ON-Type Retinal Ganglion Cells are Preferentially Affected in STZ-Induced Diabetic Mice

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PURPOSE. We investigate morphologic and physiologic alterations of ganglion cells (GCs) in a streptozocin (STZ)-induced diabetic mouse model.

METHODS. Experiments were conducted in flat-mount retinas of mice 3 months after the induction of diabetes. Changes in morphology of four subtypes of GCs (ON-type RGA2 [ON-RGA2], OFF-type RGA2 [OFF-RGA2], ON-type RGC1 [ON-RGC1], and ON-OFF type RGD2 [ON-OFF RGD2]) were characterized in Thy1-YFP transgenic mice. Using whole-cell patch-clamp recording, passive membrane properties and action potential (AP) firing properties were further investigated in transient ON- and OFF-RGA2 cells.

RESULTS. Morphologic parameters were significantly altered in the dendrites branching in the ON sublamina of the inner plexiform layer (IPL) for ON-RGA2 cells and ON-OFF RGD2 cells. Much less significant changes, if any, were seen in those arborizing in the OFF sublamina of the IPL for OFF-RGA2 and ON-OFF RGD2 cells. No detectable changes in morphology were seen in RGC1 cells. Electrophysiologically, increased resting membrane potentials and decreased membrane capacitance were found in transient ON-RGA2 cells, but not in transient OFF-RGA2 cells. Similar alterations in AP firing properties, such as an increase in AP width and reduction in maximum spiking rate, were shared by these two subtypes. Furthermore, in response to depolarizing current injections, both cells generated more APs suggesting an enhanced excitability of these cells in diabetic conditions.

CONCLUSIONS. These differential changes in morphology and electrophysiology in subtypes of GCs may be responsible for reduced contrast sensitivity known to occur during the early stage of diabetic retinopathy.

Keywords: diabetic retinopathy, ganglion cells, dendrites, intrinsic membrane property, K+ currents

Diabetic retinopathy (DR), the most common complication of diabetes, is a leading cause of blindness in adults.1–3 Although DR has long been recognized as solely a vascular disease,1,4–6 increasing evidence shows that this complication also may be considered a neurodegenerative disorder, since damage to retinal neurons and visual function deficits, such as reduced contrast sensitivity, could be observed before the onset of vascular symptoms.4,5,7–22

It is known that retinal ganglion cells (GCs), output neurons in the retina, are some of the severely damaged retinal neurons in diabetes.5 Loss of GCs has been reported in diabetic patients and animal models of diabetes.5,17,19–21,23–25 Consistent with this, the amplitudes of the pattern electroretinogram (ERG) and the scotopic threshold response (STR), which are likely related to GC and amacrine cell activities,26–28 were reduced in such circumstances.20,29–32 However, there are little data concerning changes in morphologic and electrophysiologic properties of GCs at individual cell levels.33–36 Moreover, GCs could be categorized into several subgroups according to morphologic and physiologic criteria. Morphologically, GCs could be classified into RGA, RGB, RGC, and RGD subgroups based on their soma sizes and dendritic characteristics using the nomenclature of He’s group.37 Based on their light response properties, GCs are functionally classified into ON, OFF, and ON-OFF subtypes.38 It was reported previously in type-1 diabetic mice that the spontaneous spiking activity of ON-GCs, but not OFF-GCs was significantly increased compared to that in normal retinas.56 However, whether morphology and physiology of these GC subtypes could be affected differentially in diabetes remains an open question.

We investigated how four subtypes of GCs (ON-RGA2, OFF-RGA2, ON-RGC1, and ON-OFF RGD2) labeled by yellow fluorescent protein (YFP)39 were changed in morphologic features at the early stage of hyperglycemia in a streptozocin (STZ)-induced diabetic Thy1-YFP-H mouse (maintained under the C57BL/6j background) model of human type-1-like diabetes. Using whole-cell patch clamp recording techniques, we further explored changes in passive and active membrane properties of ON- and OFF-RGA2 cells in this mouse model. Our data clearly shows that GCs/GC dendrites mediating ON- and OFF-signaling are affected differentially in early experimental diabetes.
MATERIALS AND METHODS

Animals and Induction of Diabetes

All animal protocols were made in accordance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research and were approved by the Animal Care and Use Committee of Fudan University. All experimental mice were housed in a 12:12-hour light/dark cycle. Thy1-YFP-H transgenic mice (003782), male and female (6–7 weeks old), purchased from the Jackson Laboratory (Bar Harbor, ME, USA) and maintained under the C57BL/6J background, were used for morphologic analysis. This mouse line carries a reporter gene under direction of the mouse Thy1 gene promoter (Tg[Thy1-YFP]23Jrs) and Thy1-YFP is expressed throughout the entire neuronal structure in small numbers of all morphologic subtypes of GCs. Male C57BL/6j mice, purchased from SLAC Laboratory Animal Company (Shanghai, China) were used for electrophysiologic experiments.

The mice were assigned randomly to diabetic or control groups. Hyperglycemia was induced following the procedures described previously with minor modifications. After being fasted for 4 hours, mice in the diabetic group received an intraperitoneal injection of 85 mg/kg STZ (Sigma-Aldrich Corp., St. Louis, MO, USA), freshly dissolved in sodium citrate buffer (1%, pH 4.2), for 3 consecutive days. Control animals received injections of an equal volume of citrate buffer. Blood glucose concentrations were measured using a glucometer (Accu-Chek Advantage, Roche, Germany) at several time points: before injection, after 7 days, and at 1, 2, and 3 months after the initial injection. Animals with fasting blood glucose concentrations ≥ 250 mg/dL (13.9 mM) were selected for experiments.

Immunohistochemistry

Retinas, isolated from Thy1-YFP mice deeply anesthetized, were fixed in 4% paraformaldehyde in PBS and then blocked with 6% donkey serum, 1% bovine serum albumin, and 0.3% Triton X-100 in 0.1 M PBS for 2 hours at room temperature. The retinas were incubated with the following primary antibodies diluted in blocking solution: chicken anti-GFP (1:1000 dilution; AVES Labs, Inc., Tigard, OR, USA) and goat anti-choline acetyltransferase (ChAT; 1:1000 dilution; Millipore, Billerica, MA, USA) for 3 days at 4°C. Immunoreactivity was detected with the following secondary antibodies: Alexa Fluor 488-conjugated donkey anti-chicken IgG (1:200 dilution, Jackson ImmunoResearch Laboratories, West Grove, PA, USA) for labeling GFP; Alexa Fluor 555-conjugated donkey anti-goat IgG (1:200 dilution; Invitrogen, Carlsbad, CA, USA) for ChAT, which can reveal the boundaries of the inner plexiform layer (IPL) by labeling somata of cholinergic amacrine cells. All retinas were flat-mounted and coverslipped, ganglion cell side up.

Image Capture and Analysis

All GCs were viewed and scanned with an Olympus FV1000 confocal laser scanning microscope (Olympus Corporation, Tokyo, Japan) using a ×40 objective lens. Image stacks were collected at intervals of 1 μm from the optical nerve layer to the inner part of the INL, with a high resolution of 1024 × 1024 pixels.

GCs were classified using the nomenclature of He’s group. Complete soma-dendritic profile reconstruction of individual GCs was obtained by manually tracing using Neurolucida software (MicroBrightFields, Inc., Colchester, VT, USA), and analyses were performed with Neurolucida Explorer software (MicroBrightFields, Inc.). The following morphologic parameters were measured to evaluate alterations in morphology during the early stage of hyperglycemia: (1) Soma size was calculated by drawing contour lines around each cell body. (2) Dendritic field size was calculated by measuring the area enclosed by the outermost segments of the distal dendritic branches. (3) Total dendritic length was the sum of the length of all dendritic branches of individual GCs. (4) Dendritic branch number was the total number of all the branches of individual GCs. Sholl analysis was used to quantify dendritic complexity as a function of distance from the soma. That is, a set of concentric circles were drawn centering on the soma at 10-μm intervals, and the number of dendrites intersecting each circle was counted.

Electrophysiologic Recordings

Retinas were prepared following the procedures described previously with minor modifications. In brief, before each experiment, animals were dark adapted for 2 to 4 hours. All experiments were performed under dim red light or infrared illumination. Retinas were dissected immediately and placed in extracellular solution gassed with 95% O2 and 5% CO2. The extracellular solution contained (in mM): 125 NaCl, 2.5 KCl, 1 MgCl2, 2 CaCl2, 1.25 NaH2PO4, 20 glucose, and 25 NaHCO3. The flat-mount retina was placed in a recording chamber with ganglion cell side up, which was positioned on the stage of an upright microscope (Axioskop 2 FS Mot; Carl Zeiss, Jena, Germany). Oxygenated bathing solutions at 32°C were continuously perfused into the recording chamber at a flow rate of 1.5 to 2 ml/min with a peristaltic pump.

Cells and pipettes were viewed on a video monitor coupled to a CCD camera (C11440; Hamamatsu, Hamamatsu City, Shizuoka Prefecture, Japan) mounted on the microscope. The pipette was advanced to a RGA2 cell in the ganglion cell layer (see Results for details) using visual control under infrared illumination. Spike activities in response to a 1-second green light stimulus were recorded extracellularly with patch electrodes that were made using a micropipette puller (P-97, Sutter Instrument Co., Novato, CA, USA) and of 4–7 MΩ tip resistance when filled with the extracellular solution in the cell-attach configuration. Whole-cell patch clamp recordings were made by patch electrodes filled with an intracellular solution containing the following (in mM): 120 K-glucosate, 5 NaCl, 5 KCl, 5 HEPES, 1 MgCl2, 0.1 guanosine 5-triphosphate, and 0.1% Lucifer yellow, adjusted to pH 7.4 with KOH. The pipettes controlled by a motor-driven micromanipulator (MP-285, Sutter) were connected to a patch-clamp amplifier (EPC-9; Heka Elektronik, Lambrecht/Pfalz, Germany). Fast capacitance was fully canceled and cell capacitance was canceled by the circuits of the amplifier as much as possible. Data were acquired at a sampling rate of 20 kHz and then stored for further analysis. To further identify types of the recorded cells, Lucifer yellow in the pipette was diazymed into neurons to reveal cell morphology. Three-dimensional cell morphology was visualized in flat-mount retinas using Lucifer yellow fluorescence with the Olympus confocal laser scanning microscope.

Light Stimulation

A green-light light-emitting diode (LED; λ = 525 nm) was used to deliver a full-filled light stimulation to the retina through the microscope condenser. The LED was controlled by Pulse software and the light intensity was adjusted by varying the output voltage from the software. The stimulus intensity varied from 3.36 × 108 to 3.36 × 1011 photons/cm²/s.
D were used for this analysis. Cm was calculated using the equation, Cm = τm/Rm, whereas blood glucose levels in the STZ-treated mice were increased by more than 3-fold at all post-injection time points. The gray dashed line indicates 250 mg/dL (13.9 mM). **P < 0.001 vs. control.

Analysis of Physiologic Data

A range of physiologic parameters was examined, including resting membrane potential (Vm), membrane resistance (Rm), membrane time constant (τm), membrane capacitance (Cm), and spiking behaviors. The specific methods for obtaining these parameters are described: (1) Vm was the averaged resting membrane potential recorded under current-clamp mode. (2) Rm was obtained by calculating the ratio ΔV/ΔI, where ΔV is the voltage change caused by an injection of 50 pA hyperpolarizing current (ΔI; see Fig. 4C). (3) τm was the time constant of the single-exponential decay curve, fitting the voltage changes after the onset of a current step. Only the data obtained in cells with a correlation coefficient being > 0.990 were used for this analysis. Cm was calculated using the equation, Cm = τm/Rm.

Action potential (AP) properties were measured as follows (see Fig. 5). Under current clamp, depolarizing current steps of increasing amplitudes were applied to each GC. The AP threshold was defined as the membrane potential at the point of inflection at the onset of the first AP that was induced by the lowest-amplitude current step. The AP amplitude was measured from the threshold to the peak potential. The AP width was measured as the full width at half height. The instantaneous frequency (in Hz) was defined as the inverse of the time between the closest two APs in response to current injections. The maximum firing rate of GC was calculated from the interval between the first and second spikes generated by the strongest current step tested that did not produce a spike block. Typically, the first pair of APs generated by a large amplitude current injection was the fastest.

Chemicals

All chemicals were purchased from Sigma-Aldrich Corp. Concentrated stock solutions were freshly made and then diluted to working concentrations with extracellular medium before experiments.

Statistical Analysis

Data analysis was performed using Clampfit 8.0 (Molecular Devices, Sunnyvale, CA, USA) and Origin 9.0 (OriginLabs, Northampton, MA). Data are presented as means ± SEM. To identify significant differences, Student’s t-test was used in all instances, except for the data shown in Figures 7E, 7F, 8E, and 8F, in which two-way repeated measures (RM) ANOVA followed by post hoc Sidak’s multiple comparisons test was used. In all cases, P < 0.05 was considered statistically significant.

RESULTS

Characterization of Diabetic Mouse

Figure 1A shows the changes in blood glucose concentrations in Thy1-YFP transgenic mice at different times after intraocular injections of STZ. The blood glucose concentrations of these mice were sharply increased from 103.14 ± 15.15 mg/dL (5.73 ± 0.21 mM) before STZ injection to 543.8 ± 14.04 mg/dL (19.10 ± 0.78 mM) 1 month after injection and they remained at this higher level thereafter for 3 months. Meanwhile, no increase in body weight was seen in diabetic mice over the same period (Fig. 1B), while age-matched control mice showed a gradual weight gain during the first 3 months.

Morphology

Targeting of Transgenically Labeled GC Subtypes. The Thy1-YFP transgenic mouse line, in which individual GCs (30-60 cells per retina), including their somata, axons, and dendrites, are clearly labeled by YFP, was used for morphologic analysis. Four subtypes (ON-RGA2, OFF-RGA2, RGC1, and RGD2) with different morphology,37 which functions have been well explored,48-51 were chosen for detailed analysis of changes in morphologic features in diabetes. RGA2 cells, which are equivalent to β-GCs,57 exhibit a large receptive field center, short response latency, and fast conducting axon.48-49 RGD2 cells are bistratified GCs and they respond transiently to the onset and termination of a light stimulus and show a strong directional selectivity to a moving rectangle.57,50 RGC1 cells are ON direction-selective cells and respond to a stationary flashing spot with sustained spiking during light onset.45,51

Changes in Morphology of RGA2 Cells in Diabetic Retinas. Changes in morphology were first examined in RGA2 cells. In the normal retina, these cells are characterized by a large soma, large dendritic field area, and four to seven primary dendrites that branch repeatedly proximal to the soma.57 They could be subdivided into two groups with dendrites stratifying either in the ON (ON-RGA2) or OFF sublamina of the IPL (OFF-RGA2). Figures 2A and B show the stacked confocal fluorescence images of two typical ON-RGA2 cells (green) respectively from an age-matched control mouse and a diabetic one with hyperglycemia for 3 months.
These images are projections from a series of section scans across the entire dendritic fields. The dendritic stratification patterns of these two cells are shown below as side view images (Figs. 2C, 2D), in which the dendrites occupy the lower half of the ON sublamina of the IPL, somewhat below (vitreal to) the ON ChAT-labeled band (red). Soma areas of ON-RGA2 cells were unchanged (335.75 ± 9.51 μm² [n = 30, from 14 mice] in diabetic vs. 329.90 ± 9.51 μm² [n = 39, from 9 mice] in control, P = 0.58; Table 1). Total dendritic lengths of ON-RGA2 cells in diabetic mice also were not significantly different from those obtained in control mice (4554.04 ± 118.30 μm in diabetic vs. 4692.81 ± 194.87 μm in control, P = 0.87; Table 1). By processing three other morphologic parameters for dendrites in ON and OFF sublaminae of the IPL separately, there were no significant differences in total dendritic lengths and branch numbers for either ON or OFF sublamina between diabetic and control retinas (P > 0.21 in the two cases; Table 1), but a statistically significant decrease in dendritic field areas in the ON sublamina (20,324.28 ± 1722.44 μm² in diabetic vs. 30,129.08 ± 2621.89 μm² in control; P < 0.05), not for dendrites in the OFF sublamina (30,020.97 ± 1407.17 μm² in diabetic vs. 31,843.83 ± 1141.74 μm² in control; P = 0.35). Additionally, Sholl analysis revealed that in the ON sublamina the numbers of dendritic intersections were not significantly different except for the location 40 μm far from the soma (Fig. 3E). No such changes occurred for the dendrites in the OFF sublamina (Fig. 3F).

**Laminar-Specific Dendritic Alterations in RGD2 Cells in Diabetic Retina.** RGD2 cells are bistratified ON-OFF direction-selective GCs. As shown in Figure 4A, RGD2 cell is shown in Figure 3A, which had extremely thin and recursive dendrites that arborized in ON and OFF sublaminae of the IPL. Diabetic RGD2 cells did not show changes in soma size (194.87 ± 7.44 μm² in diabetic n = 15, from eight mice) vs. 194.87 ± 7.44 μm² in control [n = 17, from eight mice], P = 0.91; Figs. 3A-D, Table 1). Instead, C57BL/6J mice, with a background on which the transgenic mouse line was originally created, were used. We found that in diabetic vs. control, Student’s t-test.

**RGD2 Cells were Unchanged in Morphology in Diabetic Retinas.** RGC1 cells exhibit medium dendritic fields and smooth, recursive dendrites extending from large primary ones and branching in the inner most tier of the IPL. They represent the ON direction-selective cells. As shown in Table 1, for all morphologic parameters examined, no differences were found between diabetic and control retinas, including soma area, total dendritic length, dendritic field area, dendritic branch number, and number of dendritic intersections (P > 0.55 in all cases; n = 14, from six diabetic mice; n = 15, from nine control mice).

**Electrophysiology**

Changes in Passive Membrane Properties of RGA2 Cells. Use of the transgenic mouse line for electrophysiologic experiments that require a large number of GCs for each special subtype GC to accumulate data is poorly economic, since only a small population of GCs are YFP-labeled in this line. C57BL/6J mice, with a background on which the transgenic mouse line was originally created, were used. We first determined the identity of a cell being recorded according to its light response feature and then reconfirmed it by its ability to respond to light stimuli in different directions.
FIGURE 2. Dendritic alterations of ON- and OFF-RGA2 cells in diabetic retinas of Thy-1 YFP mice. (A, B) Maximum intensity projection confocal fluorescent images of two typical ON-RGA2 cells respectively in whole-mounted control (A) and diabetic (B, green for YFP) retinas. Arrows, axons. (C, D) Side views of the same cells in (A, B), showing the dendritic stratification patterns, in which the boundaries of the IPL are shown by ChAT-labeled somata of cholinergic amacrine cells (red). The areas in dotted rectangle are enlarged in the bottom panels. (E, F) Maximum intensity projection confocal fluorescent images of typical OFF-RGA2 cells from control (E) and diabetic (F) retinas. (G, H) Side views of the same cell in (E, F), showing the dendritic stratification depth of the dendritic arbor within the off sublamina. (I) Sholl analysis revealing the increased branches of proximal dendrites (30–80 μm away from somata) and reduced branches of distal dendrites (120 and 140–210 μm away from somata) of ON-RGA2 cells in diabetic retinas. (J) Sholl analysis showing no changes in the number of dendritic intersections along dendrites of OFF-RGA2 cells in diabetic retinas. *P < 0.05 and **P < 0.01 vs. control. OFF, OFF sublaminae of the IPL; ON, ON sublaminae of the IPL. Scale bar: 25 μm.
morphologically by filling the cell with Lucifer yellow. GC subtypes were identified according to well-established morphologic and physiologic criteria.46,52,53 RGA2 cells/α-GCs, which are characterized by large (~20 μm) somata, could be distinguished easily from other GCs and displaced amacrine cells.36,37,54 Based on their light response properties, α-GCs could be further classified into four subtypes: transient ON (with a brief burst at the start of the bright phase), sustained ON (with maintained firing during the bright phase), transient OFF (with a burst of spikes at the start of the dark phase followed by rapid decay to little or no firing), and sustained OFF (with maintained firing during the dark phase and little or no firing during the bright phase).46 All four physiologic subtypes share similar morphology.46

Transient ON and OFF cells were chosen for physiologic analysis because these two cell subtypes were rather commonly encountered and stable recordings from these cells were easily obtained under our experimental conditions. Figures 4A and 4B show the maximum intensity projection confocal fluorescent images of a transient ON-RGA2 cell and a transient OFF-RGA2 cell filled with Lucifer yellow (green), respectively, and their dendritic stratification patterns are shown below as side view images. These two cells generated a burst of spikes respectively at light (525-nm full field stimulus) onset (right in Fig. 4A) and offset (right in Fig. 4B) under dark-adapted conditions with cell-attached recording.

Under current-clamp mode, a range of passive membrane parameters were examined (Fig. 4C, for details see Materials and Methods). For transient ON-RGA2 cells, the mean $V_m$ obtained in diabetic mice was significantly less hyperpolarized than that in normal animals ($-61.64 ± 0.83$ mV [$n = 21$]) in diabetic vs. $-64.42 ± 0.42$ mV [$n = 22$]) in control; $P < 0.01$; Fig. 4D, Table 2), whereas the mean $C_m$ was decreased ($53.78 ± 3.56$ pF in diabetic vs. $76.28 ± 6.68$ pF in control; $P < 0.01$; Fig. 4E). No changes in $\tau_m$ (Fig. 4F) and $R_m$ (Fig. 4G) of these cells were observed in diabetic retinas ($P > 0.13$ in the two cases).

No differences in all passive membrane properties examined in transient OFF-RGA2 cells were detected between control and diabetic retinas ($P > 0.08$ in all cases; Figs. 4H–K).

**Alterations in Active Membrane Properties of RGA2 Cells.** Whether AP properties were changed in diabetic retinas

![Figure 3. RGD2 cells show laminar-specific alterations in their dendritic structure.](image)

(A, B) Maximum intensity projection confocal fluorescent images of RGD2 cells from control (A) and diabetic (B; green for YFP) retinas. Arrows, axons. (C, D) Side views showing the dendritic stratification patterns within the IPL (red for ChAT). (E, F) Sholl analysis revealing the decreased branching of dendrites in the ON sublamina (asterisk in E) and unchanged branching of dendrites in the OFF sublamina (F). *$P < 0.05$ vs. control. Scale bar: 25 μm.
was further examined. Under current clamp mode, we measured and compared the spike width, threshold, and amplitude of transient RGA2 cells in normal and diabetic mice. Figures 5A and 5B show the spike waveforms of transient ON-RGA2 cells in control and diabetic retinas, respectively. AP widths were measured as the full width at half height (dashed lines in Figs. 5A, 5B). Statistical analysis showed that the mean AP width of transient ON-RGA2 cells was larger in diabetic retinas (0.35 ± 0.01 ms, n = 22) than in control ones (0.27 ± 0.01 ms, n = 22; P < 0.01; Fig. 5C, Table 2). However, no changes in thresholds and amplitudes of APs were seen for transient ON-RGA2 cells (threshold, −56.20 ± 0.84 mV in diabetic vs. −55.08 ± 0.36 mV in controls; amplitude, 81.51 ± 1.57 mV in diabetic vs. 84.89 ± 1.74 mV in controls, P > 0.16 in the two cases; Figs. 5D, 5E, Table 2).

Transient OFF-RGA2 cells displayed similar changes in AP properties, such as an increase in AP widths (0.30 ± 0.01 ms [n = 19] in diabetic vs. 0.26 ± 0.01 ms [n = 20] in control, P < 0.01; Figs. 5F–H), no changes in thresholds (Fig. 5I) and amplitudes (Fig. 5J, Table 2).

AP firing patterns of GCs in response to depolarization steps, which determine the signal that is sent from the retina, also were tested. Since the Vm of a cell is related to the firing rates of the cell in response to a certain current step, the pre-stimulus Vm of each GC was adjusted to the same level (approximately −65 mV) by using an appropriate current injection\(^*\) to facilitate comparisons among the data obtained in different GCs. To elicit AP firing, GCs were injected with 500 ms depolarizing current steps (+200, 300, and 400 pA). Figure 6B shows the firing rate, which was much higher than that of another cell recorded in normal retina (Fig. 6A), of a transient ON-RGA2 cell in response to 400 pA current injection in diabetic retina. The bar chart in Figure 6C shows a comparison of the mean numbers of spikes in response to current steps of three magnitudes recorded in normal and diabetic retinas. In response to all current steps, transient ON-RGA2 cells (n = 19) in diabetic retinas fired more APs than those (n = 22) in normal retinas (P < 0.05 for 500 pA, P < 0.01 for 200 pA and 400 pA), suggesting an increased excitability of these cells in diabetic mice.

The changes in firing rates of transient OFF-RGA2 cells in response to depolarizing current steps of increasing amplitudes in diabetic mice followed the same pattern of significant changes as those seen in ON-RGA2 (P < 0.01 for all cases, n = 19 for controls, and n = 14 for diabetics; Figs. 6E–G).

We also examined the maximum firing rate of GCs, which reflects the dynamic range of signal being processed by these cells. Maximum firing rates of transient ON- and OFF-RGA2 cells in diabetic mice were significantly lower than those in control mice (ON-RGA2, 353.20 ± 13.90 Hz [n = 21] in diabetic vs. 428.55 ± 11.29 Hz [n = 22] in control, P < 0.001; OFF-RGA2 cells, 387.30 ± 14.29 Hz [n = 18] in diabetic vs. 458.01 ± 10.87 Hz [n = 19] in control, P < 0.001; Figs. 6D, 6H).

### Table 2. Measurements of Membrane Properties of Two GC Subtypes in Control and Diabetic Retinas (Mean ± SEM)

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Control</th>
<th>Diabetic</th>
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<tr>
<td>ON-RGA2</td>
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<tr>
<td>Vm, mV</td>
<td>−64.42 ± 0.42</td>
<td>−61.64 ± 0.83(†)</td>
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<td>Rm, MO2</td>
<td>106.24 ± 6.53</td>
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<td>Cm, pF</td>
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<td>tms, ms</td>
<td>7.94 ± 0.73</td>
<td>6.59 ± 0.40</td>
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<tr>
<td>Number of cells/mice</td>
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<td>21/17</td>
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<tr>
<td>AP properties</td>
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<tr>
<td>Width, ms</td>
<td>0.27 ± 0.01</td>
<td>0.35 ± 0.01(†)</td>
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<tr>
<td>Threshold, mV</td>
<td>−55.08 ± 0.36</td>
<td>−56.20 ± 0.84</td>
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<tr>
<td>Amplitude, mV</td>
<td>84.89 ± 1.74</td>
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<tr>
<td>Number of cells/mice</td>
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<tr>
<td>Number of APs elicited by current injections</td>
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<td>200 pA</td>
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<td>41.86 ± 3.61</td>
<td>59.21 ± 5.87(***)</td>
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<td>51.18 ± 4.38</td>
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<td>Maximum firing rate, Hz</td>
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<td>Vm, mV</td>
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<td>−64.99 ± 0.68</td>
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<td>Rm, MO2</td>
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<td>Number of cells/mice</td>
<td>22/20</td>
<td>19/14</td>
</tr>
<tr>
<td>Maximum firing rate, Hz</td>
<td>458.01 ± 10.87</td>
<td>387.50 ± 14.29(†)</td>
</tr>
</tbody>
</table>

\* P < 0.05 vs. control, Student’s t-test.  
\(†\) P < 0.01 vs. control, Student’s t-test.  
\(***\) P < 0.001 vs. control, Student’s t-test.
constructed for isolated I_k, no significant difference was found between the two curves obtained in control and diabetic ON-RGA2 cells (two-way RM ANOVA followed by Sidak’s multiple comparisons test, \( F[1, 15] = 0.55, \ P = 0.47; \) Fig. 7E). In contrast, a significant difference was seen for the two curves of I_A densities obtained in control and diabetic ON-RGA2 cells (two-way RM ANOVA followed by Sidak’s multiple comparisons test, \( F[1, 15] = 5.96, \ P < 0.05; \) Fig. 7F). It is noteworthy that I_k and I_A densities of transient OFF-RGA2 cells were significantly decreased in diabetic retinas compared to controls (two-way RM ANOVA followed by Sidak’s multiple comparisons test: \( F[1, 22] = 7.06, \ P < 0.05 \) for I_k; Figs. 8A, 8C, 8E; \( F[1, 22] = 14.28, \ P < 0.05 \) for I_A, Figs. 8B, 8D, 8F). These results suggest that the increased AP width observed in ON- and OFF-RGA2 cells could be caused by a reduction in I_A (for ON- and OFF-type) and I_k (for OFF-type) induced by hyperglycemia, respectively.

**DISCUSSION**

Visual deficits, especially ones at the early stages of diabetes, may be induced by effects of hyperglycemia on inner retinal neurons, as demonstrated by morphologic and physiologic studies. Since a variety of GCs are responsible for diverse visual functions, a detailed analysis of the hyperglycemia-induced morphologic and physiologic changes of different subtypes of GCs is extremely necessary, since it could provide information useful for developing new treatment options targeting these cellular alterations, thus ultimately preserving vision.

**Morphology and Passive Membrane Properties of GCs/GC Dendrites Mediating ON Light Signaling are Preferentially Affected at the Early Stage of Hyperglycemia**

Experiments with ON- and OFF-RGA2 cells clearly demonstrated that hyperglycemia preferentially affected the dendrites arborizing in the ON sublamina in the IPL over those arborizing in the OFF sublamina. ON-RGA2 cells exhibited decreased dendritic field areas, whereas OFF-RGA2 cells showed no changes in dendritic field areas. It is of interest that in ON-OFF RGD2 cells that send dendrites arborizing in ON and OFF sublaminae, hyperglycemia caused a reduction in ON-stratified

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**Figure 4.** Changes in passive membrane properties of RGA2 cells in diabetic C57/Bl6j mice. (A, B) Top, maximum intensity projection confocal fluorescent images of a transient ON-RGA2 (A) and an OFF-RGA2 cell (B), showing a brief burst at the onset and offset of a light step (525-nm, 1.06 × 10^2 photons/cm^2/s), respectively. Both cells were filled with Lucifer Yellow (green). Bottom, digitally rotated views of the sample zones (square outlines) to show the stratification of ON-RGA2 (A) and OFF-RGA2 cell (B) distal dendrites in relation to the ChAT-immunoreactive processes (red). (C) A diagram showing how R_m and \( \tau_m \) were measured. R_m was obtained by calculating the ratio \( \Delta V/\Delta I \), where \( \Delta V \) is the voltage change caused by an injection of 50 pA hyperpolarizing current (\( \Delta I \)). \( \tau_m \) was the time constant of the single-exponential decay curve (black curve), fitting the voltage change after the onset of a current step. (D–G) Quantification of various parameters of passive membrane properties examined for ON-RGA2 cells in control (white bars) and diabetic retinas (black bars). (H–K) Quantification of various parameters of passive membrane properties examined for OFF-RGA2 cells in control and diabetic retinas. Cell numbers are noted in the bars (D, H). **P < 0.01 vs. control.
ON-RGA2

OFF-RGA2

**Figure 5.** Changes in active membrane properties of RGA2 cells. (A, B) Representative AP waveforms of transient ON-RGA2 cells in control (A) and diabetic (B) retinas. Dashed lines show the AP widths that are measured as the full width at half height. (C–E) Quantification of various parameters of APs examined for transient ON-RGA2 cells in control and diabetic retinas. (F, G) Representative AP waveforms of transient OFF-RGA2 cells in control (F) and diabetic (G) retinas. (H–J) Averaged values of AP width (H), threshold (I) and amplitude (J) were differentially affected in diabetic OFF-RGA2 cells. Cell numbers are noted in the bars (C, H). **P < 0.01 vs. control.

Dendritic field areas, but not in the OFF-stratified ones. All these results strongly suggested that GCs/GC dendrites mediating ON light signaling are preferentially affected at the early stage of hyperglycemia.

A possible explanation for the decreased dendritic field size of ON-RGA2 cells (Table 1) may be that longer dendrites were somehow shortened in diabetes. The occurrence of such shortening during the early stages of diabetes may lead to an...

**Figure 6.** Altered spiking patterns of RGA2 cells in diabetic mice. (A, B) Example traces from typical control (A) and diabetic transient ON-RGA2 (B) cells, showing the voltage responses to a depolarizing current injection (+400 pA, 500-ms duration). (C) Mean number of APs elicited in transient ON-RGA2 cells by depolarizing current steps of varying amplitudes. Cells (n = 19) from diabetic mice fired significantly more APs than control neurons (n = 22). (D) Averaged maximum firing rate was decreased in diabetic ON-RGA2 cells compared to control ones. (E, F) Example traces from typical control (E) and diabetic transient OFF-RGA2 cells (F), showing the voltage responses to a depolarizing current injection (+400 pA, 500-ms duration). (G) OFF-RGA2 cells (n = 14) from diabetic mice fired significantly more APs than control neurons (n = 19) in response to depolarizing current steps of varying amplitude. (H) Averaged maximum firing rate was decreased in diabetic OFF-RGA2 cells compared to control ones. *P < 0.05, **P < 0.01, and ***P < 0.001 vs. control.
increase in the number of short dendrites and a decrease in the number of long dendrites. As a result, the number of intersections at the distance from the soma less than 80 μm was increased, but it decreased when it was over approximately 130 μm, thus leading to the bell curve, yielded by Sholl analysis, to be shifted left. In contrast, no significant changes in dendritic field sizes and bell curve shapes were found in diabetic OFF-RGA2 cells compared to control ones.

An increase in total number of dendritic branches was seen in ON- and OFF-RGA2 cells. This result is different from that obtained in InsAkita mice, in which such an increase was detected only in large ON-GCs (corresponding to ON-RGA2 cells), but not in large OFF-GCs. The increase in dendritic branch numbers could be in part due to a compensatory response to a potential loss of inhibitory presynaptic inputs, as suggested by some studies conducted in diabetic animal models. In an experimental glaucoma mouse model, neither somata nor dendrites were affected at the early stage of elevated IOP .

The effect of hyperglycemia on passive membrane properties of ON- and OFF-RGA2 cells, hyperglycemia exerted actions on active membrane properties of the two cell subtypes in a similar way: hyperglycemia increased the AP width, enhanced the excitability and reduced the maximum firing rate without changing the AP threshold and amplitude in both cell subtypes.

A plausible explanation for this inconsistency may be that the morphologic parameters used in the present work were for detecting changes in dendritic regions rather than soma regions, which are mainly responsible for generating active membrane properties. If the changes in morphology are largely restricted to the dendritic regions of these cells, but it did not affect the soma region at the early stage of hyperglycemia, it would be understandable why no changes in active membrane properties were detected while the changes in morphology were detectable.

**Functional Implication of Morphologic and Physiologic Alterations in Diabetic Retinas**

A major change in GC morphology in diabetic retinas was a reduction in dendritic field size of ON-RGA2 cells. Reduced dendritic field sizes in GCs also were seen in postmortem human retinas with diabetes. It has been reported that the dendritic field size is closely related to the receptive field center dimension. Indeed, Xiao et al. have demonstrated that the receptive field size of ON-RGA cells in db/db mice is significantly reduced from 12 weeks after birth. However, whether the receptive field size of ON-RGA2 cells in STZ-induced diabetic mice is reduced should be further explored. Moreover, it should be noted that in contrast to the our results...
and that of Meyer-Rusenberg et al., enlarged dendritic fields of RGA cells were observed in STZ-induced diabetic rats. It has been well established that ON and OFF signaling pathways and the interactions between them in the visual system are closely involved in contrast detection. In mice with ON pathway knockout, optokinetic responses were noted only at high contrasts, suggesting an impaired visual contrast detection ability. It is reasonable to suppose that impaired visual contrast sensitivity, which has been recognized as an early sign of neural retinal dysfunction in diabetic patients and visual contrast sensitivity, which has been recognized as an early sign of neural retinal dysfunction in diabetic patients and visual contrast sensitivity, which has been recognized as an early sign of neural retinal dysfunction in diabetic patients and visual contrast sensitivity, which has been recognized as an early sign of neural retinal dysfunction in diabetic patients and visual contrast sensitivity, which has been recognized as an early sign of neural retinal dysfunction in diabetic patients.

With the AP threshold being unaltered, the fact that the resting membrane potential of ON-RGA2 cells became less hyperpolarized in diabetic retinas suggests that hyperglycemia could make the membrane potential of these cells closer to the AP threshold. This means that these cells would generate more APs to a certain depolarizing current step in diabetic retinas implying an enhanced excitability of these cells. Less hyperpolarizing membrane potentials of ON-RGA2 cells may be due to a reduction of presynaptic inhibition of GCs, which has been suggested by several studies in various animal models. It is shown that the reduced presynaptic inhibition led to an increase in spontaneous spiking activity of ON-GCs in STZ-induced diabetic mice. Spontaneous spiking activity of a neuron could be regarded as a background noise. The increased background noise could result in a decreased signal-to-noise ratio, meaning that it is more difficult for the animal to detect a luminance increment on a background (i.e., an elevation in luminance threshold). Indeed, an elevated luminance threshold in ON-GCs was reported in db/db mice.

Moreover, the reduced maximum firing rates of ON- and OFF-RGA2 cells in diabetic mice (Figs. 6D, 6H) suggest a reduced dynamic range of visual signals that can be processed by these cells.

In summary, the effects of early hyperglycemia on GC morphology and passive membrane properties were cell subtype-dependent with GCs/GC dendrites mediating light ON signaling being preferentially affected. These differential changes in morphology and electrophysiological function in subtypes of GCs may in part account for visual function defects in early diabetes.

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References


