the antibody can be regarded as Wfs1-specific in the retina. However, there is a remote possibility that the anti-Wfs1 antibody detected a protein at ~70 kDa other than Wfs1. This possibility will be verified by the immunoblot analysis of retinal extracts from *Wfs1* knockout mice, and by in situ hybridization histochemistry in normal retinal sections.

Differences in localization of *Wfs1* expression between the mRNA and protein

There are clear differences in the localization of *Wfs1* expression between the mRNA and protein. In the retina, *Wfs1* mRNA was expressed in the ONL, INL, and GCL where cell bodies are concentrated, while Wfs1 protein was expressed not only in the ONL, INL, and GCL, but also in the OPL and IPL, where processes of retinal cells are accumulated (Fig. 2). Similar differences were also observed in the CA1 field of the hippocampus. In this region, *Wfs1* mRNA expression was confined to the pyramidal cell layer where cell bodies of pyramidal neurons are located, while Wfs1 protein was present not only in the pyramidal cell layer but also in the two strata (strata radiatum and oriens) where processes of pyramidal neurons are extended (Fig. 9A-C). Since the specificity of the anti-Wfs1 antibody in the CA1 field was strictly verified by the immunoblot analysis (present study) and by using *Wfs1* knockout mice (Ishihara et al., 2004), it is reasonable to speculate that the differences are not attributable to a non-specific immunoreaction of the antibody, but to divergence in the localization of *Wfs1* expression between the mRNA and protein. In the retina, Wfs1 was expressed in all neuron types (photoreceptors, horizontal cells, bipolar cells, non-displaced and displaced amacrine cells, and RGCs), and in Müller cells. Cell bodies of these cells are confined to the ONL, INL, and to GCL, and *Wfs1* mRNA expression was also confined to these layers. Therefore, there is little discrepancy in the localization of *Wfs1* expression between the mRNA and protein.

In addition, a neurobiological study reported that Wfs1 protein in the brain is found at higher steady-state levels than expected from the relatively low amount of *Wfs1* mRNA

(Hofmann et al., 2003). Based on this evidence, it is reasonable to accept that the *Wfs1* mRNA expression is weaker than the protein expression in the retina. Therefore, results obtained achieve a reconciliation between *Wfs1* mRNA and protein expression in the retina.

Comparison with previous findings

Yamamoto et al. (2006) showed strong WFS1 immunolabeling in RGCs and optic nerve glial cells of the cynomolgus monkey. In the mouse, Wfs1 was expressed not only in RGCs but also in photoreceptors, horizontal cells, bipolar cells, amacrine cells, and in Müller cells of the retina. In the optic nerve, Wfs1 was present solely in astrocytes. In the brain, Takeda et al. (2001) described Wfs1 expression in layer II of the rat visual cortex. In the mouse, Wfs1 was expressed in the SC and SCN as well as in layer II of the visual cortex. These findings indicate that Wfs1 expression in RGCs, optic nerve glial cells, and in layer II of the visual cortex is similar among various mammalian species.

Retina

Photoreceptors As for *Wfs1* mRNA expression in the inner segment, verification is necessary, since the inner segment is not a common site of mRNA accumulation. Results obtained clearly showed that *Wfs1* mRNA signals detected by anti-sense probes were much stronger than those detected by sense probes (Fig. 2A,B). In addition, several histochemical studies already reported the distribution of mRNA signals in the inner segment (Bumsted et al., 1997; Cowlen et al., 2003; Nogami et al., 2006; Acar et al., 2007). Thus, it is reasonable to speculate that *Wfs1* mRNA is present in the inner segment.

Wfs1 protein immunoreactivity was observed in a majority of cell bodies in the ONL (Fig. 2C). Since rods make up 97.2% and cones, 2.8%, of all the photoreceptors in the C57 mouse retina (Jeon et al., 1998), the results obtained suggest that Wfs1 is expressed at least in rods. We also demonstrated that both *Wfs1* mRNA and protein were expressed in the inner segments and cell bodies of photoreceptors. Since Wfs1 was not expressed in the outer

segments, it is possible that Wfs1 is not directly involved in phototransduction proper in this segment. Instead, Wfs1 is probably distributed as a ER membrane protein in the inner segments and cell bodies of photoreceptors (Takeda et al., 2001; Hofmann et al., 2003), and is considered to be responsible for the maintenance of phototransduction. In addition, slight photoreceptor dysfunction is suspected in Wolfram syndrome patients (Yamamoto et al., 2006), since the subjective dark adaptation curve in Wolfram syndrome patients shows a diminution of both cone and rod adaptation (Mtanda et al., 1986).

Horizontal cells Since Wfs1-immunoreactive horizontal cells were calbindin-D-28K positive, Wfs1 was expressed at least in the axon-bearing type (Haverkamp and Wässle, 2000). This evidence indicates for the first time a possible role for this cell type in the pathologic course of Wolfram syndrome. In Wolfram syndrome patients, low visual acuity and color visual disturbance are observed (Mtanda et al., 1986; Bitoun, 1994; Seynaeve et al., 1994; Barrett et al., 1997). According to a review by Wässle (2004), horizontal cell dendrites are inserted as lateral elements into the invaginating contacts of cone pedicles, and horizontal cell axon terminals form the lateral elements within rod spherules. Traditionally, it is assumed that horizontal cells release the inhibitory transmitter GABA (γ-aminobutyric acid) and provide feedback inhibition at the photoreceptor synaptic terminal. As horizontal cells summate light signals from several cones, such feedback would cause lateral inhibition, through which a cone's light response is reduced by the illumination of neighboring cones. This mechanism is thought to enhance the response to the edges of visual stimuli and to reduce the response to areas of uniform brightness (Wässle, 2004). Horizontal cell feedback in fish and turtle retinae seems to be cone-specific. However, no such chromatic organization of horizontal cell feedback has been observed in the primate retina, including the human retina (Dacey et al., 1996; Wässle, 2004). Thus, dysfunction of WFS1 protein in horizontal cells might be involved in the low visual acuity in Wolfram syndrome patients rather than

color visual disturbance.

Bipolar cells The Wfs1 immunoreactivity in rod and ON-cone bipolar cells is reliable for the following reasons. Wfs1/Goα double labeled cells were observed in both the intermediate row of the INL (where cone bipolar cells are distributed) and in the outer row of the INL (where rod bipolar cells are located) (Haverkamp and Wässle, 2000). The immunoreactivity was verified by absorption experiments (Fig. 3G-I). Finally, certainty of the immunoreactivity was also supported by the weak *Wfs1* mRNA signals in the outer and intermediate rows of the INL (Fig. 2A,B).

Wfs1 immunoreactivity in OFF-cone bipolar cells was not examined in the present study. Markers for OFF-cone bipolar cells offered by Haverkamp and Wässle (2000) are Pep19, recoverin, glutamate transporter 1 (GLT-1), and caldendrin. In their study, all antibodies against these marker proteins were generated by a rabbit (Haverkamp and Wässle, 2000). Unfortunately, the anti-Wfs1 antibody was also generated by a rabbit, and the antibody produced perikaryon staining as the antibodies against the marker proteins did (Haverkamp and Wässle, 2000). To examine Wfs1 expression in the OFF-cone bipolar cells, it is necessary to obtain other OFF-cone bipolar cell-specific antibodies generated by an animal other than the rabbit.

Amacrine cells Strong Wfs1 expression was present in cholinergic amacrine cells (Figs. 3J-K, 4A-F). These cholinergic amacrine cells are starburst amacrine cells (Jeon et al., 1998), occurring as matching pairs of displaced (ON) and nondisplaced (OFF) amacrine cells, and their dendrites form two narrow strata in the IPL (Fig. 3K; Haverkamp and Wässle, 2000). It is known that cholinergic amacrine cells are a key element of the direction-selective circuitry. It is likely that both presynaptic and postsynaptic mechanisms are involved in the generation of direction-selective light responses (Yoshida et al., 2001; Euler et al., 2002; Fried et al., 2002; Taylor and Vaney, 2002, 2003; Wässle, 2004). Thus,

dysfunction of WFS1 protein in cholinergic amacrine cells might contribute to the disturbance of direction-selective light responses in Wolfram syndrome patients.

RGCs (Retinal ganglion cells) Since RGCs make up only 41% of all the neurons in the GCL of the C57 mouse retina (Jeon et al., 1998), we carefully examined Wfs1 expression in RGCs by Wfs1/tracer double labeling and by Wfs1/retinal ganglion cell-specific-marker double immunohistochemistry. Wfs1 expression in RGCs is reliable for the following reasons. Wfs1 expression was detected in RGCs retrogradely labeled with Fluorescent Latex Microspheres (Fig. 4G-I) or with Fluoro-Ruby (Fig. 5A-C), and the expression was verified by the control (preabsorption) experiments (Fig. 4J-L). Wfs1 expression was detected in RGCs immunolabeled with retinal ganglion cell markers: tubulin, βIII isoform, and Brn-3a (Fig. 4M-R). Non-cholinergic but Wfs1-immunoreactive cells were distributed in the GCL (Fig. 4A-F). Probably, most of these cells are Wfs1-immunoreactive ganglion cells, since the majority of displaced amacrine cells are cholinergic (Voigt, 1986; Brecha et al., 1988; Haverkamp and Wässle, 2000). Finally, the majority of calbindin-D-28K immunolabeled cells in the GCL were double-labeled with Wfs1 (Fig. 3M-O). A proportion of these Wfs1/calbindin-D-28K double-labeled cells are RGCs, since calbindin-D-28K is a marker for both RGCs and displaced amacrine cells in the GCL (Haverkamp and Wässle, 2000). Thus, Wfs1 is present in RGCs as well as in displaced amacrine cells in the GCL.

It is not well known which types of RGCs express Wfs1. Figure 4P-R shows that Wfs1 immunoreactivity is detected in both strongly and weakly Brn-3a-immunolabeled ganglion cells. Since Brn-3a is expressed at high levels in small ganglion cells but not in large ganglion cells, it is possible that Wfs1 is expressed in both small and large ganglion cells (Xiang et al., 1995; Haverkamp and Wässle, 2000).

IPL (Inner Plexiform layer) The mouse IPL is subdivided into five sub-layers of equal thickness. These sub-layers can be easily defined by immunolabeling the retina for the

calcium-binding proteins calbindin and calretinin, which shows three strongly labeled horizontal strata of processes (Fig. 3N; Haverkamp and Wässle, 2000; Wässle, 2004). Since the three Wfs1-immunoreactive strata in the IPL corresponded to those immunoreactive for the calcium-binding proteins (Fig. 3M-O), Wfs1 can be used as a marker for the three strongly labeled horizontal strata. In addition, the three strata contain Wfs1-immunoreactive processes of calbindin-D-28K-labeled amacrine and ganglion cells (Fig. 3M-O), since calbindin-D-28K is a marker for both amacrine and ganglion cells (Haverkamp and Wässle, 2000). Of these strata, the inner and outer strata also contain Wfs1-immunoreactive processes of cholinergic amacrine cells, since the two strata were immunoreactive for ChAT (Fig. 3J-L; Haverkamp and Wässle, 2000).

According to a review by Wässle (2004), the outer stratum contains the processes of the OFF-cholinergic amacrine cells, the dendrites of OFF-alpha cells, and the outer dendritic branches of direction selective cells. This band is densely packed with synapses and $GABA_A$ receptors (Brandstätter et al., 1995), and is where transient light responses and OFF direction-selective responses are calculated (Roska and Werblin, 2001). The intermediate stratum separates the OFF sublamina (outer) from the ON sublamina (inner). The polyaxonal amacrine cells (Ölveczky et al., 2003) ramify in this band, as do two GABA-containing amacrine cells. These cells contain, as well as GABA, a neuromodulator (nitric oxide and a catecholamine, respectively). Their functions are unknown. The inner stratum contains the axon terminals of an ON bipolar cell (Brown and Masland, 1999), the processes of the ON-cholinergic amacrine cells, the dendrites of ON-alpha cells, and the inner dendritic branches of direction-selective cells. This stratum is also densely packed with synapses and $GABA_A$ receptors, providing the circuitry for ON-transient light responses and ON direction-selective responses (Wässle, 2004). Thus, it is speculated that the inner stratum contains Wfs1-immunoreactive processes of bipolar cells, as well as those of amacrine and ganglion cells.

Müller cells Wfs1 protein was expressed strongly in endfeet of Müller cells, moderately in internal radial processes, and weakly in cell bodies, whereas *Wfs1* mRNA signals were weak in the middle row of the INL where cell bodies of Müller cells are located. These results suggest the turnover of Wfs1 protein in Müller cells to be slower than that in other Wfs1-positive retinal neurons. As described above, Wfs1 protein was distributed densely in the endfeet of Müller cells, but sparsely in cell bodies. This evidence indicates that Wfs1 protein accumulates in the endfeet of Müller cells. Elucidating the cause of this accumulation might provide a clue as to the biochemical function of Wfs1 in glial cells including Müller cells.

Although Wolfram syndrome patients often develop diabetes mellitus early on (median age 6 years, range 3 weeks to 16 years; Barrett et al., 1997), they rarely develop diabetic retinopathy (Mtanda et al., 1986; Bitoun 1994; Seynaeve et al., 1994; Barrett et al., 1997). Diabetic retinopathy is accompanied by a proliferation of new retinal vessels under hypoxic conditions. The proliferation is mediated by Müller cells via the release of vascular endothelial growth factor (VEGF) and transforming growth factor β or via direct contact with endothelial cells (Bringmann and Reichenbach, 2001). In Wolfram syndrome patients, it is suggested that the functions of Müller cells are disrupted by loss-of-function mutations in the *WFS1* gene. Thus the proliferation of new retinal vessels might be hampered by dysfunctional Müller cells in Wolfram syndrome patients.

Optic nerve

Mice lack intraretinal myelination and a well-developed lamina cribrosa but exhibit a marked concentration of astrocytic filaments at the retinal optic nerve junction (Morcos and Chan-Ling, 2000). Based on this evidence, we divided the mouse optic nerve into three parts (i, afd, and afs) defined by the position of the sensory retina, and by the distribution of astrocytic filaments. These criteria for the optic nerve subdivisions are appropriate since the

distribution of GS-positive cells corresponded to the afs part. Thus mouse optic nerve is also divided into three parts by the position of the sensory retina and by the distribution of GS-positive cells as shown in Figure 8Q.

Wfs1-positive astrocytes were distributed in the optic nerve, but not in the retina, optic chiasm, or optic tract (Figs. 8A-I, 10C,D). This evidence suggests the astrocytes in the optic nerve to be different from those in the retina, optic chiasm, and optic tract. Further studies are required to clarify the morphological and functional differences between Wfs1-positive astrocytes in the optic nerve and Wfs1-negative astrocytes in the optic chiasm and the optic tract. These studies could provide valuable insights into the physiological role of Wfs1 protein in astrocytes.

Vision-related brain structures

Superior colliculus The superficial gray layer receives visual inputs directly from the retina and occipital cortex and contains cells that project extrinsically to dorsal thalamic nuclei (Edwards et al, 1986), whereas the intermediate gray layer receives indirect retinal inputs by way of the lateral division of the ventral lateral geniculate nucleus (Brauer and Schober, 1982). Wfs1-positive neurons in the intermediate gray layer as well as those in the superficial gray layer might be involved in visual functions. Neuropathological studies have demonstrated neuronal loss and gliosis in the SC of Wolfram syndrome patients (Genís et al., 1997; Shannon et al., 1999). These findings might be attributed to dysfunctional SC neurons in Wolfram syndrome patients due to loss-of-function mutations in the *WFS1* gene.

Suprachiasmatic nucleus The SCN is a circadian pacemaker. In the SCN, Wfs1-positive neurons were distributed in the dorsomedial region. This region does not receive direct retinal inputs, but does receive inputs from non-visual sources. The region sends large numbers of axons to the hypothalamus, and small numbers of axons to the thalamus including the paraventricular thalamic nucleus (PVT). In the PVT, circadian timing information from

the SCN is conveyed to multiple limbic structures including the amygdala and the limbic cortical areas (Watts and Swanson, 1987; Kawano et al., 2001; Leak and Moore, 2001). Thus, it is speculated that Wfs1-positive neurons in the dorsomedial part of the SCN provide circadian timing cues to the hypothalamus, the thalamus, and even to the multiple limbic structures without receiving direct retinal inputs.

Visual Cortex The laminar distribution of Wfs1-positive neurons in layer II was present throughout the mouse neocortex (Kawano et al., unpublished observation), as already described in the rat (Takeda et al., 2001). Therefore, the distribution is not restricted to the visual cortex. Few thalamic afferents to the visual cortex terminate in layer II (afferents to V1 principally arise in the dorsal lateral geniculate nucleus; Peters and Feldman, 1976; afferents to V2 mainly arise in the lateral posterior nucleus; Olavarria, 1979), but associational afferents from other visual cortical areas terminate in layer II (Coogan and Burkhalter 1990, 1993). Layer II neurons send associational fibers to the other visual cortical areas (Miller and Vogt, 1984a; Sanderson et al, 1991). Apart from the associational connections, the commissural neurons and terminals are concentrated in a narrow region (the border between V1 and V2L) where the vertical meridian is represented (Cipolloni and Peters, 1979; Cusick and Lund, 1981). In this region, layer II neurons send commissural fibers to and receive commissural fibers from the opposite cortex (Miller and Vogt, 1984b; Sefton et al., 1991). In addition, local circuit neurons are also located in layer II. These neurons make widespread connections within the same layer and project strongly to layer V (Burkhalter, 1989; Sefton and Dreher, 1995). Therefore, Wfs1-immunoreactive punctuations in layer V might be attributed to the strong projections from Wfs1-positive neurons in layer II to layer V. Further studies by using tract-tracing methods are required to clarify the fiber connections of Wfs1-positive neurons in layer II. Neuroradiological and neuropathological studies have shown that there is mild cerebrocortical atrophy in Wolfram syndrome patients (Rando et al,

1992; Scolding et al., 1996; Shannon et al., 1999). The atrophy might be attributed to the dysfunctional cortical layer II neurons in Wolfram syndrome patients resulting from loss-of-function mutations in the *WFS1* gene.

Optic Atrophy

Optic atrophy is one of the minimal diagnostic criteria for Wolfram syndrome (Barrett et al., 1997). In this section, we will discuss the pathogenesis of optic atrophy in Wolfram syndrome based on the results obtained. Wfs1 was expressed in all neuron types (RGCs, amacrine cells, bipolar cells, horizontal cells, and photoreceptors) and Müller cells of the retina, in astrocytes of the optic nerve, and in neurons of the SC and the SCN. Out of these cells, candidates for causative cells for optic atrophy in Wolfram syndrome are not only RGCs but also amacrine cells, bipolar cells, SC neurons, SCN neurons, Müller cells, and astrocytes in the optic nerve, since it is speculated that candidate neurons express Wfs1 and are directly connected with RGCs and that cell bodies or axons of RGCs are surrounded by candidate glial cells.

First, we will discuss whether RGCs are the principal candidates. In this case, autosomal dominant optic atrophy (ADOA) is useful for comparisons with Wolfram syndrome. ADOA is one of the primary inherited optic neuropathies, and has been attributed to mutations in the *OPA1* gene (Alexander et al., 2000; Delettre et al., 2000; Votruba et al., 2003). OPA1 protein expression is present in RGCs in the mouse, rat, and human (Aijaz et al., 2004; Pesch et al., 2004; Ju et al., 2005). The pattern electroretinogram (PERG) in ADOA patients shows an abnormal N95:P50 ratio, with a reduction in the amplitude of the N95 waveform (Berninger et al., 1991; Holder et al., 1998). Since the PERG N95 component is postulated to be specific for the retinal ganglion cell (Ryan and Arden, 1988), this finding supports a ganglion cell origin for ADOA (Votruba et al., 2003). By contrast, the ERG tests in Wolfram syndrome patients revealed normal or only slightly reduced responses suggesting

that the pathogenesis of the optic atrophy does not lie in the retina, but primarily affects the optic nerve (Niemeyer and Marquardt, 1972; Mtanda et al., 1986; Seynaeve et al., 1994; Barrett et al., 1997). In addition, Barrett et al. (1997) concluded that the reduced visual acuity not due to a refractive error and color vision defect suggested a site of pathology in the visual pathway proximal (posterior) to the eye. Thus, it is possible that the dysfunction of RGCs in Wolfram syndrome patients is mild and that the pathogenesis of optic atrophy is not attributable to the RGCs proper.

Previous clinical, pathological, and neurobiological studies weakly support the notion that amacrine cells, bipolar cells, SC neurons, SCN neurons and Müller cells are the principal candidates. Although Wfs1 was expressed strongly in amacrine cells and weakly in bipolar cells, there have been few findings of functional abnormality in the INL of Wolfram syndrome patients by using electroretinograms (ERGs; Niemeyer and Marquardt, 1972; Mtanda et al., 1986; Seynaeve et al., 1994; Barrett et al., 1997). In the mouse SC, Wfs1-positive cells were distributed in the superficial gray layer where retinal afferents terminate. In Wolfram syndrome patients, neuronal loss and gliosis are observed in the SC (Genís et al., 1997; Shannon et al., 1999). It is possible that optic atrophy is induced by retrograde degeneration of RGCs from the SC. In this case, the degenerated RGCs would be M-cells and K-cells (Y-cells and W-cells in the cat) not P-cells (X-cells in the cat; Garey, 1990; Goebel et al., 2004). By contrast, there is neuronal loss in the LGN mainly involving layers 3-6 which are P-cell relay layers (Garey, 1990; Genís et al., 1997; Goebel et al., 2004) or neuronal loss in all six layers of the LGN (Shannon et al., 1999). If SC neurons are the principal candidates, it is difficult to explain the loss of neurons in the LGN involving the P-cell relay layers. In the mouse SCN, Wfs1-positive neurons are distributed in the dorsomedial part where retinal afferents do not directly terminate. Since strong Wfs1 expression is present in Müller cells, and since RGCs are surrounded by Müller cells, there is a possibility that loss-of-function of

Müller cells induces degeneration of RGCs in Wolfram syndrome patients. A neurobiological study by using NSE-Hu-Bcl-2 transgenic mice demonstrated that early postnatal Müller cell death leads to retinal degeneration but not optic nerve degeneration (Dubois-Dauphin et al., 2000). It is improbable that Müller cells are the principal candidates. Thus it is speculated that astrocytes in the optic nerve are the principal candidate for the causative cells for optic atrophy in Wolfram syndrome patients.

Since Wfs1 is expressed in many tissues, the reason why astrocytes in the optic nerve and not other cell types are principally affected by *WFS1* mutations which cause the optic atrophy in Wolfram syndrome is unknown. A biochemical study by using *Xenopus* oocytes suggested that WFS1 protein serves directly as a novel endoplasmic reticulum (ER) calcium channel or, alternatively, as a regulator of ER calcium channel activity. *WFS1* mutations associated with Wolfram syndrome reduce the susceptibility to cation block. It is possible that WFS1 protein-mediated regulation of intracellular calcium provides an important protective function in neurons and/or glial cells that are dependent on the ER for calcium signaling (Haydon, 2001; Osman et al., 2003). Recently, a functional study indicated that WFS1 protein expression increases in response to ER stress and that the protein plays a physiological role in protecting cells from ER stress-induced apoptosis (Ueda et al., 2005). Although the biochemical function of WFS1 in neurons and/or glial cells in the visual system remains to be investigated, it is possible that WFS1 mutations in the neurons and/or glial cells cause a disruption of the WFS1-mediated regulation of intracellular calcium levels and/or of the ER stress responses, and a consequent malfunction of electrophysiological activity in the neurons and/or glial cells (Haydon, 2001; Volterra and Meldolesi, 2005; Serfert et al., 2006). This loss-of-function may impair axons of RGCs leading to optic atrophy.

Wfs1 was localized to the afd part of the mouse optic nerve where GS immunoreactivity was almost negative (Figs. 6B, 8Q). This evidence suggests that a lack of

GS in the afd part might augment the damage to the optic nerve caused by glutamate. Recently, vesicular glutamate release from axons was demonstrated not only in the corpus callosum but also in the optic nerve of rodents after the propagation of action potentials (Kukley et al., 2007; Ziskin et al., 2007). Thus impaired glutamate clearance attributable to a lack of GS in the afd part may affect the viability of optic nerve axons in the mouse, including the *Wfs1* knockout mouse.

Conclusion

In summary, Wfs1 was present not only in RGCs but also in photoreceptors, horizontal cells, bipolar cells, amacrine cells, and Müller cells of the retina, in astrocytes of the optic nerve, and in neurons of the SC, the SCN, and of the visual cortex. Interestingly, Wfs1 was localized to the afd part of the optic nerve where GS immunoreactivity was almost negative. These results suggest that mutant WFS1 may contribute to the dysfunction of WFS1-expressing neurons and/or glial cells which may in turn lead to optic atrophy in Wolfram syndrome. They also suggest that the lack of GS in the afd part might augment the damage to the optic nerve caused by glutamate. Although these notions are difficult to test experimentally, the availability of the Wfs1 mouse model could offer opportunities for further investigation. These studies are required to determine the exact physiological role of Wfs1 protein in the biology of vision and to obtain more insights into its pathophysiological roles in optic atrophy in Wolfram syndrome.

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