A Controlled Release System for Long-Acting Intravitreal Delivery of Small Molecules

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Purpose: The short half lives of small molecules in the vitreous requires frequent repeated intravitreal injections that are impractical for treatment of chronic eye diseases. We sought to develop a method for increasing the intravitreal half-life of small-molecule drugs.

Methods: We adapted a technology for controlled release of drugs from macromolecular carriers for use as a long-acting intravitreal delivery system for small molecules. As a prototype, a small molecule complement factor D inhibitor with an intravitreal half-life of 7 hours was covalently attached to a 4-arm PEG40kDa by a self-cleaving β-eliminative linker with a cleavage half-life of approximately 1 week.

Results: After intravitreal injection in rabbits, the drug was slowly released in the vitreous, and equilibrated with the retina and choroid. The intravitreal half-life of the intact PEG-drug conjugate in the rabbit was 7 days, and that of the released drug was 3.6 days. We simulated the anticipated pharmacokinetics of the delivery system in human vitreous, and estimated that the half-life of a 4-arm PEG40kDa conjugate would be approximately 2 weeks, and that of the released drug would be approximately 5 days.

Conclusions: We posit that a linker with a cleavage half life of 2 weeks would confer a half life of approximately 7 days to a released small molecule drug in humans, comparable to the half life of approved intravitreal injected macromolecular drugs.

Translational Relevance: With this technology, a potent small molecule with an appropriate therapeutic window should be administrable by intravitreal injections in the human at once-monthly intervals.

Introduction

Intravitreal (IVT) injection has become an important drug delivery modality for many diseases of the eye. IVT injection minimizes systemic exposure and allows intraocular drug exposures not otherwise achievable. However, because IVT therapy is an invasive procedure that often requires long-term serial injections, IVT drugs require long IVT half lives (t1/2) and dosing intervals.

Macromolecules show low clearance in the vitreous that is related to their molecule diffusivity through the chamber1; indeed, it has been shown that the hydrodynamic radius (RH) of a macromolecular drug is directly related to its half-life in the rabbit vitreous. Currently used IVT drugs include large proteins—a Fab (ranibizumab), mAb (bevacizumab), and a Fc-receptor conjugate (aflibercept)—having IVT half lives of 7 to 10 days in a human (Table 1). PEGylation of aptamers and smaller proteins has also been used to increase the hydrodynamic radius of drugs and IVT half-lives. Successful examples include a PEGylated aptamer (pegaptanib) and a small protein DARPin (abicipar pegol); interestingly, despite its smaller size, the PEGylated protein abicipar has a longer vitreous half-life than larger macromolecular proteins. In short, the current drugs for IVT
injection have IVT half-lives clustered between approximately 7 and 13 days in a human. The 4- to 8-week dosing interval commonly used for IVT-administered macromolecular drugs requires that they transit multiple half-lives and have high peak-to-trough ratios each dosing cycle; however, this is tolerable because these drugs have wide therapeutic windows, and few off-target effects in the eye.

In contrast to macromolecules, small molecules and peptides have high clearance in the vitreous. With IVT half lives of only approximately 1 to 24 hours, unless formulated as sustained-release implants, they require frequent repeated IVT injections that are impractical for treatment of chronic eye diseases. Because there are so many potential therapeutic targets in the eye, there is a large unmet need for a simple, effective way to increase the residence time of small molecules in the vitreous.

A possible approach to extend the IVT half life of such drugs is to attach them to a soluble macromolecular carrier, such as PEG, to effectively increase their hydrodynamic radius, and thus half life. PEG provides the additional benefit of solubilizing hydrophobic small-molecule drugs. However, whereas attachment of PEG to larger multifunctional drugs, such as aptamers or small proteins, can be achieved at nonessential sites of the drug, attachment of PEG to a small molecule having only a few functional groups is likely to impair activity. One approach to circumvent this problem is to convert the small molecule drug to a macromolecular prodrug that will retain a long IVT half-life because of large hydrodynamic radius, and slowly release the native, pharmacologically active small drug over a long duration.

We have developed a general prodrug approach for half-life extension of therapeutics in which a drug is covalently tethered to a long-lived carrier, such as PEG, by a linker that slowly self-cleaves to release the native drug. Here, a macromolecular carrier is attached to a linker that is attached to an amine group of a drug or a prodrug via a carbamate group (1; Scheme 1); the β-carbon has an acidic carbon–hydrogen bond (C–H) and also contains an electron-withdrawing “modulator” (Mod) that controls the pKₐ of that C–H. Upon hydroxide ion-catalyzed proton removal, a rapid β-elimination occurs to cleave the linker-carbamate bond and release the free alkene products, 2. The rate of drug release is proportional to the acidity of the proton, and that is controlled by the chemical nature of the modulator; thus, the modulator chemically controls the drug release rate in a predictable manner.

We have previously shown that approximately 40 kDa PEGylated fluorescent conjugates show an IVT half life of approximately 7 days in the green monkey without apparent toxicity. In the present work we describe the preparation and characterization of a releasable PEGylated prodrug of DS29740219, a...
potent small molecule inhibitor of complement factor D (CFD) that has potential as a therapeutic for dry age-related macular degeneration (AMD).13,14 We also report the intravitreal pharmacokinetics of the macromolecular prodrug, which indicates that the released drug can be kept above its IC50 for up to approximately 1 month. The results indicate that PEGylated prodrugs may provide a practical, general technology platform for discovery and delivery of long-acting small molecule drugs for IVT injection.

Materials and Methods

The source of specialized materials is provided along with their use in Supplementary Materials. Detailed synthetic, conjugation, and analytic procedures are described. In vitro kinetic procedures are provided, as are in vivo pharmacokinetic methods and analyses.

Chemistry

Synthesis of DS29740219 (4)

The aminoethyl analog 4 was prepared by catalytic reduction (Pd/C) of the reported corresponding cyanomethyl precursor.15 Compound 4 showed a half-maximum inhibitory concentration (IC50) of 53 nM for in vitro inhibition of CFD, and 95 nM in an alternate pathway-mediated hemolysis assay.

Synthesis of PEG-4 Conjugates

As depicted in Scheme 2, treatment of commercially available 4-pentenoic acid with isobutylene/H2SO4 gave tbutyl 4-pentenoate 5, which was epoxidized with mCPBA. The epoxide was readily resolved using Jacobsen’s kinetic resolution.16 The resolved epoxide 6 was opened with a nucleophile (MeSO2Na for MeSO2 and NaCN for CN) to introduce the linker modulator group. The resulting linker-alcohols 7A,B were activated in a two-step process, first converting them to the chloroformates (triphosgene, pyridine) and then to the hydroxysuccinimidyl carbonates 8A,B (HOSu, pyridine).

Reaction of 4 with 8A,B to provide 9A,B was rapid and quantitative, and removal of the ester group cleanly provided the linker-drugs 10A,B ready for conjugation with PEG-amine (Scheme 3). Conjugation was most conveniently performed by in situ activation of the linker-drug using hexafluorophosphate azabenzotriazole tetramethyl uronium (HATU), and the conjugates 11A,B were isolated by dialysis followed by precipitation to remove small molecule impurities. In contrast to the poor water solubility of 4, the PEG-conjugates 11A,B were soluble in water at more than 100 mg/mL.

A corresponding nonreleasable conjugate 12 was prepared as a control by reacting 4 with PEG40kDa tetra(succinimidyl carboxymethyl ester) (Scheme 4). As with 11A,B, the PEG-conjugate 12 was soluble in water at more than 100 mg/mL.

In Vitro Release Kinetics

The conjugates were examined for release of 4 under accelerated in vitro conditions at pH 8.4, 37°C, using high-performance liquid chromatography (HPLC) analysis (Fig. 1). The data were fit to first-order release profiles, giving observed half-life values of 17.5 (11A) and 90 hours (11B) that, assuming hydroxide-catalyzed cleavage,11 extrapolate to 175 and 900 hours, respectively, at pH 7.4.
cleavage rate of 11B was much slower than the expected IVT rate of elimination of PEG_{40kDa} it was deemed unsuitable for IVT use. With the stable conjugate 12, no release of 4 was observed for at least 200 hours at pH 8.4.

**IVT Pharmacokinetics**

**IVT Models and Pharmacokinetic Data in the Rabbit**

We have previously reported kinetic analyses of a one-compartment model for β-eliminative release of drugs from soluble macromolecular carriers. As in Scheme 5, the drug is released from the conjugate in a first-order process with rate constant $k_1$, the drug is cleared with $k_2$, and the conjugate is cleared with rate constant $k_3$. If $k_2 \gg (k_1 + k_3)$, at longer times the slopes of plots of ln[PEG-Drug] and ln[Drug] versus time both approach $k_1 + k_3$. If the clearance rate ($k_3$) of the conjugate is known, it can be subtracted from the slope of the ln[PEG-Drug] versus time plot ($k_1 + k_3$), to obtain the in vivo linker cleavage rate constant, $k_1$.

To estimate $k_2$, parent compound 5 ug of 4/eye was administered by IVT injection of New Zealand White rabbits and concentrations in the vitreous were...
measured over time using HPLC–tandem mass spectrometry. The C versus t plot shows a brief distribution phase, followed by a first-order elimination of 4 from the vitreous (Fig. 2). Analysis of the C versus t plot using a 2-compartment model \((SI)\) indicated a terminal \(ke_{IVT} = 0.31 \text{ hr}^{-1}\) and \(V_d = 0.57 \text{ mL}\), with intercompartmental IVT transfer rates of \(k_{12,IVTout} = 0.20 \text{ hr}^{-1}\) and \(k_{21,IVTin} = 0.17 \text{ hr}^{-1}\); one-compartment analysis, with weighting \(1/Y^2\), showed an IVT terminal half life of 6.9 hours.

To estimate the elimination rate, \(k_3\) of the releasable PEG-4 conjugate, we used the corresponding stable conjugate 12 as a surrogate. Conjugate 12 (465 nmol of 4) were administered by IVT injection to each eye of the subject rabbits, and the IVT levels were measured over 28 days (Fig. 3A). Here, the IVT half life was 167 hours in the rabbit, which exceeds the 90-hour IVT half life of the PEGylated aptamer pegatanib and the 144-hour IVT half life of the long-acting PEGylated DARPin, abicipar pegol (Table 1). Very low levels (<0.01% of 12) of 4 were also detected but did not impact our conclusions so we did not investigate its origin.

The IVT C versus t plot of releasable conjugate 11A (465 nmol 4/eye) as well as free 4 released from 11A over 28 days is shown in Figure 3A. We analyzed the data as a one-compartmental model (below) as well as a multicompartment model \((SI)\) to accommodate the initial brief distribution phase. Both models provide a similar terminal IVT elimination phase of \(k_{b,IVT} = 0.19 \text{ d}^{-1}\) (\(t_{1/2} = 86 \text{ hours or 3.6 days}\)). Because the IVT elimination rate, \(k_{IVT}\), of 11A represents the sum of the prodrug elimination and drug release rates, \(11 k_{IVT} = k_1 + k_3\), using \(k_3\) determined for 12 we calculate an IVT linker cleavage rate, \(k_1\), of 0.094 \text{ days}^{-1}. The 177-hour half life for release of 4 from the releasable conjugate 11A in the vitreous is in excellent agreement with the in vitro cleavage half life of 175 hours described above. As expected, the C versus t plot of released 4 in the vitreous parallels that of 11A with a similar half life of 2.9 days (69 hours).

The efficiency of drug utilization from a prodrug, such as 11A, can be described by the partition ratio \((PR)\), \(k_1/(k_1 + k_3)\), which represents the fraction of the prodrug that releases 4 during its IVT residence. In the present case, 11A shows a high efficiency of 0.74.

We also analyzed the 4 released from 11A in the retina and choroid, because these are the target ocular structures of the CFD inhibitor; the C versus t plots are shown in Figure 3B, along with the IVT C versus t data of released 4 reproduced from Figure 3A. Higher levels of 4 were observed in the retina compared with the vitreous, but the terminal elimination rates were similar. In the choroid, lower levels of 4 formed from 11A were present compared with the vitreous or retina; however, the terminal elimination rate of 4 was almost 2-fold slower than from the vitreous or retina.
Simulations in the Human Eye

With several reasonable assumptions, we can simulate how a releasable PEG40KDa-drug conjugate studied in the rabbit would behave in the human eye. As described above, the half-life of a drug released from a PEG-drug conjugate by a β-eliminative linker \( (k_{el} = k_1 + k_3) \) is driven by the rate of the linker cleavage \( (k_1) \) and the elimination of the PEG40KDa conjugate \( (k_3) \). Here, \( k_1 \) is species independent and can be controlled over a wide range by the linker used.\(^{11}\) However, the rate of elimination of the carrier, \( k_3 \), is species specific and with slow-cleaving linkers where \( k_3 > k_1 \) represents a theoretical upper limit for the IVT half life of the released drug. Shatz et al.\(^1\) have recently shown that the IVT half life of macromolecules in the rabbit show a linear correlation with RH with a slope of 0.65 days/nm RH. In the rabbit, the IVT half life of the stable PEG40KDa conjugate \(^{12}\) is 7 days, which agrees well with the 6 days predicted for a macromolecule with RH 9.3 nm.\(^{18}\) In a human, the half-life values of all Food and Drug Administration approved IVT macromolecules is 1.8- to 2.8-fold (average 2.2) longer than in the rabbit (Table 2). Hence, the IVT half life of an intact PEG40KDa conjugate (e.g., \(^{12}\)) in a human should be approximately 2 weeks, and from \( k_{IVT} = k_1 + k_3 \) the \( t_{1/2,IVT} \) in the human of \(^{11}\) and the \(^4\) released from \(^{11}\) should be approximately 112 hours. If we were to use a linker with a cleavage rate of 2 weeks, the \( t_{1/2,IVT} \) of \(^4\) released from a PEG40KDa-conjugate in the human vitreous should be approximately 7 days.

### Discussion

The primary objective of this work was to determine the IVT half-life extension that could be achieved for a small molecule released from a 4-arm PEG40KDa-drug conjugate after IVT injection.

Four-arm PEG40KDa was chosen as the nanocarrier for the following reasons: (1) PEG conjugation increases the water solubility of hydrophobic small-molecules, (2) a four-arm PEG40KDa polymer has a high RH of 9.3 and provides long IVT half-life.

<table>
<thead>
<tr>
<th>Compound</th>
<th>( t_{1/2,IVT} ), hr</th>
<th>( t_{1/2,IVT} ), d</th>
<th>CL, mL/d(^a)</th>
<th>( V_{dss} ), mL(^b)</th>
<th>( C_{max} ), uM</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>6.9</td>
<td>0.29</td>
<td>3.5</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>170</td>
<td>7.0</td>
<td>0.22</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>11A</td>
<td>86</td>
<td>3.6</td>
<td>0.36</td>
<td>1.6</td>
<td>210(^b)</td>
</tr>
<tr>
<td>Vitreous</td>
<td>69</td>
<td>2.9</td>
<td>NA</td>
<td>NA</td>
<td>6.7</td>
</tr>
<tr>
<td>Retina</td>
<td>60</td>
<td>2.5</td>
<td>NA</td>
<td>NA</td>
<td>14</td>
</tr>
<tr>
<td>Choroid</td>
<td>140</td>
<td>5.9</td>
<td>NA</td>
<td>NA</td>
<td>0.70</td>
</tr>
</tbody>
</table>

NA, not applicable.
\(^a\) Calculated from noncompartmental analysis.
\(^b\) Calculated as \( C_0 \) for 11A.
extension, (3) four equivalents drug can be attached per equivalent of carrier to minimize the volume of IVT injection, and (4) high molecular weight PEG shows little or no IVT toxicities.

Compound 4 was prepared as a prototype small-molecule inhibitor of CFD for potential treatment of geographic atrophy resulting from AMD. An IC\textsubscript{50} of approximately 50 nM was determined for 4 in an in vitro inhibition assay of human CFD and approximately 90 nM in an alternative pathway-mediated hemolysis of rabbit erythrocytes. The molecule also possesses a primary amine for convenient chemical attachment to â-eliminative linkers by a carbamidomethylation group.

The CFD inhibitor 4 was appended to the ends of four-arm PEG\textsubscript{40K} through a releasable â-eliminative linker with a MeSO\textsubscript{2} modulator to give 11A, or through a stable linker to give 12. In vitro, the half-life for cleavage of the linker in 11A was 175 hours at pH 7.5, 37°C; in contrast, 12, which lacks a â-eliminative linker, was inert. When the stable PEG-conjugate 12 was injected IVT in the rabbit and the vitreous concentration measured over time, we observed a half life of 7 days, close to the half life of 6 days predicted from its R\textsubscript{H}. With the cleavable conjugate 11A, the linker cleavage half life was 177 hours in the vitreous, and the IVT half life was 3.6 days; expectedly, the released 4 from 11A showed a similar apparent IVT half life of approximately 3 days.

Within approximately 1 day after IVT injection, the inhibitor 4 released from 11A reached equilibrium in the retina and choroid, the presumed locations of the target CFD. The C\text{max} of 4 in the retina was approximately 2-fold higher than in the vitreous, and approximately 20-fold higher than in the choroid. However, whereas the elimination rate of 4 from the retina was similar to that in the vitreous, elimination from the choroid was approximately 2-fold slower.

The IVT half-life extension achieved by â-eliminative release of 4 from 11A compared with direct injection of 4 is approximately 10-fold in the rabbit (i.e., the half life is 7 hours for IVT-injected 4 versus 70 hours for 4 released from the PEG-drug conjugate 11A). This magnitude of half-life extension should translate to other molecules attached to PEG\textsubscript{40K} by the same â-eliminative linker because the half life of released drugs is driven by the rate of the linker cleavage and the elimination of the PEG\textsubscript{40K} conjugate from the IVT compartment.

Available data indicates that the IVT half life of macromolecules in humans are approximately 2-fold longer than the corresponding IVT half life in rabbits. Thus, we could estimate that the IVT half life of a four-arm PEG\textsubscript{40K} in a human would be approximately 2 weeks, and comparable to that of abicipar pegol, the long acting PEGylated DARP\textsubscript{in}. For the linker with cleavage half life of 177 hours used here, we calculate from k\textsubscript{<sub>0} = k\textsubscript{1} + k\textsubscript{3} that the IVT half life in a human of the released drug should be approximately 4.8 days. However, if a â-eliminative linker with a cleavage half life of 14 days were used, the IVT half life in humans should be approximately 1 week, comparable to that of most macromolecular IVT drugs. Thus, providing the therapeutic window of a drug is sufficiently wide to allow four half lives with C\text{max}/C\text{min} ≥ 8, the drug delivery system described here should allow a once monthly or longer dosing interval of a small molecule.

In summary, IVT injection of a PEG\textsubscript{40K} nanocarrier attached to a small molecule drug via a releasable â-eliminative linker could maintain the released drug at therapeutic levels in the vitreous for periods comparable to approved IVT macromolecular drugs (i.e., 1 month or longer). The technology described here could serve as a screening platform for identifying potent small molecules that may have therapeutic utility in the eye. This could provide a large benefit of determining pharmacodynamic effects of a long-acting small molecule before investing efforts in developing a final delivery system. Further, once a drug with appropriate efficacy and therapeutic window is found, the releasable PEG\textsubscript{40K}-drug platform could serve as a delivery system in the therapeutic formulation. The largest limitations of the technology might be the capacity of the carriers, or the IVT therapeutic window of the released drug. Finally, even longer IVT half-life extension of small molecules might be achieved using â-eliminative linkers tethered to carriers with longer IVT half lives. Potential candidates for such carriers might include hyaluronic acid with a t\textsubscript{1/2,IVT} approximately 30 days, the recently reported long-lived L-Arg peptide-conjugated nanocarriers, or previously described Tetra-PEG hydrogel microspheres attached to drugs via â-eliminative linkers.

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