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AAV cis-regulatory sequences are correlated with ocular toxicity

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Adeno-associated viral vectors (AAVs) have become popular for gene therapy, given their many advantages, including their reduced inflammatory profile compared with that of other viruses. However, even in areas of immune privilege such as the eye, AAV vectors are capable of eliciting host-cell responses. To investigate the effects of such responses on several ocular cell types, we tested multiple AAV genome structures and capsid types using subretinal injections in mice. Assays of morphology, inflammation, and physiology were performed. Pathological effects on photoreceptors and the retinal pigment epithelium (RPE) were observed. Müller glia and microglia were activated, and the proinflammatory cytokines TNF-α and IL-1β were up-regulated. There was a strong correlation between cis-regulatory sequences and toxicity. AAVs with any one of three broadly active promoters, or an RPE-specific promoter, were toxic, while AAVs with four different photoreceptor-specific promoters were not toxic at the highest doses tested. There was little correlation between toxicity and transgene, capsid type, preparation method, or cellular contaminants within a preparation. The toxic effect was dose-dependent, with the RPE being more sensitive than photoreceptors. Our results suggest that ocular AAV toxicity is associated with certain AAV cis-regulatory sequences and/or their activity and that retinal damage occurs due to responses by the RPE and/or microglia. By applying multiple, sensitive assays of toxicity, AAV vectors can be designed so that they can be used safely at high dose, potentially providing greater therapeutic efficacy.

Significance

Adeno-associated viral (AAV) gene therapy is becoming an important therapeutic modality, especially for ocular diseases, due to its efficiency of gene delivery and relative lack of pathogenicity. However, AAV sometimes can cause inflammation and toxicity. We explored such effects using injections into the mouse eye. We found a strong correlation of toxicity and inflammation with the use of promoters that were broadly active, or specifically active in the retinal pigment epithelium. AAVs with photoreceptor-specific promoters were found to be nontoxic at all doses tested. These studies reveal that safer vectors can be designed if assays for relevant and specific cell types are developed and tested with a range of vectors with different genomic elements.


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Results

Photoreceptor Toxicity Is Correlated with Promoter Specificity. Serotype 8 AAV (AAV8) viruses expressing either GFP or no transgene ("null") under the control of different promoters were injected subretinally into neonatal mice (CD-1). Neonatal mice were used as we have been able to achieve complete infection of the RPE and retina using animals of this age (33). In addition, less tissue damage is induced, and/or is repaired, by injection at this early stage compared with the mature stage. The retinas and RPE were harvested for histological analysis at 30 d postinfection (or as indicated). The CMV promoter/enhancer sequence drives robust transgene expression in cone photoreceptors and the RPE, as well as other cell types (vector map shown in SI Appendix, Fig. S1) (33). AAV8-CMV-GFP induced photoreceptor toxicity and glial activation, indicated by cone OS shortening, ONL thinning, cone photoreceptor loss, and up-regulation of GFAP in retinal glial cells, the Müller glia (Fig. 1). In contrast, GFP expression driven by the photoreceptor-specific promoters, including RedO (28, 29), Rho (29, 30), RK (31), and CAR (29, 32), induced no retinal toxicity or glial activation (Fig. 1 and SI Appendix, Fig. S2). To determine if toxicity was due to protein expression, AAV8-CMV-null that did not express any transgene was tested. AAV8-CMV-null was just as toxic as AAV8-CMV-GFP (Fig. 1C and SI Appendix, Fig. S2).

RPE Toxicity Is Induced by AAV Vectors with Broadly Active Promoters and an RPE-Specific Promoter. Promoter-specific AAV toxicity also was observed in the RPE, which is efficiently transduced by subretinally delivered AAV. We developed a semiquantitative assay to measure the RPE toxicity level to compare among vectors. Whole RPE flatmounts were stained with phalloidin, which labels the f-actin borders of the hexagonal RPE array. These were imaged with a spinning-disk microscope and scored for the morphology, using a grading system with six grades that we devised. Grade 0 indicates completely normal RPE morphology and grade 5 indicates complete RPE loss (Fig. 2A). Four representative areas in the midperiphery of each flatmount were imaged and evaluated by four independent scorers who did not know the vector type/dose, with the average score for each flatmount shown in Fig. 2B. With this evaluation system, we found that the broadly active promoters, CMV, CAG, and UbIC, induced strong RPE toxicity, while none of the photoreceptor-specific promoters induced RPE toxicity (Fig. 2B and SI Appendix, Fig. S3). We also found that RPE damage is long-lasting and increases with time postinfection (SI Appendix, Fig. S4). The Best1 promoter was also tested for toxicity as it can drive strong expression in the RPE at a level comparable to that of CMV or CAG (27). Interestingly, AAV8 with Best1 promoter also induced RPE toxicity in the RPE (Fig. 2B and SI Appendix, Fig. S3). Table 1 shows a strong correlation between toxicity and the promoter used.

AAV Toxicity Was Not Found to Be Dependent on the Preparation Method. To determine if the preparation method contributed to AAV toxicity, several different AAV8 preparation and purification methods were tested by our laboratory. In addition, stocks of the same genomes and capsids were obtained from three different virus core facilities. In all cases, toxicity was observed. Furthermore, we examined toxic and nontoxic preparations on protein gels to examine the level of contamination by cellular proteins. We found that the level of cellular protein contaminants did not correlate with toxicity (SI Appendix, Fig. S5). Finally, endotoxin level in the plasmids for vector preps was unlikely to contribute to the toxicity as endotoxin-free plasmid prep kits were used. In addition, our test for endotoxin, and those of the core facilities, showed that endotoxin levels were very low in the preparations which were tested.

The Severity of Photoreceptor and RPE Toxicity Is Dependent upon the Dose of AAV. AAV vectors are injected subretinally at a wide range of doses (from 1E10 vg per eye to 1E12 vg per eye) in clinical trials (21, 22, 34, 35). To investigate whether AAV-induced toxicity is dose-dependent, we injected AAV8-CMV-GFP viruses at three doses (5E8, 1E9, and 2E9 vg per eye) into neonatal CD-1 mice. RPE toxicity was evaluated at 30 d postinfection. There was a clear
correlation between the severity of toxicity to the RPE and virus dose. A lower dose of 5E8 vg per eye induced RPE cell enlargement with some loss of RPE cells (approximately grade 3), while a higher dose of 2E9 vg per eye caused nearly complete RPE loss (approximately grade 5) (Fig. 3 A–C).

Photoreceptor toxicity was examined in preparations where the RPE and retina were kept together, so that neighboring RPE and photoreceptor cells could be inspected for local effects. Cone OS were stained by peanut agglutinin (PNA), which was used as a proxy for overall photoreceptor health. Severe photoreceptor toxicity was seen at the doses of 1E9 and 2E9 vg per eye such that cone OS were largely absent (Fig. 3 E and F). However, photoreceptors were less sensitive to AAV toxicity than RPE, as AAV8-CMV-GFP–infected RPE demonstrated clear abnormalities in morphology at the low dose (5E8 vg per eye), while neighboring cone OS were largely normal (Fig. 3 A and D). RPE and cone OS loss were usually found in the same area, which could have resulted from higher local infection or an amplifying effect between compromised RPE and photoreceptors. Damage to the RPE and retina was always restricted to the infected area. When the entire retina/RPE was not infected, the toxicity did not spread beyond GFP-positive areas (SI Appendix, Fig. S6). These results show that the severity of RPE and photoreceptor toxicity is positively correlated with the dose of toxic

Fig. 1. Retina toxicity is induced by broadly active but not retinal cell-type-specific promoters. (A and B) Wild-type retinas of CD-1 mice were infected at P0 with the indicated viruses at either high (3E9 vg per eye) or low dose (8E8 vg per eye) and harvested at P30 for histology. Retinal cross-sections were stained for short- and medium/long-wavelength opsins (red) (A) and for GFAP (red) (B). Loss of opsin staining and up-regulated expression of GFAP were observed in the retinas infected with AAV8-CMV-GFP. (Scale bars, 100 μm.) (C) Quantification of ONL thickness at 1 mm from optic nerve head (ONH). Data are presented as mean ± SD. n = 3–17 per group. One-way ANOVA analysis with Tukey test. **P < 0.01; NS, not significant between the designated group and the uninjected group.

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and toxicity was defined as a score C

C

B

cells in the ONL and GFAP up-regulation

Phalloidin

F

C

www.pnas.org/cgi/doi/10.1073/pnas.1821000116

RPE and retina damage is dose-dependent. Representative images of cpfl3 RPE cells were observed following + +

Upper

mutations, which can lead to Xiong et al.

SI

A

AAV8-CMV-GFP CMV immediate-early promoter and enhancer (23) Harvard vector core (Addgene no. 67634) Y Y

AAV5-CMV-GFP As above As above Y Y

AAV8nC80-CMV-GFP As above As above Y Y

AAV8m8-CMV-GFP As above As above Y Y

AAV8-CMV-null As above Harvard vector core (pAAV-MCS8) Y Y

AAV8-Ubic-GFP Human UbiC promoter (24, 25) Substituted CMV in pAAV-CMV-GFP with UbiC promoter (Addgene no. 11155) L Y

AAV8-CAG-GFP CMV immediate-early enhancer + chicken beta actin promoter (26) E. Boyden laboratory (Addgene no. 37825) Y Y

AAV8-RedO-GFP Human red opsin (28) B. Roska laboratory (29) N N

AAV8-Rho-GFP Human rhodopsin (30) B. Roska laboratory (29) N N

AAV8-CAR-GFP Mouse cone arrestin promoter (32) B. Roska laboratory (29) N N

AAV8-RK-ZsGreen Human rhodopsin kinase (31) T. Li laboratory (31) N N

AAV8-Best1-GFP Human Bestrophin 1 (27) Cloned into AAV vector by C.L.C. laboratory L Y

Vector name/serotype Promoter/regulatory sequence full name (refs.) Vector origin Toxicity to retina Toxicity to RPE

AAV8-CMV-GFP (Low dose)

AAV8-CMV-GFP (Medium dose)

AAV8-CMV-GFP (High dose)

Fig. 3. RPE and retina damage is dose-dependent. Representative images of RPE and retina of P30 CD-1 mice following infection at P0 with low dose (8E8 vg per eye), medium dose (1E9 vg per eye) and high dose (2E9 vg per eye) of AAV8-CMV-GFP. (A–C) The RPE (labeled with phalloidin staining) and (D–F) photoreceptors (labeled with PNA) from the same areas are shown in upper and lower panels. (Scale bars, 50 μm.)

AAV Toxicity Manifests Across Mouse Strains and Is Associated with Multiple Capsid Types. To test whether toxicity is associated with a serotype other than type 8, we tested additional capsid types for transmission of a toxic genome. We also tested an additional mouse strain and expanded the type of assay to include clinically relevant in vivo imaging, using a fundus camera, and using optical coherence tomography (OCT), which can detect alterations in retinal and RPE structure. Postnatal day 0 (P0) mice were injected with AAV5, another commonly used capsid type, carrying CMV-GFP at a low dose (8E8 vg per eye) and a high dose (3E9 vg per eye) or AAV8-CMV-GFP as a positive control for toxicity. To test a mouse strain that avoids some of the light sensitivity of albino strains, such as the CD-1 strain, we injected the pigmented C57BL/6j strain. This pigmented strain was chosen as it is free of rd8 and cpfl3 mutations, which can lead to morphological and functional deficits in the retina (36, 37). As an initial measure of infection and to assess potential injection trauma, we used a fundus camera with a fluorescent light source to image GFP and eye morphology (Fig. 4A). Eyes receiving a low dose of AAV8-CMV-GFP or AAV5-CMV-GFP showed a variable degree of GFP expression in the RPE cells (Fig. 4A), similar to that observed in cross-sections (SI Appendix, Fig. S7) and flatmounts. Sparse GFP+ RPE cells were observed following infection of AAV8-CMV-GFP or AAV5-CMV-GFP at high dose, presumably due to death of RPE cells (Fig. 4A and SI Appendix, Fig. S7). Eyes injected with a nontoxic preparation of AAV8-CAR-GFP showed uniform distribution of GFP in photoreceptors (Fig. 4A). We also injected a mixture of two viruses, AAV8-RedO-GFP and AAV8-Best1-GFP (at a ratio of 5:1) to mimic the expression pattern of toxic CMV-GFP (i.e., RPE, most cones and some rods) to determine if this mixture of expression patterns might trigger toxicity. The GFP pattern of this combination gave bright RPE expression and uniform photoreceptor labeling and looked distinctly different from the toxic CMV-GFP (Fig. 4A). Using OCT, similar observations were made. Largely normal retinal layers were seen following infection with both low and high doses of AAV8-CAR-GFP or the combination of AAV8-RedO-GFP +AAV8-Best1-GFP (Fig. 4B). In contrast, infection with the low dose of AAV8-CMV-GFP or AAV5-CMV-GFP resulted in diminished outer limiting membrane (OLM) and inner segment/outer segment bands, created disturbances in the RPE bands, and led to intrusions into the subretinal-RPE space (Fig. 4B). Such intrusions may represent infiltrating immune cells (arrows in Fig. 4B, Upper). At high dose, infection with AAV8-CMV-GFP or AAV5-CMV-GFP resulted in more dramatic OCT manifestations with decreased ONL thickness and larger subretinal intrusions (Fig. 4B, Lower). Overall, these in vivo imaging results correlate well with our observations of toxic effects on photoreceptors and the RPE seen in histological preparations (Figs. 1 and 2 and SI Appendix, Fig. S7).
We also tested two engineered capsid types. AAV-CMV-GFP was packaged in Anc80, a capsid engineered to be less effectively neutralized by prior exposure to extant AAVs (3). Toxicity was also seen with AAVAnc80-CMV-GFP (Table 1). An AAV2 capsid derivative, 7m8, was developed for use in intravitreal injections, that is, injections into the cavity within the eyeball on the opposite side of the retina from the subretinal space (2). Intravitreal injections are used routinely and safely for the delivery of drugs for age-related macular degeneration. However, we tested the 7m8 capsid using subretinal injections, rather than intravitreal, to keep the injection site constant among vectors tested. AAV7m8-CMV-GFP also was toxic (Table 1). As we observed toxicity using AAV8, AAV5, Anc80, and 7m8, toxicity was not restricted to a particular capsid type.

Assessment of AAV Toxicity Using Clinical Measures of Visual Activity. Human vision can be assayed physiologically using electroretinograms (ERGs) under lighting conditions that assess rod versus cone function. Vision in animals can additionally be assessed by measuring the functional deficit in rods and the rod pathway from rods, scotopic conditions (low light levels without background light) for the ERG were used, while for cone and cone pathway function, photopic conditions (with background light to saturate the rods) were used. The a-wave provides a measure of photoreceptor function, while the b-wave provides a measure of ON-bipolar cell activity that also indicates the level of synaptic signaling between photoreceptors and their synaptic partners, the bipolar cells. Injection of the high dose of AAV8-CMV-GFP resulted in a significant drop in the a-wave (~84%, \( P < 0.001 \)) and b-wave amplitudes (~71%, \( P < 0.0001 \)) in scotopic conditions (Fig. 5 A and B), suggesting a severe functional deficit in rods and the rod pathway. Under photopic conditions, the AAV8-CMV-GFP–injected groups showed a 50–70% decrease in b-wave amplitudes at all light intensities (Fig. 5 C and D), compared with the group injected with the combination of AAV8-RedO-GFP plus AAV8-Best1-GFP, and an approximately fivefold increase in I1/2 (Fig. 5D, Insert), a measure of the flash intensity giving 50% maximal response (38). These observations indicate that the cones or cone pathway in the animals injected with AAV8-CMV-GFP were much less sensitive to light as they required fivefold more photons to reach the 50% maximal response.

Injected mice also were tested in the optomotor assay, which measures visual acuity by assessing the motor response of mice under photopic conditions. The scotopic ERG a-wave amplitude was 49% lower \( (P < 0.05) \) in mice injected with low-dose AAV8-CMV-GFP than in mice injected with the combination of AAV8-RedO-GFP and AAV8-Best1-GFP (Fig. 5B). The scotopic b-wave implicit time was significantly delayed (27 ms slower than control, \( P < 1 \times 10^{-8} \)) (Fig. 5B). In addition, the photopic ERG showed that the I1/2 of the low-dose AAV8-CMV-GFP–injected eyes was approximately twofold higher (i.e., twofold less sensitive to light) than that of eyes injected with the same dose of AAV8-RedO-GFP plus AAV8-Best1-GFP (Fig. 5D, Insert). These results demonstrate that the retinal damage induced by AAV8-CMV-GFP toxicity can result in visual deficits, in correlation with the dose of administered virus.

Microglia Activation Is Associated with AAV-Induced Toxicity. Microglia are the main innate immune cell type in the retina (40). We examined whether they were activated in retinas infected with AAV at 30 d postinfection. Iba1 is a marker of microglia and increases in intensity with activation (41). We examined Iba1 staining and found that there were significantly more Iba1-positive microglia in the retina after infection with high dose (3.9E9 vg per eye) AAV8-CMV-GFP (Fig. 6A). Activated microglia migrated to the ONL and subretinal space, where they adopted an amoeboid or activated morphology (Fig. 6A and SI Appendix, Fig. S8A). In contrast, microglia number, localization, and morphology did not change significantly in retinas infected with AAV8-RedO-GFP (Fig. 6A and B). Microglia responses were very sensitive to toxic viruses, as their activation was evident in low-dose (3.8E8 vg per eye) AAV8-CMV-GFP–infected retinas (Fig. 6B and SI Appendix, Fig. S8A). To confirm the increase of microglia, we examined microglia numbers using a transgenic mouse strain, Cx3cr1-GFP, in which microglia are marked by GFP (42). This strain was injected with AAV8-CMV-TdTomato (3.8E8 vg per eye), which utilizes the
same CMV enhancer/promoter as the toxic AAV8-CMV-GFP. The percentages of all live retinal cells that were GFP+ microglia were analyzed using flow cytometry. A threefold increase of GFP+ microglia was observed in the AAV8-CMV-TdTomato-infected retinas compared with un.injected or PBS-injected retinas (Fig. 6C).

Activated microglia, and potentially other cell types, may increase their expression of proinflammatory cytokines, such as TNF-α, IL-1β, IL-6, and/or IFN-γ. We tested this possibility by examining the levels of RNA for these genes by qPCR in the dissected retinas at 30 d postinfection. TNF-α and IL-1β were highly up-regulated in retinas infected with the toxic viruses, while the levels of IL-6 and IFN-γ were not significantly changed (Fig. 6D). The increase of TNF-α and IL-1β expression correlated with the dose of the injected toxic viruses (Fig. 6D and SI Appendix, Fig. S8B).

**Discussion**

Ocular delivery of AAV vectors is relatively safe, as shown by the results of several clinical trials (4, 6, 7, 43–45). Subretinal injection of AAV is the route used to administer virus for treatment of LCA, retinitis pigmentosa, and choroideremia (11, 22, 35). However, the sensitive assays that we were able to conduct in mice have shown that there can be several manifestations of toxicity from subretinal injections of AAV. Toxicity was seen with more than one type of capsid and did not correlate with preparation methods, endotoxin level, nonviral protein contamination, or mouse strain. The lack of correlation with preparation method is in agreement with the results from previous studies (46, 47). The two variables showing the strongest association to toxicity were the promoter and the viral dose. It is likely that other variables can contribute to toxicity in other cases (e.g., stocks with a high degree of endotoxin, or perhaps empty capsids,
May be problematic). Our results show the importance of sensitive and organ-specific assays for different manifestations of toxicity. Ophthalmologists can use standard examination equipment to employ familiar consensus language and grading scales developed for clinical studies of uveitis (48). OCT, autofluorescence, and microperimetry are routinely used in preoperative planning for human gene therapy in the eye. In the posttreatment follow-up period, these modalities can then be used to quantitate changes from baseline across many parameters including retinal layer thickness, number of inflammatory cells (OCT), RPE viability and stress (autofluorescence), and retinal sensitivity (microperimetry) (49, 50). These strategies would allow for the development of safer vectors, reducing the likelihood of problems as a greater number of patients are treated.

In human clinical trials, the dose of AAV used in subretinal injections ranges from 1E10 vg per eye to 1E12 vg per eye (21, 22, 34, 35). So far, most ocular gene therapy trials have used AAV2, and thus less is known about the safety and efficacy of AAV8 or other capsid types. However, AAV8, and likely other capsid types under development, offer advantages in terms of number of cells, and/or the cell types, infected. In our study, AAV8 encapsidated toxic genomes were toxic at a dose of 5E8 vg per eye or higher. A recent study, also conducted by subretinal injections in mice, reported similar dose-dependent AAV retinal toxicity. They showed that AAV8/CAG-GFP at a dose of 5E9 vg per eye and above were toxic (18). Interestingly, they observed toxicity using a rhodopsin promoter to drive GFP. The dose that led to this toxicity was 1E11 vg per eye, which was 30-fold higher than our highest dose of a vector using a rhodopsin promoter. As dose is an important variable, the higher dose may be the reason for the toxicity of the AAV-Rho-GFP. In fact, it is difficult to extrapolate and compare results across studies, as different subjects/animals, injection routes, and age at injection are used. We used the somewhat unusual time point of P0 for our injections, but this is unlikely to be the cause of the toxicity that we observed. In collaborative studies using pigs, where injections were done to animals at 2 to 3 mo of age, toxicity also was seen using AAV8-CMV-GFP.* Moreover, other studies reporting ocular toxicity used injections into adults (16–21). One other variable making it difficult to compare among studies is the vening issue of titer. Different groups use different methods to titer, and even for a given stock large differences can be reported, as was well illustrated in a trial where multiple groups measured the titer of the same stock, with differences of up to 100-fold reported (51). Toxic doses for different AAV serotypes are unlikely to be the same, as the cellular tropisms of different AAV serotypes can vary greatly (52). In fact, we noticed a correlation in toxicity among different capsids carrying toxic genomes and the degree of RPE infectivity, with AAV5 > AAV8 > AAV2. Overall, our results, and those of others (15, 16, 18), emphasize the importance of testing the dose of specific vectors with sensitive assays of several phenotypic aspects of relevant cell types. Most assays conducted to date examine only a few parameters, such as neutralizing antiserum or gross inflammation and tissue damage.

In light of clinical trials conducted in the eye, it is interesting that two promoters shown to be toxic in our studies have been used safely in humans. The Best1 (also called VMD2) promoter has been used to express the RPE gene, MERTK, to treat one form of retinitis pigmentosa (11, 53). The AAV2-VMD2-hMERTK vector, when administered at 5E9 or 4E9 vg per eye in Sprague-Dawley rats, did not cause any obvious retinal damage compared with the saline-injected eyes (53). Of note, they did not examine RPE morphology in flatmount preparations, which may be a more sensitive measure of RPE stress. In the follow-up clinical trial, six patients who received either 5.9E10 vg or 1.8E11 vg of AAV2-VMD2-hMERTK vector did not develop severe complications (11). However, in patients with MERTK mutations there is defective RPE phagocytosis, and geographic atrophy existed at baseline. In these patients, there was an expansion of perifoveal atrophic areas, regardless of whether the eye received AAV2-VMD2-hMERTK. Intervention late in the course of the disease, and the fact that a phase I study is not designed to test for efficacy, may have been the reasons that atrophy was not arrested, as suggested by the authors. However, it is also possible that a rescue effect of the VMD2-hMERTK vector was blunted by RPE toxicity. In our study, we used an assay to specifically examine RPE morphology with administration of AAV8-Best1-GFP (5E8 vg per eye) and found that it showed toxicity for mouse RPE cells. Reducing the level of AAV8-Best1-GFP to 1E8 vg per eye, as in the nontoxic low-dose group, minimized toxicity while still providing a good level of GFP expression in the RPE (Fig. 4). In addition to the

Best1 promoter in use in human trials, the CAG promoter is used in the LCA2 vector, Luxturna, approved by the Food and Drug Administration, using a dose that minimizes toxicity (6). However, since subretinal infections of human eyes result in local infection of ~10% of retinal or RPE cells, the clinical benefits are more limited than what would be ideal. If safer vectors could be developed a greater number of cells could be transduced, likely creating greater benefit to the patients, and the concern for safety could be lowered for all injections.

As discussed above, a key observation in our study is that toxicity correlated with promoter type, with broadly active promoters and an RPE-specific promoter leading to toxicity, and photoreceptor-specific promoters being benign. Toxicity also has been seen with broadly active promoters, and not with cell-type-specific promoters, in other tissues, including the heart (54, 55) and the central nervous system (56, 57). However, a systematic investigation of several of each type of promoter has not been reported. One mechanism that might explain toxicity is that the broadly active promoters tend to drive higher expression of transgenes than cell-type-specific promoters. GFP protein has been shown to be toxic via reactive oxygen species and apoptosis (58, 59). However, toxicity cannot be solely attributed to GFP or any other transgene protein, as AAV8-CMV-null is as toxic as AAV8-CMV-GFP (Figs. 1 and 2), and other non-GFP proteins were seen to be toxic when expressed by CMV or CAG AAV vectors. Another hypothesis is that the CMV sequence present in both the CMV and CAG vectors, stimulates an innate immune response, as CMV is a virus that activates the innate immune system naturally (60). Arguing against this, the UbIC and Best1 promoters are human in origin and also were toxic. Another possibility is that there is a common sequence motif among the toxic vectors. Toll-like receptor 9 (TLR9), which senses unmethylated CpG DNA, can detect the AAV genome and set off innate and adaptive immune responses (61), and CpG-depleted AAV vectors can evade TLR9-mediated immune detection (62). We examined the set of viruses that we tested and failed to find any correlated sequence motifs. A search for toxic sequences using deletions and chimeric viral genomes may be better able to detect toxic and/or protective sequences. In addition to innate immune sensing of DNA sequences, capsids also can be sensed, as TLR2, which is on the cell surface, can sense AA2 and AAV8 capsids in Kupffer cells and liver sinusoidal endothelial cells (63). All capsids tested here led to toxicity when used to package nontoxic genomes, arguing against capsids alone stimulating toxic responses, at least at the doses tested here.

In addition to the sequence of an AAV genome, other aspects of an AAV genome may contribute to toxicity. The study of retinal toxicity by Khabou et al. (18) used a self-complementary (sc) AAV8-Rho-GFP, which was toxic at a high dose, while we did not observe toxicity using an ss AAV8-Rho-GFP, although it was tested at a much lower dose. Previous studies have shown that the double-stranded genome of scAAV can trigger a stronger immune response than ssAAVs, at least in part by activating the TLR9 pathway (64, 65). Further studies with scAAV vs. ssAAV using other cell-type–specific promoters and a wider range of doses will provide more insight into the correlation between toxicity and this aspect of genome structure.

It is of interest to consider the cell types that might be sensing the virus. The RPE and microglia are good candidates for this function. The RPE is situated between the rich vascular bed of the choriocapillaris and the retina, constitutes a portion of the blood-retinal barrier, and expresses at least several genes of the innate immune system, including the TLRs (66–68). Our observations favor a model in which the RPE is a primary sensor of toxic vectors, as all toxic vectors had promoters that were active within the RPE, including the RPE-specific promoter, Best1. The other two retinal glial cell types, Müller glia and astrocytes, are possible sensors of virus, as they also can respond to inflammatory stimuli (69–71). However, Müller glia are not yet born at P0 when we inject virus, and astrocytes are just beginning to migrate into the retina at P0 (72). However, it is possible that the inflammation seen in other studies of AAV infection of the retina following vitreal injections (73, 74) was due to sensing by one or both of these cell types, or endothelial cells. These previous studies used injections into mature animals where these cell types would be present and very accessible to vitreally delivered virus. Microglia also can sense and respond to virus (75), and given their activation by the toxic, but not by the nontoxic viruses, it is likely that they are involved. We did not see GFP in microglia following infection with any virus, but it has been reported that they are difficult to infect in vivo (76). However, it could be that they are infectable, but that they shut down viral gene expression. Detection of viral genomes using the newer and more sensitive DNA FISH methods may resolve this issue (77, 78). The other cell types at the injection site, the retinal neurons, particularly photoreceptors, generally do not express genes encoding sensors of innate immunity (79–82) and thus would not be expected to react directly to viral transcription and/or RNA. What is being sensed in the RPE and/or microglia? Our data are consistent with transcription from a nonchromosomal genome, which, if true, would be a novel mechanism, and/or some form of viral RNA. The ITRs in AAV vectors have been shown to have promoter activity (83, 84). If an ITR generates an anti-sense transcript, it could hybridize to a sense transcript, creating a hairpin or stem-loop structure that is recognized as a trigger for innate immunity (85). Future studies of cellular responses via analysis of RNA changes following infection with toxic and nontoxic viruses, within different cell types, immediately and later after infection might reveal the primary responders as well as secondary effects. Follow-up studies using genetics in mice may further delineate the responsible pathways and cell types. Although not all studies conducted in mice can be extrapolated to other species, these data can provide a starting point for experiments that are more difficult to conduct in large animals and may be predictive of safer vector structures for human gene therapy.

Materials and Methods

Mice. CD-1 and C57BL/6J mice were purchased from Charles River Laboratories and were kept on a 12-h light/12-h dark cycle. All animal procedures performed were approved by the Institutional Animal Care and Use Committee of Harvard University and by Hong Kong Department of Health under Animals Ordinance Chapter 340, and animal care was carried out in accordance with institutional guidelines.

Plasmids. pAAV-CMV-GFP and pAAV-CMV-null vector plasmids were obtained from the Vector Core, Philadelphia. pAAV-CMV-CAG-GFP was a gift from the T. Li laboratory, National Eye Institute, Bethesda, Maryland (90). pAAV-RK-ZsGreen was a gift from the T. Li laboratory, National Eye Institute, Bethesda, Maryland (90). pAAV-CAG-GFP (from Addgene no. 11155 (21, 22, 77)) was a gift from Jeng-Shin Lee to Harvard DF/HCC DNA Resource Core. pAAV-UBIC-GFP was made by replacing the CMV promoter in AAV-CMV-GFP with that of human UbIC from Addgene no. 11155 (21, 22, 77). pAAV-CAG-GFP (from the E. Boyden laboratory) was obtained from Addgene (Addgene no. 37825). pAAV-RedGFP, pAAV-Rho-GFP, and pAAV-CAR-GFP were gifts of the B. Roska laboratory, Friedrich Miescher Institute for Biomedical Research, Basel (29). pAAV-RK-ZsGreen was a gift from the T. Li laboratory, National Eye Institute, Bethesda, Maryland (31). pAAV-Best1-GFP was cloned by replacing the CMV promoter of the pAAV-CMV-GFP-BGHpA vector (Upenn virus core, id: PV0101) with the S853–39 bp region of human Best1 promoter region by Gibson ligation (27). pAAV-CMV-TdTomato were cloned by replacing GFP with TdTomato coding sequence by Gibson ligation. pAAV rep/Cap 2/2, 2/8 and Adenovirus helper plasmids were obtained from University of Pennsylvania Vector Core, Philadelphia, pAAV7m8 and pAAVANC80 plasmids were gifts from J. Flannery, University of California, Berkeley, CA (2) and L. Vandenberghe, Harvard Medical School, Boston (3).

AAV Vector Production and Tittering. Recombinant AAV8 vectors were produced as previously described, and AAV7m8 vectors were produced using the same protocol as for AAV2 (86). Briefly, AAV vector, rep/cap packaging plasmids, and adenoviral helper plasmids with polyhistidine and added to HEK293T cells (HCL4517; Thermo Scientific). Seventy-two hours after transfection, supernatant was collected for AAV8 preparations, and cells were harvested for AAV7m8 preparations (87). AAV8 vectors in the
supernatant were precipitated (mixed with 8.5% wt/vol PEG-6000 and 0.4 M NaCl for 2 h at 4 °C, centrifuged at 7,000 × g for 10 min, and resuspended in virus buffer (150 mM NaCl and 20 mM Tris, pH 8.0). For AAV7m8 viruses, the cell pellet was resuspended in virus buffer, followed by three cycles of freeze–thawing, and Dounce-homogenized. Cell debris was pelleted at 5,000 × g for 20 min, and the supernatant was run on an iodixanol gradient. Recovered AAV vectors were washed three times with PBS using Amicon 100K columns (EMD Millipore). RT-PCRs and protein gels were run to determine virus titers.

AAV Injection. Subretinal injection into P0 neonate eyes was performed as previously described (88, 90). Approximately 0.25 μL AAV was introduced into the subretinal space using a pulled angled glass pipette controlled by a Femtotet (Eppendorf). The fellow eyes were uninjected for within-animal controls.

OCT. OCT images of mouse eyes were taken by a commercially available OCT2 system in combination with the Micron IV fundus imaging system (Phoenix Research Labs). Detailed procedures can be found in SI Appendix.

ERG. ERGs were performed in vivo with the Espion E3 System (Diagonsys LLC) for micr0 mice (The Biogen Idec). Short-term results of a phase I trial. Hum Gene Ther Clin Dev 29:285 (2010). Directed evolution of a new AAV serotype for therapeutic delivery of the photoreceptor outer retinal type. J Virol 80:10886–10896. For AAV7m8 viruses, the cell pellet was resuspended in virus buffer, followed by three cycles of freeze–thawing, and Dounce-homogenized. Cell debris was pelleted at 5,000 × g for 20 min, and the supernatant was run on an iodixanol gradient. Recovered AAV vectors were washed three times with PBS using Amicon 100K columns (EMD Millipore). RT-PCRs and protein gels were run to determine virus titers.

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