Phototransduction by Retinal Ganglion Cells That Set the Circadian Clock

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Light synchronizes mammalian circadian rhythms with environmental time by modulating retinal input to the circadian pacemaker—the suprachiasmatic nucleus (SCN) of the hypothalamus. Such photic entrainment requires neither rods nor cones, the only known retinal photoreceptors. Here, we show that retinal ganglion cells innervating the SCN are intrinsically photosensitive. Unlike other ganglion cells, they depolarized in response to light even when all synaptic input from rods and cones was blocked. The sensitivity, spectral tuning, and slow kinetics of this light response matched those of the photic entrainment mechanism, suggesting that these ganglion cells may be the primary photoreceptors for this system.

The SCN is the circadian pacemaker of the mammalian brain, driving daily cycles in activity, hormonal levels, and other physiological variables. Light can phase-shift the endogenous oscillator in the SCN, synchronizing it with the environmental day-night cycle. This process, the photic entrainment of circadian rhythms, originates in the eye and involves a direct axonal pathway from a small fraction of retinal ganglion cells to the SCN (1–3). A striking feature of this neural circuit is its apparent independence from conventional retinal phototransduction. In functionally blind transgenic mice lacking virtually all known photoreceptors (rods and cones), photic entrainment persists with undiminished sensitivity (4). Candidate photoreceptors for this system are nonrod, noncone retinal neurons, including some ganglion cells, that contain novel opsins or cryptochromes (5–8).

To determine whether retinal ganglion cells innervating the SCN are capable of phototransduction, we labeled them in the rat retina by retrograde transport of fluorescent microspheres injected into the hypothalamus (9). In isolated retinas, whole-cell recordings were made of the responses of labeled ganglion cells to light (10) (Fig. 1, A to E). In most of these cells (n = 150), light evoked large depolarizations with superimposed fast action potentials (Fig. 1, E to G) (11). The light response persisted during bath application of 2 mM cobalt chloride (Fig. 1F; n = 42), which blocks calcium-mediated synaptic release from rods, cones, and other retinal neurons (12). In contrast, other ganglion cells prepared and recorded under identical conditions but not selectively labeled from the SCN (control cells) lacked detectable responses even when labeled with both fluorescent beads and LY (n = 5). Whole-cell recordings revealed normal light responses when LY was omitted from the internal solution (n = 8). In contrast, control cells lacked cobalt-resistant light responses even when labeled with both fluorescent beads and LY (n = 12; Fig. 1I). These data indicate that retinal ganglion cells innervating the SCN are intrinsically photosensitive.

To determine if these cells could serve as the primary photoreceptors for circadian entrainment, we assessed congruence between their photic properties and those of the entrainment mechanism. The responses of a single cell to narrow-band stimuli of various intensities showed that at each wavelength, peak depolarization increased with stimulus energy (Fig. 2, A and B). Intensity-response curves exhibited a consistent slope when plotted in semilogarithmic coordinates (Fig. 2B), as expected for responses mediated by a single photopigment (principle of univariance). The horizontal displacements of the curves from one another reflect the spectral dependence of the pigment’s quantum efficiency and yield the spectral sensitivity function shown in Fig. 2C (red curve). Other cells exhibited similar action spectra (Fig. 2C, green curve) (15). These action spectra closely matched that predicted for a retinal-based pigment with peak sensitivity at 484 nm (Fig. 2C, black). They also resemble action spectra derived behaviorally for circadian entrainment in rodents (16, 17), as expected if these ganglion cells function as primary circadian photoreceptors (18). Judging from available spectral evidence, the phototopigment in these ganglion cells is more likely to be a retinaldehyde-based opsin such as melanopsin (5, 19, 20) than a flavin-based cryptochrome (21).
The threshold and dynamic range of the light response in these ganglion cells were also similar to those of the entrainment mechanism. Threshold retinal irradiance for a full-field stimulus was about $5 \times 10^{13}$ photons s$^{-1}$ cm$^{-2}$ at 500 nm ($\lambda_{\text{max}}$, $n = 3$). This corresponds to an in vivo corneal irradiance of $\approx 2 \times 10^{13}$ photons s$^{-1}$ cm$^{-2}$, comparable to thresholds for circadian phase shifts in rodents ($\approx 10^9$ to $10^{11}$ photons s$^{-1}$ cm$^{-2}$ at 500 nm) (22–24) and to ocular illumination by the dawn sky. Response saturation in photosensitive ganglion cells occurred at irradiances $\approx 3$ logarithmic units above threshold (Figs. 2B and 3C), matching the dynamic range of entrainment behavior (16, 23, 24) and many SCN neurons [(25), but see (26)].

The circadian entrainment mechanism integrates light energy over very long time scales, exhibiting little adaptation, and responds poorly to brief stimuli (24, 27). Similar features were evident in the behavior of photosensitive ganglion cells. Constant illumination depolarized cells tonically and elevated spike frequency, and the amount of depolarization was monotonically related to stimulus energy (Fig. 3). Response kinetics were much slower than typical for ganglion cells. Latencies to response onset ($P_{\text{on}} > 3$ standard deviations above baseline) were typically several seconds and ranged from several hundred milliseconds for saturating stimuli (Figs. 1F and 2A) to $\approx 1$ min near threshold (Fig. 3B, bottom trace). Latencies from stimulus onset to peak depolarization were typically 10 to $20$ s (range: $\approx 2$ s to 2 min) and inversely

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**Fig. 1.** Labeling and light responses of rat ganglion cells innervating the SCN. (A) Fluorescence photomicrograph showing deposit (white arrow) of mixed red and green fluorescent microspheres (appears as yellow) in the SCN. The red arrows mark boundaries of contralateral SCN. Acidine orange was used for green fluorescent Nissl counterstain. ox, optic chiasm; III, third ventricle. Scale bar, 500 μm. (B) Two ganglion cells back-filled from the SCN, photographed in whole mount with rhodamine filter set to show retrograde labeling. The cell at right was patched and recorded. Scale bar, 20 μm. (C) Same cells viewed under blue excitation, to show LY filling of the recorded cell. (D) Camera lucida drawing of cell filled in (C), as viewed in the whole mount after antibody to LY immunostaining (35). Scale bar, 100 μm. (E) Strong depolarization and fast action potentials evoked in this cell (D) by a light pulse indicated by step in horizontal line below. [F to H] Evidence for the intrinsically photosensitive ganglion cells selectively retro labeled from the SCN. (F and G) The light response apparent in control Ames solution (black traces) persisted during bath application of 2 mM CoCl$_2$ (red traces) either alone (F) or in combination with a drug mixture blocking ionotropic and metabotropic glutamate receptors as well as ionotropic GABA and glycine receptors (G) (14). The absence of evoked spikes during drug application probably reflects depolarization block (tonic sodium channel inactivation) because weaker stimuli evoked spikes (40). (H) Light response recorded from the isolated soma of a ganglion cell retro labeled from the SCN. The cell body was bathed in an enzyme solution (papain, $\approx 20$ units/ml) with a puffer pipette and then mechanically removed from the retina with an empty patch pipette under visual control, amputating its dendrites and axon. (I and J) Control recordings from a conventional ganglion cell (Fig. 4C) labeled nonselectively by a deposit of rhodamine beads in the optic chiasm and filled with LY. Light evoked no detectable response (I), although synaptic transmission was not blocked and responses to current injection were normal (J) (+50 pA). Retinal irradiance of stimuli (in photons s$^{-1}$ cm$^{-2}$): (E) $7 \times 10^{12}$, (F) $2.6 \times 10^{13}$, (G) $7.2 \times 10^{12}$, (H) $\approx 1 \times 10^{13}$, and (I) $\approx 9 \times 10^{12}$. Stimuli in (E), (F), and (G) were 500 nm.
related to stimulus energy. Repolarization after intense stimuli required several minutes and was sometimes punctuated by spontaneous depolarizations and spike bursts lasting up to a minute each (Fig. 3B). Voltage responses evoked in another cell by 4-min stimuli varying in intensity (log10 irradiance in photons s-1 cm-2 indicated at left; 500 nm). Note tonic depolarization, maintained spiking, and, for near-threshold stimulus (bottom trace), extremely long response latency. (C) Magnitude of maintained depolarization as a function of stimulus energy for the cell in (B) (open circles) and for two other cells. Bathing medium: Ames.

The data identify a distinct ganglion cell type in the mammalian retina with characteristic dendritic profile and stratification pattern, extraordinarily sluggish and tonic light responses encoding ambient light level, and axonal projections to the SCN. The most striking feature of this cell type, however, is its apparent capacity for intrinsic phototransduction. The correspondences between the photic properties of these cells and those of the entrainment mechanism suggest that these unconventional ganglion cells may represent the primary photoreceptors for synchronizing the circadian clock to environmental time.

Melanopsin (5, 7) is probably the photopigment responsible for the intrinsic sensitivity of these cells to light, as it is selectively expressed in the small subset of ganglion cells that are intrinsically photosensitive and innervate the SCN (32, 33). In amphibians, certain nonretinal cells contain melanopsin, and these cells, too, are photosensitive, with action spectra resembling those of photosensitive rat ganglion cells (Fig. 2C) (5, 19, 20). Melanopsin exhibits marked sequence similarity to invertebrate opsins (5, 7), which, unlike vertebrate opsins, retain their photosensitized retinaldehyde chromophore and typically trigger depolarizing light responses when activated. These properties may help to explain why photosensitive ganglion cells differ from conventional retinal photoreceptors in their response polarity and lack of dependence on the pigment epithelium. Cryptochromes, blue-light-absorbing, flavin-based pigments, have been proposed as circadian photopigments (8), but spectral evidence (Fig. 2C) (21) weighs against their mediating the light response in intrinsically photosensitive ganglion cells.

Note added in proof: Further evidence for the presence of melanopsin in ganglion cells innervating the SCN has emerged (34).

References and Notes
9. Methods. Procedures conformed to NIH guidelines and were approved by Brown University’s Institutional Animal Care and Use Committee. Rats (Sprague-Dawley; 56 to 70 days of age, 265 to 355 g; n = 256) were anesthetized with ketamine [60 mg/kg intraperitoneal (ip)] and medetomidine (0.4 mg/kg ip). Fluorescent latex microspheres (rhodamine-labeled, alone or mixed with fluorscein-labeled microspheres; Lumalfuor, 0.1 to 0.3 μl) were deposited unilaterally into the hypothalamus through glass pipettes tilted 10° from vertical. As expected (1), deposits involving the ventral hypothalamus but sparing the optic chiasm labeled a few ganglion cells to as many as several hundred scattered over the retina. These cells are the focus of this report. Deposits spreading to the optic chiasm nonspecifically labeled thousands of ganglion cells, some of which were targeted for control recordings. Deposits involving overlying structures but sparing the SCN and chiasm labeled no ganglion cells.
10. Rats were anesthetized (Nembutal, 120 mg/kg ip) 2 to 8 days after tracer injection, and their eyes were removed and enucleated. Eyecups were rinsed in an enzyme solution [collagenase/dispeps (2 mg/ml); DNase (Sigma A1420; 0.1 mg/ml) in Ames medium, 1 min] to remove vitreous. Retinas were isolated, affixed to a cover slip with gelatin, vitreal surface up, and mounted in a chamber (Warner RC-26GLP). Retinas were maintained...
at room temperature in bicarbonate-buffered Ames medium, and fluorescent-labeled cells were identified as described (35). Detachment from pigment epithelium and exposure to bright light during dissection (\(1 \times 10^{10}\) photons \(s^{-1} \cdot \text{cm}^{-2}\) received at 500 nm) and epifluorescence examination (\(3 \times 10^{10}\) photons \(s^{-1} \cdot \text{cm}^{-2}\) at 560 nm) presumably strongly bleached rod and cone photopigments. Ganglion cell somata were excised by microdissection. Whole-cell current clamp recordings were made with an intracellular amplifier (Cyg-nus Technologies DR-886, Delaware Water Gap, PA) and micropipettes (3 to 7 megohms) containing 125 mM K-Gluconate, 5 mM NaCl, 4 mM KCl, 10 mM EGTA, 10 mM HEPES, 4 mM adenosine triphosphate-Mg\(_2\), 7 mM phosphocreatine, 0.3 mM guanosine triphosphate-tris, LY-0.1% w/v) and biocytin (0.5% w/v). Resting potentials were not measured for liquid junction potentials. Light stimuli were introduced from below with the microscope’s 100-W tungsten-halogen lamp and transillu-mination optics. Neutral density and narrow-band inter-fERENCE filters (Oriel, Stratford, CT) controlled stimulus energy and wavelength. Energies were measured with a calibrated radiometer (UDT Instruments, Baltimore, MD). Except where noted, all stimuli were full-field and spectrally unfiltered.

11. The probability of obtaining such light responses was very high among back-filled cells in very sparsely labeled retinas but declined substantially when labeled ganglion cells were isolated > 100, presumably because of involvement of the chiasm reduced labeling specificity. Peak depolarizations for saturating stimuli typically ranged from 15 to 30 mV.

12. Cobalt chloride was superfused at a concentration (2 mM in Ames) that blocks all light-evoked transmitter release from rods and cones in rat retina (36) and eliminates the otherwise robust light responses of ganglion cells in rat and cat eye cup preparations (37). Small chamber volume (<200 µl) and inlet tubing dead space (<2 ml) ensured complete exchange in minutes. Light responses also persisted when 2 mM Ca\(^{2+}\), replaced 2 mM Ca\(^{2+}\), in a bath solution containing 126 mM NaCl, 3 mM KCl, 1.3 mM NaH\(_2\)PO\(_4\), 2 mM MgSO\(_4\), 26 mM NaHCO\(_3\), and 10 mM dextrose (\(n = 2\)).

13. In darkness, resting potentials of photosensitive (~46.7 ± 14.8 mV; \(n = 114\)) and control ganglion cells (~48.5 ± 11.0 mV; \(n = 45\)) were statistically indistinguishable (P = 0.2; t test).

14. For micropipettes (\(n = 4\); including that shown in Fig. 1C), the drug solution consisted of 2 mM CoCl\(_2\), 100 µM M 4; including that shown in Fig. 1C), the drug solution consisted of 2 mM CoCl\(_2\), 100 µM M

15. Sensitivity usually deteriorated noticeably within 30 to 120 min of break-in, probably because of cell dialysis. The group data in Fig. 2C (accumulated peak action, and diaminobenzidine histochemistry were as described (35).


31. Receptive fields were probed with spots or bars generated by placing an aperture in the microscope’s spectrally unfiltered transilluminating tungsten beam and focusing it on the tissue with a >20 objective lens. There was substantial spatial summation within the receptive field, but no surrounding antagonism, an otherwise ubiquitous feature of ganglion cell receptive fields.

42. We thank B. Wooten for assistance with the spectral analysis; M. Seibert for help with the receptive field study; T. Nguyen for technical assistance; and H. Wässle, B. O’Brien, J. McIlwain, I. Provencio, M. Slaughter, and L. Peichl for their valuable comments on the manuscript. Supported by NIH grant EV12793 to D.M.B.

Metabolic Enzymes of Mycobacteria Linked to Antioxidant Defense by a Thioredoxin-Like Protein

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Mycobacterium tuberculosis (Mt) mounts a stubborn defense against oxidative and nitrosative components of the immune response. Dihydrolipoamide dehydrogenase (Lpd) and dihydrolipoamide succinyltransferase (SucB) are components of α-ketoadid dehydrogenase complexes that are essential for photoreceptors and OFF bipolar cells and between all bipolar cells and both amacrine and ganglion cells, and 50 µM picrotin and 0.3 µM strychnine to block ionotropic gamma-aminobutyric acid (GABA) and glycine receptors mediating most inhibition by amacrine cells. In two other cells, this cocktail was supplemented with 200 µM hexamethonium bromide to block nicotinic acetylcholine receptor and either 500 or 2000 µM 1-octanol to block gap junctions; light-evoked depolarizations were not attenuated. Blockade typically enhanced depolarization (e.g., Fig. 1, F and G; mean depolarization = 18.5 mV in control medium and 26.7 mV during blockade; \(n = 7\)) in all cases. As expected, mem- brane resistance due to loss of synaptic currents or of intrinsic calcium conductances. Resting potential was not significantly altered by synaptic blockade (membrane resistance decrease = 59.2 ± 0.6 µs in Ames and 51.5 mV during blockade; \(n = 7\)).

15. Sensitivity usually deteriorated noticeably within 30 to 120 min of break-in, probably because of cell dialysis. The group data in Fig. 2C (accumulated peak action, and diaminobenzidine histochemistry were as described (35).


31. Receptive fields were probed with spots or bars generated by placing an aperture in the microscope’s spectrally unfiltered transilluminating tungsten beam and focusing it on the tissue with a >20 objective lens. There was substantial spatial summation within the receptive field, but no surrounding antagonism, an otherwise ubiquitous feature of ganglion cell receptive fields.

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Mtb peroxiredoxin alkyl hydroperoxide reductase (AhpC) is linked to Lpd and SucB by an adaptor protein, AhpD. The 2.0 angstrom AhpD crystal structure reveals a thioredoxin-like active site that is responsive to lipoamide. We propose that Lpd and SucB (the only lipoic protein detected in Mtb), AhpD, and AhpC together constitute a nicotinamide adenine dinucleotide (reduced)–dependent peroxidase and peroxynitrite reductase. AhpD thus represents a class of thioredoxin-like molecules that enables an antioxidant defense.

Mtb peroxiredoxin alkyl hydroperoxide reductase (AhpC), a member of the peroxiredoxin family of nonheme peroxidases, protects hetero- logous bacterial and human cells against oxidative and nitrosative injury (3, 4). The redundancy of peroxiredoxins in Mtb complicates interpretation of the phenotype of an ahpC-deficient mutant (5). AhpC metabolizes perox- ides (6) and peroxynitrite (7) via a conserved
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