Pharmacokinetics of a Sustained-Release Dexamethasone Intravitreal Implant in Vitrectomized and Nonvitrectomized Eyes

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PURPOSE. To evaluate dexamethasone pharmacokinetics after implantation of a sustained-release dexamethasone (DEX) intravitreal implant in nonvitrectomized and vitrectomized eyes.

METHODS. The right eyes of 25 rabbits underwent vitrectomy; contralateral eyes served as nonvitrectomy controls. The 0.7-mg DEX implant was injected into both eyes, and drug concentrations were determined in the vitreous humor and retina for 31 days (on days 2, 8, 15, 22, and 31).

RESULTS. DEX was present in nonvitrectomized and vitrectomized eyes for at least 31 days. There were no statistically significant differences in DEX concentration between nonvitrectomized and vitrectomized eyes at any time point (P > 0.05). The maximum concentration of DEX in nonvitrectomized versus vitrectomized eyes for vitreous humor was 791 ng/mL (day 22) versus 731 ng/mL (day 22), respectively, and for retina it was 4110 ng/mL (day 15) versus 3670 ng/mL (day 22), respectively. Mean absorption (AUC0-tlast) of dexamethasone in nonvitrectomized and vitrectomized eyes was not different for both the vitreous humor (13,600 vs. 15,000 ng/day/mL; P = 0.73) and retina (67,600 vs. 50,200 ng/day/mL; P = 0.47).

CONCLUSIONS. The vitreoretinal pharmacokinetic profiles were similar between nonvitrectomized and vitrectomized eyes. These observations are consistent with clinical findings of the DEX implant in patients who have undergone vitrectomy and should reduce concerns about the use of the DEX implant in eyes that have undergone vitrectomy. (Invest Ophthal Vis Sci. 2011;52:4605–4609) DOI:10.1167/iovs.10-6387

Vitrectomy is a mainstay of treatment for the severe complications associated with persistent posterior segment disease.1–4 However, for many patients, the chronic and recurrent nature of posterior segment disease necessitates continued drug therapy after surgery.1,2,4 Experience with vascular endothelial growth factor (VEGF)5 and a number of drugs, including triamcinolone acetonide,6,7 amphotericin B,8 and 5-fluorouracil,9 suggests that some drugs are cleared more rapidly in vitrectomized eyes. Therefore, differences in pharmacokinetics between nonvitrectomized and vitrectomized eyes may influence the clinical effectiveness of drug therapy. Intravitreal clearance of drugs intended for the treatment of posterior segment disease should be established in vitrectomized eyes before intravitreal dosing is considered in these patients.

Intravitreal delivery of corticosteroids10–17 and anti-VEGF antibodies18–22 are addressing many of the problems associated with conventional therapies for the treatment of posterior-segment inflammation and macular edema. The dexamethasone (DEX) implant (Ozurdex; Allergan, Inc., Irvine, CA) is a sustained-release preparation of DEX embedded in a bioerodible copolymer consisting of poly(lactic-co-glycolic acid) that has been approved by the United States Food and Drug Administration (FDA) for the intravitreal treatment of macular edema after branch or central retinal vein occlusion.23,24 Pharmacokinetic and pharmacodynamic data suggest that when injected into the posterior segment, the DEX implant releases DEX into the vitreoretinal tissues for up to 6 months.24 Moreover, clinical trials in patients with persistent macular edema have shown that the DEX implant is well tolerated and results in improved visual acuity that is maintained for up to 180 days after administration.13,25–27 Although some information is available on the pharmacokinetics of DEX in the vitreous,14,28–30 the effect of vitrectomy on the pharmacokinetics of the DEX implant has not been examined. The objective of this study was to compare the vitreoretinal pharmacokinetics and in vivo drug release profile of the DEX implant in nonvitrectomized and vitrectomized eyes.

METHODS

Animal Model and Study Design

The study complied with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research and was conducted in accordance with the FDA Good Laboratory Practice Regulations and applicable Animal Welfare Act Regulations. The study was approved by Allergan’s Animal Care and Use Committee.

The study used young, male, Dutch-belted rabbits weighing 1.8 to 2.5 kg that were 5 to 12 months old. Animals were maintained in a temperature- and humidity-controlled environment with a 12-hour day/12-hour night cycle. Standard rabbit feed and purified water were offered ad libitum.

A single-treatment design was used, with one treatment group and terminal samples from each animal at necropsy. The right eyes of 25 animals underwent vitrectomy; left eyes did not. Four weeks after vitrectomy, a single bilateral intravitreal implantation of the DEX-DDS...
was made into both eyes. Ocular tissue samples were collected at necropsy on days 2, 8, 15, 22 and 31 after implantation (five animals per time point).

Animals were examined daily for morbidity and mortality. The intraocular pressure (IOP) of both eyes of each animal was measured before vitrectomy, 2 weeks after vitrectomy, once weekly after administration of the DEX implant, and before necropsy. IOP was measured at approximately the same time of day after the administration of an ophthalmic topical anesthetic (0.5% proparacaine hydrochloride; Wilson Ophthalmic Corp., Mustang, OK).

Vitrectomy
Animals were anesthetized with intravenous 15 mg/kg ketamine hydrochloride (Ketaset; Fort Dodge Animal Health, Fort Dodge, IA) and 1 mg/kg acepromazine maleate (Prom Ace; Fort Dodge Animal Health). The right eyes of 25 animals were prepared for vitrectomy with 2.5% phenylephrine hydrochloride (AK-Dilate; Akorn Inc., Buffalo Grove, IL) and 1% tropicamide ophthalmic solution (Alcon Laboratories, Fort Worth, TX) and were washed with 5% povidone iodine solution (Betadine 5% sterile prep solution; Alcon Laboratories). Animals underwent vitrectomy as follows: the eye was proptosed, and two ports of vitrectomy were marked 4 mm behind the corneal limbus. A trocar with a 25-gauge port was inserted into the vitreous at each mark through a short sclerotic tunnel. The infusion cannula was connected to a bottle of sterile balanced salt solution. A near complete subtotal vitrectomy was performed with an 1100 to 1500/min cutter rate and 300 to 600 mm Hg aspiration pressure for 10 to 12 minutes per eye. The vitreous cavity was filled with the sterile balanced salt solution, the trocars were removed, and topical antibiotic and 1% atropine sulfate ophthalmic solution (Bausch & Lomb, Tampa, FL) were applied to the conjunctival sac. The topical antibiotic and atropine were also applied for 3 days after surgery. The contralateral (left) eye was not vitrectomized.

Intravitreal Administration Procedure
Four weeks after vitrectomy, animals received a single, administration of 0.7 mg DEX. Animals were anesthetized with ketamine hydrochloride and acepromazine maleate, as described, and 0.5% proparacaine hydrochloride ophthalmic drops (Wilson Ophthalmic Corp., Mustang, OK) were applied topically. The eyes were prepared for administration of the DEX implant with 5% povidone iodine (Betadine 5% sterile ophthalmic prep solution; Alcon Laboratories) followed by sterile balanced salt solution. A 22-gauge needle of a preloaded DEX implant applicator was introduced through the dorsotemporal quadrant of the eye, approximately 4 mm posterior to the limbus. The DEX implant was deployed in the inferior temporal region of the vitreous using the single-use applicator. Topical antibiotic was applied after the procedure. The location of the DEX implant was confirmed by funduscopy, Heidelberg retina angiography examination, or both.

Tissue Collection and Handling
Animals were euthanized with an intravenous injection of pentobarbital sodium (Eutha-6; Western Medical Supply, Arcadia, CA). Both globes were enucleated and immediately frozen in liquid nitrogen. After the cornea, iris, ciliary body, and lens were excised, the globes were bisected transversely into two hemispheres, one with the DEX implant and one without the DEX implant. Care was taken to ensure that the sample without the DEX implant was not contaminated with implant remnants during dissection, and instruments were cleaned (with alcohol followed by distilled water) between samples to ensure that there was no cross contamination during dissection. Retina was dissected from both hemispheres (i.e., with and without the DEX implant) and was analyzed separately. Samples were stored at −20°C or lower until analyzed.

Drug Determination
The concentration of DEX in the total retina (nanogram per gram) was calculated by dividing the total amount of DEX from retinal samples dissected from both hemispheres by the total tissue weight. The concentration of DEX was analyzed separately for the vitreous humor. Only data for the vitreous humor hemispheres without the implant are reported because these data describe the concentration of soluble DEX released from the implants. Data for the vitreous humor hemispheres with the implant were not reported.

Liquid-liquid extraction was used to extract DEX from the samples, as described previously. Briefly, the internal standard, beclomethasone, was added to the retina and vitreous humor samples, and the organic phase was separated by liquid extraction with 95% methanol:5% water (retina samples) or methyl tert butyl ether (vitreous humor samples). Dried residues were reconstituted with 70% methanol/5% water (retina samples) or methyl tert butyl ether (vitreous humor samples). Dried residues were reconstituted with 70% methanol/5% water (retina samples) or methyl tert butyl ether (vitreous humor samples). Dried residues were reconstituted with 70% methanol/5% water (retina samples) or methyl tert butyl ether (vitreous humor samples).

Pharmacokinetic Analysis
DEX pharmacokinetic data were analyzed using a noncompartmentalized model in a Watson laboratory information system, version 6.3 (Thermo Electron Corporation, Waltham, MA). The following parameters were calculated: maximum mean concentration (Cmax), time to reach maximum mean concentration (Tmax), area under the concentration-time curve (AUC<sub>0-tlast</sub>), and AUC interval.

The content of the DEX implant batch used in this study consisted of 678,000 ng DEX and 22,000 ng polymer. The percentage of drug released from the implants. Data for the vitreous humor hemispheres with the implant were not reported.

Statistical Analysis
Data were analyzed using the Watson laboratory information system, version 6.3. Sample concentrations and pharmacokinetic data were described by means ± SD except for AUC<sub>0-tlast</sub>, for which the mean ± SEM was used. Outliers in repetitive measurements were identified using the Q-test. Differences between nonvitrectomized and vitrectomized eyes were determined using the paired Student t-test; P < 0.05 was considered significant.

RESULTS
Clinical Observations
All animals appeared physically healthy and exhibited no overt signs of toxicity during the study, and none died. The location of the implants in the 25 nonvitrectomized and 25 vitrectomized eyes was confirmed by funduscopy before necropsy or Heidelberg retina angiography. Generally, implants were observed in their original position in the inferior temporal region.
Ocular Concentrations and Pharmacokinetic Profiles

Sustained release of DEX was evidenced by high intraocular concentrations of steroid that were maintained for at least 31 days in the vitreous humor and retinas of both nonvitrectomized and vitrectomized eyes (Fig. 1). Overall, there were no statistically significant differences in the concentration of DEX between nonvitrectomized and vitrectomized eyes for either tissue at any time point (Table 1). As expected, the mean maximum concentration of DEX was approximately fivefold higher in the retina than in the vitreous humor (Table 2) and was similar between nonvitrectomized and vitrectomized eyes for the retina (4110 ng/g vs. 3670 ng/g, respectively) and for the vitreous humor (791 ng/mL vs. 731 ng/mL, respectively).

The mean $T_{\text{max}}$ was the same in the vitreous humor of nonvitrectomized and vitrectomized eyes and in the retinas of vitrectomized eyes (22 days). Mean $T_{\text{max}}$ was slightly shorter in the retinas of nonvitrectomized eyes (15 days). There were no significant differences in the absorption ($AUC_{\text{0-tlast}}$) of DEX between nonvitrectomized and vitrectomized eyes for both the vitreous humor (13,600 ng · days/mL vs. 15,000 ng · days/mL; $P = 0.73$) and the retina (67,600 ng · days/g vs. 50,200 ng · days/g; $P = 0.47$; Table 2).

Release of DEX from the DEX Implant

By day 31, the percentage of DEX remaining in the implant was similar in nonvitrectomized (5.0% ± 3.3%) and vitrectomized (4.2% ± 5.4%) eyes.

DISCUSSION

In this study, we have demonstrated similar vitreoretinal DEX pharmacokinetics after administration of the 0.7-mg DEX implant in nonvitrectomized and vitrectomized eyes. The concentration-time profiles for DEX were congruent for nonvitrectomized and vitrectomized eyes for both vitreous humor and retina for the duration of the study. Overall, our findings should reduce concerns with the use of the DEX implant in the eyes of patients who have undergone vitrectomy.

After vitrectomy, the vitreous is often replaced with an aqueous saline solution of lower viscosity than the normal vitreous humor. In vitro data suggest that DEX diffuses more quickly through saline solutions than normal vitreous humor.

Moreover, an earlier study examining the in vivo release of DEX sodium m-sulfobenzoate from a biodegradable poly(lactic acid) (PLA) implant suggests that the pharmacokinetics of DEX may be different in nonvitrectomized and vitrectomized eyes. In this earlier study conducted in rabbit eyes, the release of DEX from the PLA implant (which has chemical similarities with the DEX implant) was 2.5 times more rapid in vitrectomized eyes than in nonvitrectomized eyes. In contrast, the release of DEX from the DEX implant in our study was similar between nonvitrectomized and vitrectomized eyes. This suggests that the dissolution rates of sustained-release DEX from the implant were not different between the balanced salt solution used to replace the vitreous humor in vitrectomized rabbit eyes and normal vitreous humor. Further, assessment of the PLA implant found a good correlation between in vitro and in vivo release for vitrectomized eyes but not for nonvitrectomized eyes. This finding suggests that DEX release from the PLA implant depends on the physicochemical properties of the milieu, with more rapid release into aqueous saline buffer, compared with the more viscous vitreous.

The anatomic and physiological differences between rabbit eyes and human eyes should be considered when applying the findings of this study to human eyes. Findings from this study suggest that release of drug from the DEX implant is relatively fast (1–2 months) in rabbit eyes compared with, for example, monkey eyes, in which DEX is released from the implant for up to 6 months. The factors that can affect drug release from the implant are the implant characteristics (e.g., drug-polymer interactions), the solubility of drug in the vitreous humor, and the proximity of the implant to the primary elimination path.

### Table 1. Dexamethasone Concentration in the Vitreous Humor and Retina after Administration of the 0.7-mg Dexamethasone Implant in NonVit and Vit Eyes

<table>
<thead>
<tr>
<th>Day</th>
<th>Vitreous Humor (ng/mL)</th>
<th>Retina (ng/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NonVit</td>
<td>Vit</td>
</tr>
<tr>
<td>2</td>
<td>95.7 (63.7)</td>
<td>236 (284)</td>
</tr>
<tr>
<td>8</td>
<td>513 (250)</td>
<td>271 (243)</td>
</tr>
<tr>
<td>15</td>
<td>560 (426)</td>
<td>487 (481)</td>
</tr>
<tr>
<td>22</td>
<td>791 (367)</td>
<td>731 (484)</td>
</tr>
<tr>
<td>31</td>
<td>203 (135)</td>
<td>687 (980)</td>
</tr>
</tbody>
</table>

Data are mean (SD) for $n = 3$ to 5.
Given the lipophilic nature and the relatively low molecular weight of DEX, elimination is largely driven by diffusion through the retina.\textsuperscript{33}–\textsuperscript{35} In rabbit eyes, the implant is placed closer to the retina than in monkey eyes to avoid the large rabbit lens. Therefore, placement of the implant closer to the primary elimination pathway in rabbit eyes may increase the speed at which drug is released from the implant.\textsuperscript{34} However, once drug is released, factors such as vitreoretinal kinetics and route of elimination govern the rate of drug clearance from the vitreous,\textsuperscript{36} and the intravitreal half-life of DEX is expected to be similar between different species. Indeed, the estimated half-life of intravitreal DEX phosphate has been reported to be 3.5 hours in healthy rabbit eyes\textsuperscript{37} and 5.5 hours in patient eyes coadministered DEX and vancomycin for the treatment of endophthalmitis.\textsuperscript{38} Therefore, based on a vitreous volume of 1.4 mL in rabbit eyes and 4 mL in human eyes, we can estimate that the vitreal clearance of DEX is 8 mL/d in rabbit eyes and 12.1 mL/d in human eyes. These findings suggest that the vitreal clearance of the sustained-release DEX in human eyes is unlikely to be greatly different from the vitreal clearance observed in this study. Moreover, given that greater than 90% of DEX had been released from the DEX implant by day 31, this follow-up time was considered sufficient for determining the effect of vitrectomy on the pharmacokinetics of the DEX implant in rabbit eyes. Although this study was conducted for 1 month, pharmacokinetic data from a 9-month study of the DEX implant in primate eyes suggests that DEX is present at high concentrations in the vitreous humor and retina for up to 60 days and can be maintained for 6 months after administration of the implant.\textsuperscript{24} These data support the clinical findings of the DEX implant in nonvitrectomized patients with persistent macular edema, in which the DEX implant was well tolerated and provided sustained improvements in visual acuity for 180 days.\textsuperscript{15,\textsuperscript{25}–\textsuperscript{27}} In addition, the sustained release of DEX in the present study was consistent with preliminary clinical evidence from an open-label study\textsuperscript{30} of the DEX implant in vitrectomized eyes of patients with diabetic macular edema. In this pilot study, statistically significant improvements from baseline in central retinal thickness and visual acuity were observed 6 months after patients received the implant.

Given that the completeness of vitrectomy may influence the rate of clearance of many drugs,\textsuperscript{8} the extent of vitrectomy should be considered when comparing findings between nonvitrectomized and vitrectomized eyes. In this study, a near complete subtotal vitrectomy was performed and the pharmacokinetics of the DEX implant between nonvitrectomized and vitrectomized eyes were similar, which suggests that the extent of vitrectomy was not an important consideration in the interpretation of our results. Moreover, the variation in the concentrations of DEX found in the vitreous humor and retina is unlikely to be a result of differences in the extent of vitrectomy in some eyes and at some time points. Considerable variation in DEX concentrations were observed in both nonvitrectomized and vitrectomized eyes, and this variation most likely occurred as a result of small implant remnants contaminating the “no implant” vitreous humor fractions or small remnants in some retinal tissue samples. In addition, because all concentrations of DEX measured in the no implant samples in this study were well below the solubility of DEX in water (i.e., 100,000 ng/mL), our findings are likely to reflect differences in the concentration of soluble DEX in the vitreoretinal tissues.

In conclusion, this study has demonstrated similar pharmacokinetics of DEX in nonvitrectomized and vitrectomized eyes after administration of a 0.7-mg DEX implant. These data are relevant because they support the clinical findings that have been reported for the DEX implant in nonvitrectomized and vitrectomized eyes of patients with persistent macular edema.

Acknowledgments

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References


Table 2. Pharmacokinetic Parameters of Dexamethasone in the Vitreous Humor and Retina after Administration of the 0.7-mg Dexamethasone Implant in NonVit and Vit Eyes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NonVit</th>
<th>Vit</th>
</tr>
</thead>
<tbody>
<tr>
<td>C\textsubscript{max}, ng/mL</td>
<td>791 (367)</td>
<td>731 (484)</td>
</tr>
<tr>
<td>T\textsubscript{1/2}, days</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>AUC\textsubscript{0-tlast}, days/mL</td>
<td>13,600 (2270)</td>
<td>15,000 (3280)</td>
</tr>
<tr>
<td>AUC interval, days</td>
<td>0–31</td>
<td>0–31</td>
</tr>
</tbody>
</table>

Data are mean (SD) for C\textsubscript{max} (n = 3 to 5) and mean (SEM) for AUC\textsubscript{0-tlast}.


