ATP-Induced Photoreceptor Death in a Feline Model of Retinal Degeneration

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PURPOSE. To develop and characterize a feline model of retinal degeneration induced by intravitreal injection of adenosine triphosphate (ATP).

METHODS. Nineteen normally sighted adult cats received 100 μL intravitreal injections of ATP with a final concentration of 11, 22, or 55 mM at the retina. Four animals were euthanized 30 hours after injection and retinal sections examined for apoptosis using a TUNEL cell death assay. In the remaining animals, structural and functional changes were characterized over a 3-month period using a combination of electroretinography (ERG) and optical coherence tomography (OCT).

RESULTS. Using a TUNEL cell death assay, we detected widespread photoreceptor death 30 hours after injection with 55 mM intravitreal ATP. All concentrations of ATP caused loss of retinal function and gross changes in retinal structure within 2 weeks of injection. Intravitreal injection of ATP led to a rapid loss of rod photoreceptor function and a gradual loss of cone photoreceptor function within 3 months. Outer nuclear layer thickness was globally reduced by 3 months, with the inner nuclear layer including the retinal nerve fiber layer remaining intact. Structural abnormalities were observed, including focal retinal detachment with evidence of both intravitreal and intraretinal inflammation in some eyes.

CONCLUSIONS. Development of an ATP-induced feline model of retinal degeneration provides a rapid and effective large-eyed animal model for research into vision restoration.

Keywords: retinitis pigmentosa, animal model, feline, photoreceptor, ATP-induced retinal degeneration

Photoreceptor death accounts for more than 50% of cases of blindness, contributing to the disease progression of inherited retinal degenerations such as retinitis pigmentosa (RP)⁵ and age-related macular degeneration. Although the underlying cause or causes of photoreceptor death vary in these conditions, they are characterized by progressive loss of photoreceptors with functional and structural changes occurring at later stages in the inner retina.²⁻⁶ Over recent years there have been significant advances in the development of visual restorative therapies, including photoreceptor transplantation, gene therapy, optogenetic approaches, and electronic implantable devices.⁷⁻¹⁰ Animal models are an essential part of this research, as they allow for proof of principle and the testing of safety and efficacy for new technologies, such as visual prostheses.¹¹,¹²

Development of restorative strategies benefits from the use of animal models that mimic the anatomical size and structure of a human eye.¹¹ Many such animal species develop inherited retinal degenerations, including Abyssinian cats,¹³,¹⁴ Briard dogs,¹⁵,¹⁶ and Irish setters.¹⁷ In addition, transgenic pigs and rabbits have been developed.¹⁸⁻²⁰ Studies using these animals are limited by availability, high cost, and often a slow rate of photoreceptor loss. Pharmacologic methods of retinal degeneration such as sodium iodate,²¹ N-methyl-N-nitrosourea (MNU),²² and adenosine triphosphate (ATP) may provide an alternative approach, as they tend to have a faster time course and are cheaper than comparable transgenic models. To this end we decided to pursue the development of an ATP-induced model of photoreceptor degeneration in cat via intravitreal injection, as this would allow us to selectively reduce vision in one eye of the animal without any systemic side effects.

Adenosine triphosphate is ubiquitous within the body and acts as an intracellular energy transport molecule. In the central and peripheral nervous system, extracellular ATP also acts as a neurotransmitter.²⁵ Adenosine triphosphate activates two classes of purinergic receptors known as the P2X (ligand-gated cationic channel) and P2Y (G protein-coupled receptors) receptor types. Very large concentrations of extracellular ATP can lead to cell death within central nervous system neurons via the action of the purinergic receptor P2X₇.²⁶,²⁷ While the exact mechanism of cell death is still not completely understood, it is possible that chronic activation of the P2X₇-receptor causes a rapid influx of calcium ions into the cell, triggering apoptosis.²₃,²₆,²₈ P2X₇ receptors are present both pre- and postsynaptically in both the inner and outer plexiform...
layers of the retina, and the addition of high doses of extracellular ATP beyond physiological limits leads to photoreceptor death. Other retinal neurons appear to be resistant to ATP-induced cell death except at very high concentrations, possibly due to a neuroprotective effect from the adenosine receptor A3.

Although the time course and characteristics of ATP-induced degeneration have been well described in rats, it has never been tested in larger animal models. To this end the aim of this study was to characterize the effects of intravitreal injection of ATP in a feline model over a 3-month period. We chose a feline model because the eye is similar in size to that of humans; the retina and visual cortex are well described, and cats are the most commonly used large-eyed animal model in visual prosthetic research. While others have explored subretinal injections of ATP, we chose to use intravitreal injections as they provided a more practical delivery method in the feline.

**Materials and Methods**

**Anesthesia and Intracocular Injection of ATP in Cat**

Normally sighted adult laboratory cats (n = 19) were utilized in this study. Treatment of animals complied with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research, the National Health and Medical Research Council’s Australian Code of Practice for the Care and Use of Animals for Scientific Purposes (2013), and the Prevention of Cruelty to Animals Act (1986) and amendments. All studies were approved by the Royal Victorian Eye and Ear Hospital Animal Ethics Committee (RVEEH AEC; no. 10/200AB, no. 12/256AB).

Intravitreal injection of ATP was performed under anesthesia using a combination of ketamine (Ilum Ketamil, 20 mg/kg; Troy Laboratories, Sydney, NSW, Australia) and xylazine (Ilum Xylazil-20, 2 mg/kg; Troy Laboratories) injected subcutaneously. In order to maintain normal intraocular pressure, an anterior chamber paracentesis was performed using a 30-gauge needle and approximately 50 μL aqueous humor tapped from the anterior chamber. A solution containing 100 μL 0.2, 0.4, or 1 M adenosine triphosphate hydrate (Sigma Pharmaceuticals, Munich, VIC, Australia) and 0.2 mg dexamethasone to control intravitreal inflammation (Dexamethsone, 4 mg/mL; Aspen Australia, NSW, Sydney, Australia) was given following the injection. ATP, 35 we chose to use intravitreal injections as they provided a more practical method in the feline.

**Clinical Assessments**

Retinal function and structure in 15 of the ATP-injected animals were assessed 2, 6, and 12 weeks post ATP injection. Animals were anesthetized with a subcutaneous dose of ketamine (20 mg/kg) and xylazine (2 mg/kg). Depth of anesthesia was monitored via corneal reflex and respiratory rate; if the anesthesia became too light during assessment, animals were injected with a further one-third standard dose of ketamine and xylazine. During assessment the cornea was kept hydrated using topical application of a sterile saline solution (0.9%). Pupils were dilated with 1% tropicamide (Chauvin Pharmaceuticals, Surrey, England) and 2.5% phenylephrine hydrochloride (Chauvin Pharmaceuticals). With the exception of the terminal time point, subjects were rehydrated with Hartmann’s solution (2.5 mL/kg/h, subcutaneous) at the end of the assessment and allowed to recover. All assessment methodologies performed in these animals have been previously described in normally sighted cats and other animal models of photoreceptor degeneration.

**Electroretinogram**

Retinal function was assessed using a full-field flash ERG (Espion; Diagnosys LLC, Lowell, MA, USA) after 30 minutes of dark adaptation. Both the ATP-injected and the fellow control eyes were recorded simultaneously using corneal jet electrodes. In each animal the retinal response to stimulus intensities from 0.001 to 10 cd/s/m² was recorded. However, only the combined rod–cone maximal ERG response (10 cd/s/m²) is reported here. In 11 mM-injected animals, a twin-flash paradigm consisting of two consecutive flashes (10 cd/s/m², 500-ms interstimulus interval) was used to assess rod and cone responses independently. The first flash elicited a mixed response from both rod and cone pathways, while the second flash elicited responses only from the cone pathway. Rod and cone pathway a-wave amplitudes corresponding to photoreceptor and some postreceptor responses were measured from the prestimulus baseline to the a-wave trough. The b-wave amplitudes corresponding to the postreceptor response were measured from the a-wave trough to the b-wave peak. Implicit times were measured from the time of the flash presentation to the maximal amplitude of a-wave and b-wave responses.

**Optical Coherence Tomography Acquisition and Analysis**

Retinal structure was analyzed in ATP-injected and fellow control eyes using Fourier domain optical coherence tomography (OCT) (Spectralis HRA+OCT; Heidelberg Engineering GmbH, Heidelberg, Germany). In order to assess retinal structures, high-resolution line scans were taken at each time point across the temporal retina, area centralis, and nasal retina. In order to assess thickness of the retinal nerve fiber layer, a high-resolution circular scan was taken around the optic nerve. Each scan was a composite image average from 100 frames. Figures 1A and 1B show representative infrared reflectance images of the fundus displaying length and location of scans.
performed in each eye. Figures 1C and 1D show representative OCT b-scan images taken from a temporal (Fig. 1C) and circular (Fig. 1D) scan. Images were exported as tagged image files (.TIF), and retinal thicknesses were measured using custom software in ImageJ (version 1.48, http://imagej.nih.gov/ij/; provided in the public domain by the National Institutes of Health, Bethesda, MD, USA). Line scan images were separated into three distinct thickness measurements as shown in Figure 1C, defined as total retina (inner limiting membrane to border of retinal pigment epithelium [RPE] and tapetum lucidum), inner retina (inner limiting membrane to outer plexiform layer), and outer retina (outer plexiform layer to border of RPE and tapetum). Circular scan thicknesses were separated as shown in Figure 1D into total retina, retinal nerve fiber layer (RNFL, inner limiting membrane to edge of ganglion cell layer), and ganglion cell layer plus all subsequent retinal layers (GCL+; ganglion cell layer to Bruch’s membrane).

**Tissue Collection and Fixation**

At 30 hours after intravitreal injection with ATP, animals (N = 4) were deeply anesthetized using ketamine (20 mg/kg) and xylazine (2 mg/kg) and then euthanized with an overdose of sodium pentobarbital (150 mg/kg, intracardiac). The eyes were enucleated and tissue anterior to the ciliary body was dissected away. The remaining tissue was fixed in 4% paraformaldehyde for 30 minutes. After this period, the tissue was washed in phosphate-buffered solution (PBS), dissected, and then equilibrated in graded solutions of sucrose (10%, 20% [wt/vol] in PBS) for at least 30 minutes each and finally placed in 30% sucrose overnight. Control and ATP-treated tissues were embedded in optimal cutting temperature compound (Tissue-Tek; Sakura, Torrance, CA, USA), frozen, and cut at 12 μM on a cryostat (Microm, Walldorf, Germany). Sections were collected on Poly-L-lysine-coated slides (Menzel-Glaser, Braunschweig, Germany) and stored at −20°C until use.

**Cell Death Assay**

Cell death was measured using a commercially available fluorometric terminal dUTP nick-end labeling (TUNEL) kit (DeadEnd Fluoro metric TUNEL system, TB235; Promega, Madison, WI, USA) according to a method identical to that in a previous study of ATP-induced degeneration in rat.23 Using a cryostat, 12-μM sections of retina were taken both near the area centrals (~3 optic disc diameters temporal to the optic nerve) and in the peripheral temporal retina. Sections were washed twice for 5 minutes in 0.9% PBS before being digested with 0.5% Triton X-100 in PBS for 5 minutes. Sections were then washed in PBS three more times for 5 minutes and equilibrated using equilibration buffer (200 mM potassium cacodylate, pH 6.6; 25 mM Tris-HCl; 0.2 mM dithiothreitol; 0.35 mg/mL bovine serum albumin [BSA]; 2.5 mM cobalt chloride) for 10 minutes. A reaction mix (equilibration buffer, 50 μM fluorescence-12-dUTP, 100 μM deoxyadenosine triphosphate, 10 mM Tris-HCl, 1 mM EDTA, terminal deoxynucleotidyld transferase, recombinant enzyme) was applied to the sections for 1 hour at 37°C in darkness. This reaction was stopped using an SSC buffer (0.3 M sodium chloride, 0.15 M sodium citrate, pH 7.2), and the sections were rinsed with PBS an additional three times for 5 minutes. Sections were covIPPed with a Mowiol-based antifade mounting medium (Polysciences, Inc., Warrington, PA, USA) and photomicrographs taken on a laser scanning confocal microscope (Carl Zeiss, Göttingen, Germany) with air objectives at ×20 and ×10 magnification. Apoptotic cells were quantified manually using a cell counter application (ImageJ, version 1.48; National Institutes of Health) with five regions per section at 1-mm length each.

**Statistical Analysis**

Analyses were performed on TUNEL cell counts, ERG responses, and OCT thickness data in eyes injected with ATP.
Adenosine triphosphate induces photoreceptor death at 30 hours in cat retina. Sections of retinae labeled for apoptosis (TUNEL) are shown - and ATP-injected eyes (one-way ANOVA; \( P < 0.01 \); \( n = 4 \)). The total number of TUNEL-positive nuclei in ATP-injected eyes did not vary significantly with location (one-way ANOVA; \( P > 0.05 \); \( n = 4 \)). A similar proportion of ONL nuclei were TUNEL labeled in both central and peripheral retina (\( P > 0.05 \)). Very few TUNEL-positive cells were present in other layers in ATP-treated eyes (average 0.24 TUNEL-positive cells per mm retina, or less than 0.01% of inner retinal cells) and none in PBS-injected eyes. These data confirm that high concentrations of intravitreal ATP lead to widespread photoreceptor-specific cell death within 30 hours of injection in cat.

To investigate the optimal concentration of ATP that induced photoreceptor degeneration reliably in the cat, we injected a total of 15 animals with intravitreal ATP at concentrations of 11, 22, or 55 mM at the retina and performed PBS sham injection in the contralateral eye. Retinal structure and function were assessed using temporal OCT scans and dark-adapted ERG 2 weeks following injection. Figure 3A shows representative ERG response waveforms 2 weeks after injection with ATP or in control eyes. Representative waveforms are not shown for the PBS condition as they were identical to the control waveforms. As shown in Figure 3B, ATP caused a significant loss of photoreceptor function irrespective of the concentration injected (Kruskal-Wallis; \( P < 0.05 \); \( n = 3 \) for 22 mM-injected eyes; 4 for 11 mM-, 55 mM-, and sham-injected eyes; 8 for control eyes). The amplitudes of the b-wave were similarly affected (Fig. 3C; Kruskal-Wallis; \( P < 0.05 \); \( n = 3-8 \)). Representative extracted OP waveforms are shown in Figure 3D. Summed OP amplitudes did not differ between control and PBS sham conditions (\( P > 0.05 \)) but were significantly reduced at all ATP dosages compared to the control (Fig. 3D; \( P < 0.05 \)).

Figure 4 shows representative OCT images and a quantification of total retinal thickness across the temporal retina following injection with either ATP or PBS. Injection of 55 mM ATP induced significant reduction of total retinal thickness compared to controls and 11 mM ATP-injected eyes (Fig. 4E; Kruskal-Wallis; \( P < 0.05 \); \( n = 3 \) for 22 mM-injected eyes; 4 for 55 mM-injected eyes; 8 for control, sham-, and 11 mM-injected eyes). All other concentrations were not significantly different from controls (\( P > 0.05 \)). We evaluated retinal integrity in all animals, and observed a number of retinal detachments (white arrows in Fig. 4). Detachments resolved in cats injected with 11 mM ATP but worsened over time in cats injected with 22 and 55 mM ATP. Therefore, the 11 mM ATP concentration was selected as the ideal dose for subsequent chronic experiments. As no differences in function or structure were observed between control and PBS eyes, the two groups were combined in all subsequent experiments.

**Results**

**Intravitreal Injection of ATP Causes Photoreceptor Degeneration in Cat**

To determine whether intravitreal injection of ATP led to acute and specific photoreceptor degeneration in the cat as it does in the rat,\(^{23,24}\) we injected 55 mM ATP into the vitreous of four cat eyes and assessed the level of cell death 30 hours later using a TUNEL assay. Figure 2 shows vertical sections of retinae from PBS-injected central retina (Fig. 2A) and ATP-injected central (Fig. 2B) and peripheral (Fig. 2C) retina that were labeled for TUNEL. In order to determine whether the extent of cell death varied between ATP- and PBS-injected eyes, TUNEL-positive nuclei were quantified per millimeter of retinal section (Fig. 2D) and as a proportion of total outer nuclear layer (ONL) nuclei per mm\(^2\) (Fig. 2E). There was a significant difference between saline (0.01 cells/mm, data not shown) and ATP-injected eyes (one-way ANOVA; \( P < 0.01 \); \( n = 4 \)). The total number of TUNEL-positive nuclei in ATP-injected eyes did not vary significantly with location (one-way ANOVA; \( P > 0.05 \); \( n = 4 \)). A similar proportion of ONL nuclei were TUNEL labeled in both central and peripheral retina (\( P > 0.05 \)). Very few TUNEL-positive cells were present in other layers in ATP-treated eyes (average 0.24 TUNEL-positive cells per mm retina, or less than 0.01% of inner retinal cells) and none in PBS-injected eyes. These data confirm that high concentrations of intravitreal ATP lead to widespread photoreceptor-specific cell death within 30 hours of injection in cat.

ATP Induces Rapid Loss of Rod and Progressive Loss of Cone Function

The time course of rod and cone degeneration in cats injected with 11 mM ATP was examined using a twin flash ERG at
baseline and 2, 6, and 12 weeks after injection. Representative waveforms of rod isolated responses at various time points post ATP injection are shown in Figure 5A. Rod a-wave amplitude (Fig. 5B) was significantly reduced by 2 weeks post injection (one-way ANOVA; \( P < 0.05; n = 8 \) for 11 mM-injected eyes; 13 for control eyes). Although there was a trend of continued rod a-wave loss toward 12 weeks, the difference between ATP-injected time points was not statistically significant. Rod b-wave amplitudes (Fig. 5C) were similarly reduced by 2 weeks following injection (\( P < 0.05 \)). Representative oscillatory potentials of cone responses are shown in Figure 5D. Cone a-wave amplitude (Fig. 5E) showed a different rate of degeneration, with significant loss from baseline occurring only at the 12-week time point (\( P < 0.05 \)). Cone b-wave amplitudes (Fig. 5F) were significantly reduced by 6 weeks (\( P < 0.05 \)).

In the early stages of RP, OP amplitudes appear to be reduced at a comparatively slower rate than a-wave amplitudes.17 In order to explore this relationship in our model, OPs were analyzed separately (Fig. 6). Figure 6A shows representative OP response waveforms. Figure 6B shows summed OP amplitudes at each time point. Oscillatory potentials were significantly reduced from 2 weeks post injection (one-way ANOVA; \( P < 0.05; n = 8–13 \)). In order to evaluate whether ATP affected the OPs to a greater extent than the a-wave, we correlated the amplitude of the mixed a-wave with the amplitudes of the summed OPs and mixed b-wave. As shown in Figure 6C, the amplitude of the a-wave correlates with the amplitude of the OPs in controls (Deming regression; \( P < 0.01; n = 8–13 \)). However, 2 weeks after ATP injection, the slope of the correlation is altered (Deming regression; \( P < 0.05; n = 8–13 \)), suggesting that the OP amplitudes had decreased by a greater margin than a-wave amplitudes. Specifically, OPs were reduced even in animals in which the a-wave remained relatively intact. Figure 6D shows the correlation between the mixed a-wave and b-wave amplitudes. Amplitudes were significantly correlated at baseline and 2 weeks following ATP injection (Deming regression; \( P < 0.05; n = 8–13 \)), and the slopes of the curves were no different (Deming regression; \( P > 0.05; n = 8–13 \)), suggesting that any loss of the b-wave amplitude can be explained by losses in the a-wave.

**ATP-Induced Degeneration Reduces Outer Retinal Thickness and Leaves Inner Retina Intact**

In view of the loss of the a-wave following ATP injection, the extent and nature of structural changes within the retina following ATP injection were examined. Figure 7 shows representative OCT images from regions within the temporal retina (Fig. 7A), area centralis (Fig. 7B), nasal retina (Fig. 7C), and optic nerve head (Fig. 7D) that were imaged at different times following injection. A thinned and inconsistent ONL was clearly visible 12 weeks after injection in all retinal areas. The retina was also visibly thicker at 2 weeks when compared to the control. Optical coherence tomography images revealed multiple localized retinal detachments at all time points (white arrows), many of which settled over the course of the 12 weeks. Hyperreflective vitreous opacities (white asterisks), presumably corresponding to inflammatory cells in the vitreous, were occasionally seen at early time points but were not visible at 12 weeks.

In order to assess changes in retinal thickness following ATP injection, we analyzed the thickness of total, inner, and outer retinal components separately. Figure 8 shows thickness of the retina at different retinal eccentricities at each time point in temporal and optic nerve scans. The area centralis and nasal scan both showed similar thickness variation to the temporal scan. The temporal retina showed a reduction in total retinal thickness at 12 weeks after injection with ATP (Fig. 8A). Figures 8B and 8C show the inner (Fig. 8B) and outer (Fig. 8C) retinal thickness by eccentricity. The inner retina appeared to be thicker 2 and 6 weeks after ATP injection. In contrast, the outer retina is progressively thinner with increasing time after injection. There were no major variations in thickness across eccentricity. Using a circular scan to analyze the retina close to the optic nerve (Fig. 8D) revealed a pattern in thickness similar to that in other retinal areas, with a reduction at 12 weeks post injection. Analysis of the RNFL (Fig. 8E) showed an altered profile in ATP-injected animals but the conservation of average...
Adenosine triphosphate induces dose-dependent retinal thinning and detachment at 2 weeks. Representative temporal linear OCT sections in a control eye (A) and 2 weeks after injection with 11 mM (B), 22 mM (C), and 55 mM (D) ATP. Total retinal thickness was assessed in control, sham-injected, and ATP-injected eyes at each concentration (E). White arrows (B, C) indicate retinal detachments. The retinal thickness in eyes injected with 55 mM ATP was significantly reduced compared to control, sham-injected, and 11 mM-injected eyes (Kruskal-Wallis; \( P < 0.05; \ n = 3–8 \)). There were no other significant differences (Kruskal-Wallis; \( P > 0.05; \ n = 3–8 \)). Scale bar: 100 \( \mu m \). Asterisks indicate significant difference \( P < 0.05 \).

Figure 4. Adenosine triphosphate induces dose-dependent retinal thinning and detachment at 2 weeks. Representative temporal linear OCT sections in a control eye (A) and 2 weeks after injection with 11 mM (B), 22 mM (C), and 55 mM (D) ATP. Total retinal thickness was assessed in control, sham-injected, and ATP-injected eyes at each concentration (E). White arrows (B, C) indicate retinal detachments. The retinal thickness in eyes injected with 55 mM ATP was significantly reduced compared to control, sham-injected, and 11 mM-injected eyes (Kruskal-Wallis; \( P < 0.05; \ n = 3–8 \)). Scale bar: 100 \( \mu m \). Asterisks indicate significant difference \( P < 0.05 \).

**DISCUSSION**

The major findings of this study were that intravitreal injection of ATP in a feline model leads to rapid photoreceptor death, similar to the effects described previously in the rat.\(^{23,24}\) In particular, our results show that ATP induces rapid loss of rods prior to cones, and that neurons of the inner retina remain relatively intact. These results suggest that ATP injection may be useful in creating a feline model of retinal degeneration.

**ATP Causes Photoreceptor Degeneration in Cat**

Although ATP has been shown to cause photoreceptor degeneration in rat,\(^{25,24}\) there have been no previous studies to determine the viability of this model in an animal with an eye size comparable to that of the human eye. We found significant cell death within the ONL of the retina within 30 hours of injection of ATP into the cat vitreous. Widespread photoreceptor death accounts for our observation of functional and structural degeneration continuing out to 12 weeks in ATP-injected eyes. Although the mechanism of ATP-induced photoreceptor loss is not well understood, it is possible that direct toxicity via overactivation of P2X-receptors, which are known to be expressed by photoreceptors, explains the observations.\(^{23,29,46,49}\) Alternatively, ATP-induced effects on the RPE could also induce secondary effects on photoreceptor integrity.\(^{50,51}\)

Specific to the cat was rapid loss of rod-mediated function, followed by a gradual loss of cone-mediated function over a 12-week period. Previous characterization of the effects of ATP on rodent photoreceptor integrity showed rapid loss of both rod- and cone-mediated function.\(^{24}\) It is possible that the distribution of purinergic receptors, and thus the underlying mechanism of vulnerability in rods and cones, is different in cat retina compared to the rat. As ATP is rapidly broken down within the eye by ecto-nucleoside-triphosphate-diphosphohydrolases (E-NTPDases)\(^{52}\) it is likely that continued cone loss after the initial insult is a secondary effect instigated by widespread rod loss, as is commonly seen in both human and animal inherited retinal degenerations.\(^{53,54}\) A loss of rod function before cone function in our model is ideal as it loosely mimics the course of human RP.\(^{55,56}\)

In RP, there is a relationship between ONL thickness and residual ERG amplitude.\(^{57}\) Our model also showed a thinning of the ONL by 12 weeks post injection, but this rate of loss did not correlate closely to the loss of the ERG. It is possible that the rapid rate of degeneration in our model overwhelms the retina’s ability to remove dead and dying cells from the ONL and leads to a buildup of nonfunctional detritus in this layer. Additionally, as OCT gives only a gross representation of each layer and does not account for cell type, our quantification of the ONL may include a larger proportion of inflammatory cells that have invaded the retina in response to ATP-induced degeneration.

**ATP-Induced Inner Retinal Changes in Cat**

Although high levels of extracellular ATP primarily affected photoreceptor integrity in the cat retina, some changes in the inner retina were noted. In particular, 2 weeks following injection with 11 mM ATP, there was a reduction in the amplitude of the OPs even in animals with otherwise relatively intact a-wave
amplitudes. This runs contrary to previous findings in human patients with RP, which showed a relative survival of the OP amplitudes.47 The OPs are thought to primarily represent the function of inner retinal neurons, especially amacrine cells.40 Oscillatory potential amplitude is particularly sensitive to ischemia in even small areas of the retina,58 and loss of OPs is evident in all forms of retinal detachment even after resolution of the condition.59–61 With this in mind, it is possible that the loss of OP amplitudes observed in our model could be attributed to the localized retinal detachments we observed in many of the ATP-injected eyes. Alternatively, changes in OP amplitudes may be indicative of a direct effect of ATP on inner retinal neurons, or as a result of the inner retinal swelling we observed in animals 2 weeks after injection.

Thickness of the inner retina was significantly increased 6 weeks after injection with 11 mM ATP, but was restored by 12 weeks. This resembles inner retinal swelling as previously observed from OCT in human retinal degenerations.62–64 We propose that increased thickness represents intraretinal edema in response to ongoing degeneration. This could explain the

**FIGURE 5.** Rod and cone function is reduced within 12 weeks after injection with 11 mM ATP. Twin-flash full-field ERGs (10 cd s/m²) were used to isolate rod and cone function in control eyes and at 2, 6, and 12 weeks after injection with 11 mM ATP. (A) Representative waveforms of the isolated rod response in a control and at three time points post ATP injection. Rod a-wave (B) and b-wave (C) amplitudes were assessed at each time point. (D) Representative waveforms of the cone response in a control and at three time points post ATP injection. Cone a-wave (E) and b-wave (F) amplitudes were assessed at each time point. Rod a-wave and b-wave amplitudes were significantly reduced by 2 weeks (one-way ANOVA; \( P < 0.05; n = 8–13 \)). Cone a-wave and b-wave amplitudes were significantly reduced by 12 weeks and 6 weeks, respectively (one-way ANOVA; \( P < 0.05; n = 8–13 \)). Asterisks indicate significant difference \( P < 0.05 \).

**FIGURE 6.** Oscillatory potential amplitude reduction may indicate some inner retinal degeneration. Oscillatory potential amplitudes were digitally subtracted from mixed b-wave output and analyzed separately. (A) Representative OP waveforms in a control eye and at 2, 6, and 12 weeks after injection with 11 mM ATP. Summed OP1 through OP4 amplitudes were assessed at each time point. Mixed a-wave amplitude was correlated to summed OP amplitude (C) and mixed b-wave amplitude (D) in control eyes and at 2 weeks after injection with 11 mM ATP. Summed OP amplitude had significantly decreased by 2 weeks (one-way ANOVA; \( P < 0.05; n = 8–13 \)). The amplitude of the mixed a-wave is correlated with the amplitude of both summed OP amplitude and mixed b-wave amplitude (Deming regression; \( P < 0.01; n = 8–13 \)). Two weeks after ATP injection, the slope of the summed OP and a-wave correlation was significantly different compared to controls (Deming regression; \( P < 0.05; n = 8–13 \)), indicating a greater decrease in OP amplitude compared to loss of the a-wave. The slope of the b-wave and a-wave correlation was not significantly different at 2 weeks after ATP injection (Deming regression; \( P > 0.05; n = 8–13 \)). Asterisks indicate significant difference \( P < 0.05 \).
greater increase in thickness across the area centralis in our model; continued cone degeneration would be the primary contributor to intraretinal edema at 6- and 12-week time points, and the area centralis has the highest cone density in the cat retina.\textsuperscript{65} It seems probable that retinal swelling would not be confined solely to the inner retina in this case, but loss of the ONL would mask the increase in thickness from intraretinal edema in the outer retina when examined by OCT.

Significantly, our results show that the nerve fiber layer remained intact, suggesting that even though photoreceptors and perhaps some minor changes in the inner retina were observed, ganglion cells and their axons remain intact. This is important if this model is to be used in the future for evaluating the success of vision restoration strategies such as retinal prostheses, which require functional ganglion cells.

**ATP Injection as a Model of Retinal Degeneration**

The ATP-induced model of photoreceptor death in the feline model is potentially suitable for use as an animal model of retinal degeneration. In the cat, ATP induces a loss of outer retinal structure and function within 12 weeks while leaving the inner retina relatively intact. Although ATP is not a primary cause of photoreceptor loss in those with inherited retinal degenerations, it has been proposed to exacerbate photoreceptor loss.\textsuperscript{28,49} Moreover, remodeling of the inner retina after photoreceptor degeneration is thought to occur regardless of the initial underlying mechanism.\textsuperscript{3,5,66,67}

The feline ATP-induced model of retinal degeneration has several key advantages over transgenic larger-eyed animal models of degeneration traditionally used in vision research.\textsuperscript{11,68} Logistically, these transgenic animal models tend...
A Feline Model of Retinal Degeneration

FIGURE 9. Reduction of OCT retinal thickness is confined to the outer retina. (A–C) Analysis of total, outer, and inner retinal thicknesses in controls and at 2, 6, and 12 weeks post injection across the temporal retina (A), area centrals (B), and nasal retina (C). (D) Analysis of total retinal thickness, retinal nerve fiber layer thickness, and thickness of the retina excluding the RNFL in controls at 2, 6, and 12 weeks post injection around the optic nerve. Across the temporal retina, area centrals, and nasal retina, total and outer retinal thickness was significantly reduced by 12 weeks (Kruskal-Wallis; \( P < 0.05; n = 8 \)). At temporal and nasal locations, inner retinal thickness was significantly increased by 6 weeks (Kruskal-Wallis; \( P < 0.05; n = 6–8 \)). By 12 weeks, inner retinal thickness was no longer different compared to controls (Kruskal-Wallis; \( P > 0.05; n = 6–8 \)). Across the area centrals, inner retinal thickness remained significantly increased from 2 to 12 weeks compared to controls (Kruskal-Wallis; \( P < 0.05; n = 8 \)). Across the optic nerve, total thickness and thickness from the ganglion cell layer were significantly decreased at 12 weeks compared to controls (Kruskal-Wallis; \( P < 0.05; n = 8 \)). Retinal nerve fiber layer thickness was not significantly different from controls at any time point (Kruskal-Wallis; \( P > 0.05; n = 6–8 \)). Asterisks indicate significant difference \( P < 0.05 \).

to be prohibitively expensive to develop and maintain. Often the rate of disease progression is quite slow—for example, the Abyssinian cat model of retinal degeneration still has significant residual ERG at 3 to 4 years of age.\(^6\) A faster model of degeneration does exist in Persian cats,\(^7\) but photoreceptors do not have time to fully develop in this model before the onset of degeneration. Our pharmacologic model of degeneration therefore has the advantage of being comparatively cheap, fast-acting, and readily accessible compared to these other models. Furthermore, unilateral injection of ATP allows for normal sight in the fellow eye, which can then act as an internal control and reduce housing and ethics considerations as the affected animal retains functional vision.

An ATP-induced model of feline degeneration, however, has several limitations. As a pharmacologic model of degeneration, the disease process does not model human disease as closely as models in which genetic manipulations induce photoreceptor death. In addition, we observed multiple focal retinal detachments in some cats within 2 weeks of intravitreal injection of ATP. Unfortunately, these retinal detachments tended to worsen at high concentrations at which the degenerative process was otherwise more reliable. These detachments were visually similar to those described in a recent study of OCT in RD10 mouse.\(^7\) It may be that the acute rate of degeneration in our model interferes with and overwhems fluid transfer at the RPE, leading to retinal elevation and eventually detachment. It is also possible that ATP has a direct effect on fluid transfer at the RPE.\(^5\)

In conclusion, this study aimed to develop and characterize an ATP-induced model of retinal degeneration in the cat retina. We examined retinal function and structure using a combination of ERG and OCT imaging to determine a dose response and time course of degeneration. All concentrations of ATP tested caused widespread photoreceptor death and loss of retinal function within 2 weeks of injection. In particular, intravitreal injection with 11 mM ATP led to a rapid loss of rod and a gradual loss of cone function over a 12-week period. Outer retinal thickness continued to reduce throughout the 12-week period. The inner retina showed some evidence of intraretinal swelling, but otherwise remained intact. This ATP-induced feline model of retinal degeneration provides a new animal model for research into vision restoration.

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References


