrite of this bipolar cells makes synaptic contacts with two cone pedicles (circles). F, In a different section, three contact sites with rod spherules (circles) are clearly visible. Double-labeling immunocytochemistry same as in A and C. Scale bars: (in A) A, 20 μm; B, C, 12 μm; E, F, 10 μm.

We found ectopic bipolar synapses in CNGA3−/− and Rhod−/− single knock-out mice but not in CNGA3−/− Rhod−/− double knock-out mice, which clearly shows that the formation of ectopic synapses between rod and cone bipolar cells requires functional rods and between cone and rod bipolar cells requires functional cones. Obviously, heterologous gap junctions between rods and cones (Smith et al., 1986) cannot substitute for the endogenous light-driven input mediated by CNG channels or activation of rhodopsin. This is in line with the observed degeneration of rods and cones in the respective transgenic models. In addition, we found no altered expression of connexin36 (Cx36) in transgenic animals when compared with wild-type mice (data not shown). Therefore, it seems unlikely that upregulation of Cx36 would compensate for defects in the visual transduction cascade. It is possible that the lateral spread of the electrical signal from the network of functional rods into the inoperable cone system (and vice versa) is not sufficient, because the signal is too small to mimic by itself the endogenous photoreceptor response. Although it seems reasonable to assume, we currently do not know whether or not Cx36-mediated gap junctions are functional in the transgenic animals. Because gap junctional channels respond in a very sensitive manner to changes in the concentration of various intracellular metabolites, the entire loss of the signal transduction cascade could also have profound functional implications for the electrical coupling between rods and cones.

The expression of GluR5 at locations where OFF bipolar cells contact rod spherules (Fig. 3B, C) indicates that the ectopic rod–cone bipolar cell synapses are functional. If this is the case, the rods could provide input to both the rod-mediated and cone-mediated signaling pathways. A study of the functional properties of the ectopic synapses will require a detailed physiological analysis at the cellular level.

Three different pathways responsible for the transmission of rod signals have been postulated (Volgyi et al., 2004) (for review, see Wässle, 2004), and the gap junction protein Cx36 is essential for two of them (Deans et al., 2002). In Cx36−/− retinas, the coupling between AII amacrine and ON cone bipolar cells (primary rod pathway with the highest sensitivity) and between rods and cones (secondary rod pathway with intermediate sensitivity) is lost (Güldenagel et al., 2001). Responses of low-Intermediate sensitivity OFF ganglion cells survive in the Cx36−/− mouse retina (Volgyi et al., 2004), and they are carried by the tertiary pathway (direct contact of OFF bipolar cells with rods). Although the rod-mediated electroretinogram of

Figure 6. Vertical sections of Rhod−/− and wild-type retina double labeled for PKCα (green) and CtBP2 (red). A, Low-power image of a Rhod−/− mouse retina at pw5. PKCα immunoreactivity is visible in rod bipolar cells with axons terminating deep within the IPL. Antibodies against CtBP2 label all photoreceptor ribbons in the OPL and all bipolar cell ribbons in the IPL. INL, Inner nuclear layer. B, High-power image of PKCα and CtBP2 immunoreactivity in the OPL of a wild-type (wt) mouse. Frames indicate two cone pedicles. PKCα-labeled dendrites are in close proximity to CtBP2-labeled ribbons in rod spherules (horseshoe-shaped structure) but not to the labeled ribbons of the two cone pedicles. C, D, OPL of Rhod−/− mouse retina at pw5. Two examples of PKCα-labeled dendrites with potential contact to cone pedicles (arrows) are shown. Scale bar: (in D) A, 24 μm; B–D, 10 μm.

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CNGA3−/− mice shows no anomalous features (Biel et al., 1999), the generation of CNGA3−/−Cx36−/− double knock-out mice combined with single unit (Deans et al., 2002) or multineuron (Meister et al., 1994) recordings might be a way to study the functional properties of the ectopic rod–cone bipolar cell synapses in more detail. Given that functional ectopic synapses between ON cone bipolar cells and rods do form in CNGA3−/−Cx36−/− mice, we would expect to find low-intermediate sensitivity ON ganglion cells, which do not exist in the normal ON system (Volgyi et al., 2004). Furthermore, the data of multielectrode recordings from coneless mice strongly suggest the existence of functional rod–cone bipolar cell contacts (Soucy et al., 1998). In wild-type retina, the APB-resistant OFF pathway relies mainly on electrical coupling between rods and cones, whereas in the coneless mouse retina, the APB-resistant responses can be explained if rods connect directly to OFF bipolar cells. The fact that all ganglion cells with OFF responses were ABP-resistant indicates that not only the type 3 OFF bipolar cell makes functional synapses with rods (Tsukamoto et al., 2001) in the coneless mouse, but also the other OFF bipolar cell types. This would be comparable with our model in which the cone bipolar cells react after the missing cone input and form ectopic and most likely functional synapses with rods.

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