Computer Modeling of Bevacizumab Drug Distribution after Intravitreal Injection in Rabbit and Human Eyes

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Abstract

Age-related macular degeneration (AMD) is a progressive eye disease that causes loss of central vision and has no cure. Wet AMD is the late neovascular form treated with vascular endothelial growth factor (VEGF) inhibitors. VEGF is the critical driver of wet AMD. One common off-label anti-VEGF drug used in AMD treatment is bevacizumab. Experimental efforts have been made to investigate the pharmacokinetic (PK) behavior of bevacizumab in vitreous and aqueous humor. Still, the quantitative effect of elimination routes and drug concentration in the macula are not well understood. In this work, we developed two spatial models representing rabbit and human vitreous to better understand the PK behavior of bevacizumab. This study explores different cases of drug elimination and the effects of injection location on drug concentration profiles. The models are validated by comparing them with experimental data. Our results suggest that anterior elimination is dominant for bevacizumab clearance from rabbit vitreous, whereas both anterior and posterior elimination have similar importance in drug clearance from the human vitreous. Furthermore, results indicate that drug injections closer to the posterior segment of the vitreous help maintain relevant drug concentrations for longer, improving bevacizumab duration of action at the fovea, which is located at the center of the macula. The rabbit and human models predict bevacizumab concentration in the vitreous and fovea, enhancing knowledge and understanding of wet AMD treatment.

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1. Introduction

Retinal diseases are the most common causes of vision loss in all age groups. The retina is a multilayered nerve tissue that lines the back of the eye, and in its center lies the macula. The macula contains the photoreceptors responsible for central high-resolution color vision. A hypoxic condition in the macula can cause vascular endothelial growth factor (VEGF) overexpression. VEGF is a protein essential to blood vessel growth, and its overexpression at the macula promotes the formation of aberrant new blood vessels, causing the irremediable wet form of age-related macular degeneration (AMD). AMD damages the macula and affects the center of the visual field, limiting the patient's ability to see clearly. AMD can cause irreversible central vision loss if it is not treated in time. Despite advances in treatment, AMD remains a significant public health issue and is the leading cause of severe vision loss in individuals older than 55 years in high-income countries[1].

In the United States, around 11 million people suffer from AMD[2,3], and the total is expected to double to 22 million by 2050[4]. AMD is generally found in people older than 65 years[5,6]. There are two types of AMD: non-neovascular (dry) AMD and neovascular (wet) AMD. The most common AMD is dry AMD, which refers to the early stages of the disease when drusen deposition and possible geographic atrophy of the macula occur[7]. Dry AMD can turn into wet AMD at any stage. Wet AMD is caused by abnormal blood vessel growth under the retina, and it causes severe vision loss by disrupting the normal anatomy of the retina[8]. Early detection and treatment of AMD could reduce impairment of a patient's vision.

Treatment of inner retinal diseases is challenging due to the anatomical barriers. Different ocular therapeutic approaches have been used to treat AMD, including intravitreal injection, drug implant, laser photocoagulation, and photodynamic therapy[9]. Intravitreal injection of anti-VEGF drugs is considered the most common option in AMD treatment[10] since it allows high drug concentration to reach the retinal layer with minimal side effects from the localized ocular treatment, and the injection can be performed in-office. Bevacizumab (Avastin), a recombinant humanized monoclonal antibody that is one of the most readily available and commonly used anti-VEGF therapeutics, is considered in this work.

Some experimental studies have measured the pharmacokinetic (PK) profiles of bevacizumab in animal eye models[11–15] and in human eyes[16,17]. Existing computational models of rabbit and human eyes have focused mainly on low molecular weight drugs[18–27] or on a multi-compartment approach to the eye[28–32]. However, relatively less emphasis has been placed on developing a physiologically based three-dimensional (3D) PK model for the spatial distribution of bevacizumab in the eye.

A 3D PK model was developed for bevacizumab distribution after both intravitreal injection and bevacizumab release from PLGA microspheres[33,34]. The limitation of this work is that the drug diffusion coefficient used in the simulation was not for bevacizumab but for fluorescein, which

is about three orders of magnitude smaller than bevacizumab. Thus, bevacizumab should have a smaller diffusion coefficient[28]. Our models use an experimentally calculated value for the bevacizumab diffusion coefficient in rabbit vitreous and an estimated bevacizumab diffusion coefficient in human vitreous.

Heat, momentum, and mass transport were considered in another 3D PK model after intravitreal injection of bevacizumab[35]. The researchers considered diffusion and convection in the aqueous humor but only diffusion in the vitreous. Intravitreal injection was modeled as an instantaneous point source. The model's boundary conditions included zero concentration at the iris and choroid. A limitation of this work is the model's low accuracy in predicting bevacizumab concentration at early time points. Our models focus on the vitreous only, with a clinically relevant injection of volume 0.05 mL. Our boundary conditions are at the lens and the choroid, but the conditions imposed change based on cases discussed later for considering anterior elimination alone or in combination with posterior routes of elimination.

In treating wet AMD, the therapeutic target is to control abnormal blood vessel growth in the macula. A region of particular interest in the macula is the fovea, located at the center and contains the largest concentration of cone photoreceptors that can be disrupted in AMD. Drug transport to this region depends on the vitreous properties.

The vitreous is a colorless, transparent, gel-like material with water making up 99% of its volume. The vitreous has viscoelastic properties[36–38] and is located at the center of the eye, between the lens and the retina. The vitreous comprises 80% of the eye's volume[38] and protects the retina from any disturbing substances as the vitreous is rigidly attached to some regions of the retina. The rheological and mechanical properties of the vitreous change anisotropically with age[38]. Here, we have assumed the vitreous to be homogeneous, but our approach can incorporate spatial heterogeneity in properties in the future.

Multiple computational investigations have simulated transport through the vitreous. The most common assumption is to consider the vitreous as a porous media and use Darcy's law to solve the fluid flow problem[21,23–25,39,40]. However, if a liquefied region is also considered within the vitreous, it is common to solve the fluid flow in porous media using Brinkman's equation[39,41] to allow for convection due to shear stresses.

In this work, we develop 3D PK models for rabbit and human eyes with space and time dependence for intravitreal injection of bevacizumab in the vitreous. The vitreous is modeled by considering relevant anatomic parameters and routes of drug elimination. The models are validated using experimental PK results from rabbit and human eyes. The models allow for the calculation of bevacizumab concentration both in the vitreous and at the fovea. We determine the number of days VEGF is expected to be completely inhibited at the fovea according to an established concentration threshold. This paper describes the models' geometry, governing equations, boundary and initial conditions, case studies, solution methods, and validation in Section 2. Section 3 presents the results and analysis obtained for bevacizumab concentration at different injection locations and convection rates. This analysis provides support for the conclusions in Section 4.

2. Methods

2.1. Geometry

The 3D geometry used in this study is based on the anatomy and properties of the rabbit and human vitreous. The vitreous volume in rabbit eyes varies from 1.15 to 1.70 mL[42]. The human vitreous is approximately three times bigger, and its volume varies between 4.22 and 5.43 mL[43]. The models use 1.44 and 4.79 mL volumes for the rabbit and human vitreous, respectively. Furthermore, the vitreous is considered semispherical in our model, influenced by the geometry from Khoobyar et al.[40]; however, other physiologically based models of ocular geometry have been discussed elsewhere[9].

In the present models (Figure 1a), the vitreous is located in a 3D spherical domain with origin at $(x_v, y_v, z_v) = (0,0,0)$ mm and a radius r_v of 7.6 mm for rabbit vitreous and 10.9 mm for human vitreous. The sphere is truncated by cutting the anterior portion of the eye perpendicular to the z-axis at $z = z_h = 4$ mm and 7 mm for the rabbit and human eyes, respectively. This location represents the hyaloid membrane between the aqueous humor and the vitreous. The lens is considered a sphere of radius r_l at origin (x_l, y_l, z_l) whose volume is subtracted from the vitreous domain. Together, the hyaloid membrane and the lens form the anterior boundary surfaces of the model domains. The vitreous semispherical outer surface is divided into two regions: anterior side and posterior side. The semispherical boundary defines the anterior vitreous outer surface for all $z \geq 0$ and r_v. The semispherical boundary defines the posterior vitreous outer surface for all $z < 0$ and r_v. The fovea is at the outer surface of the vitreous at position $(x_f, y_f, z_f) = (0,0,-r_v)$, which is our target location for bevacizumab. Table 1 summarizes the geometric properties in our model.

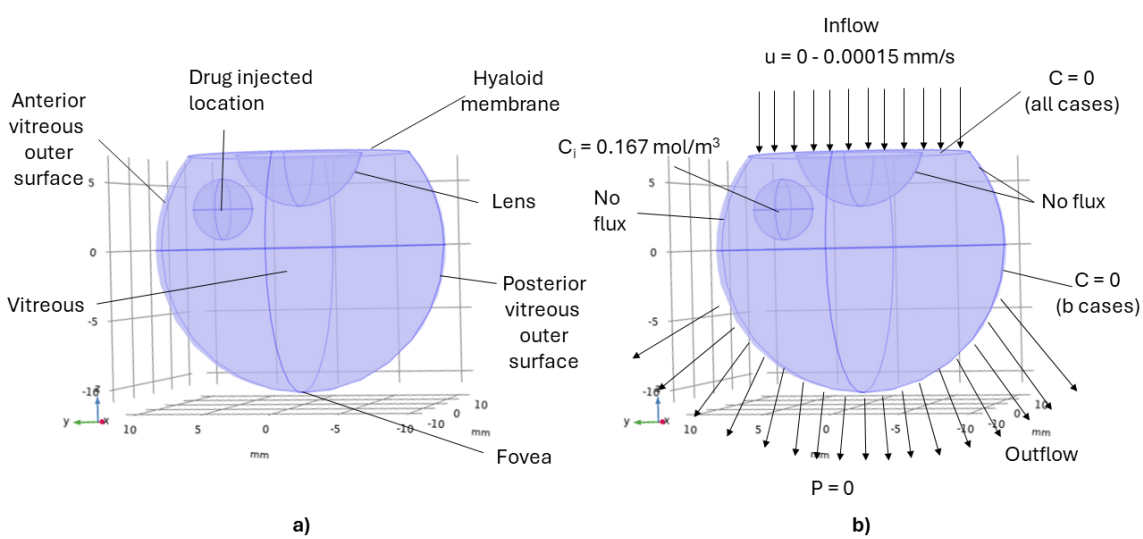

Figure 1: 3D geometry of the human eye: a) anatomical region description and b) boundary conditions. The rabbit geometry considers the same anatomical regions and boundary conditions scaled to rabbit dimensions. Dimensions for both the rabbit and human geometries are in Table 1.

Table 1: Model parameters used for the eye geometry, drug transport, Darcy's law, and macular dimensions.

Parameter[Source]	Rabbit	Human	Unit
Eye geometry			
Vitreous origin (x_v, y_v, z_v)	(0, 0 , 0)	(0, 0 , 0)	m
Vitreous radius r_v	7.6×10^{-3}	10.9×10^{-3}	m
Vitreous volume	1.44×10^{-6}	4.79×10^{-6}	m^3
Hyaloid membrane surface (z_h)	4×10^{-3}	7×10^{-3}	m
Lens origin (x_l, y_l, z_l)	(0, 0 , 4)$\times 10^{-3}$	(0, 0 , 8)$\times 10^{-3}$	m
Lens radius r_l	4.0×10^{-3}	4.9×10^{-3}	m
Fovea location (x_f, y_f, $z_f = -r_v$)	(0, 0, -7.6)$\times 10^{-3}$	(0, 0, -10.9)$\times 10^{-3}$	m
Injection bolus			
Origin for anterior vitreous dose (x_a, y_a, z_a)	(0, 4.9, -0.3)$\times 10^{-3}$	(0, 6, 3)$\times 10^{-3}$	m
Origin for middle vitreous dose (x_m, y_m, z_m)	(0, 2.5, -2.5)$\times 10^{-3}$	(0, 3, -0.5)$\times 10^{-3}$	m
Origin for posterior vitreous dose (x_p, y_p, z_p)	(0, 0, -4.5)$\times 10^{-3}$	(0, 0, -4)$\times 10^{-3}$	m
Radius of intravitreal injection r_i	2.3×10^{-3}	2.3×10^{-3}	m
Drug transport			
Drug injection concentration C_i [11,13,44]	0.167	0.167	mol/m^3
Drug diffusion coefficient D [28,45]	1.2×10^{-10}	9.13×10^{-11}	m^2/s
Reaction rate R [46]	0	0	$mol/(m^3 \cdot s)$
Darcy's law			
Density ρ [47,48]	1000	1008	kg/m^3
Viscosity μ [22]	0.001 [a]	0.001	Pa·s
Permeability κ [48]	5.8×10^{-14}	-	m^2
Permeability/viscosity κ/μ [23,26,49]	-	8.4×10^{-11}	$m^2/(Pa \cdot s)$
Inlet u at $z = z_l$ (fast convection) [40]	1.5×10^{-7} [a]	1.5×10^{-7}	m/s
Inlet u at $z = z_l$ (slow convection)	4.3×10^{-8}	3.4×10^{-8}	m/s
Outflow p at r_v and $z < 0$ [40]	0 [a]	0	Pa
Rabbit "macula" and human macula dimensions			
Diameter [50]	3.84×10^{-3} [b]	5.5×10^{-3}	m
Volume [51]	2.55×10^{-9} [b]	8.49×10^{-9}	m^3

a: assumed same as human vitreous. b: values proportional to a human macula.

The injection is considered a sphere with a volume of 0.05 mL (Figure 1). Given that a 30G needle's length usually varies between 12.7 to 15.75 mm[52], we consider different drug bolus origins to account for the potential variance in injection locations arising from differences in needle lengths and penetration depths. We define three injection locations: anterior vitreous, middle vitreous, and posterior vitreous (labeled as I–III in Figure 2, respectively).

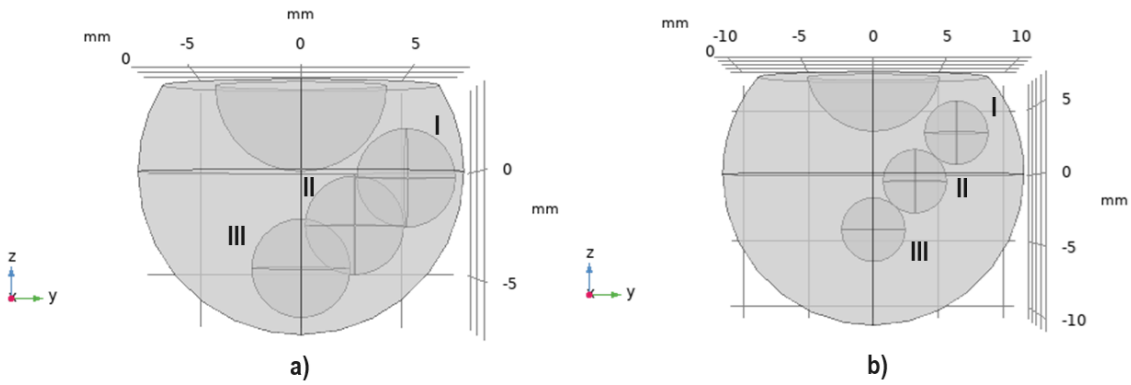

Figure 2: 3D models for vitreous of a) rabbit and b) human. Drug intravitreal injection locations are labeled as I–III for anterior, middle, and posterior locations, respectively.

2.2. *Governing equations and parameters*

2.2.1. *Drug transport*

Our PK models capture the continuum of drug movement through the vitreous. The convection-diffusion-reaction equation governs drug transport in the vitreous:

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C) - \mathbf{u} \cdot \nabla C + R \tag{1}$$

where D represents the diffusion coefficient of the drug, C is the drug concentration, $\mathbf{u}$ is the flow velocity, and R represents the reaction rate.

The PK models do not include the effect of metabolism and degradation of bevacizumab as both are negligible in the eye ($R = 0$)[46]. The drug distribution rate depends on the drug diffusion coefficient value. The diffusion coefficients of bevacizumab in rabbit and human vitreous and drug initial concentration are tabulated in Table 1.

A typical dose concentration for bevacizumab administration is 1.25mg/0.05mL[11,13,44], which is used for both humans and rabbits. The concentration at the injected location is defined as $C_i = 0.167$ mol/m^3. The initial drug concentration C_0 in the domain is defined as:

$$C_0 = \begin{cases} C_i & \text{for } (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = r_i^2 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where x_i, y_i, and z_i are given in Table 1 for the following injection positions: $i = a$ for the anterior of the vitreous nearest to the hyaloid membrane, $i = m$ for the middle of the vitreous, and $i = p$ for the posterior of the vitreous closest to the fovea. r_i is the resulting radius for a sphere of volume 0.05 mL.

2.2.2. *Fluid flow*

Assuming the vitreous is a porous media, fluid flow in the vitreous can be modeled using Darcy's law

$$\mathbf{u} = \left(\frac{\kappa}{\mu}\right)\nabla p \tag{3}$$

and the continuity equation

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \nabla\cdot(\rho\mathbf{u}) = Q_m \tag{4}$$

where $\mathbf{u}$ is the flow velocity, κ is the permeability of the vitreous, μ is the dynamic viscosity of the aqueous humor, p is the pressure, ρ is the density of the fluid, ε is the porosity, and Q_m is the mass source term, which is set to 0. The parameters used in Darcy's law are tabulated in Table 1.

In our model, the vitreous is considered a porous structure with a porosity value of $\varepsilon = 1$ as in Penkova et al.[53]. A reference pressure of $p = 1$ atm was used. Darcy's law's initial condition was zero throughout the domain ($p = 0$) before solving the steady-state pressure distribution pre-injection.

Slow (8×10^{-9} m/s)[33,34] and fast (1.5×10^{-7} m/s)[40] inlet velocities to the vitreous through the hyaloid membrane have been previously considered. We calculate a slow inlet velocity based on a constant aqueous humor production rate of 3 μL/min. Assuming that 7% of the aqueous humor production enters the rabbit vitreous and 10% enters the human vitreous[26] and using the hyaloid membrane surface areas of 0.81 cm^2 for rabbits and 1.47 cm^2 for humans (from our geometric models), we determine the corresponding slow inlet velocities. We use the same value as Khoobyar et al.[40] for the fast inlet.

Furthermore, a recent study[54] demonstrated that fluid velocity generated from eye globe expansion and deflation after intravitreal drug injections has a negligible effect on drug distribution in the eye; therefore, we do not consider any vitreous volume changes in our model.

2.3. *Boundary conditions*

The major routes of drug elimination in the eye are through the aqueous humor drainage (anterior elimination route) and blood-retinal barrier (posterior elimination route), with the anterior elimination route being the dominant one[46,48]. We consider the elimination routes via the boundary conditions (Figure 1b). We only consider the extreme cases of zero concentration ($C = 0$, which is equivalent to infinitely fast flux from the boundary) and no flux; however, others have considered the boundaries to be membranes with mass transport limitations (e.g., finite flux) between tissues[28–32,39,40].

The no-flux boundary condition for drug mass transport is defined by

$$-\mathbf{n} \cdot (-D\nabla C + \mathbf{u}C) = 0 \tag{5}$$

where $\mathbf{n}$ is the unit normal vector, D is the the diffusion coefficient of the drug, C is the drug concentration, and $\mathbf{u}$ is the fluid velocity.

The no-flux boundary condition for fluid flow is defined by

$$-\mathbf{n} \cdot (\rho \mathbf{u}) = 0 \tag{6}$$

where $\mathbf{n}$ is the unit normal vector, ρ is the density, and $\mathbf{u}$ is the fluid velocity.

2.3.1. Anterior elimination: hyaloid membrane

We consider the hyaloid membrane surface as the boundary for the anterior elimination route. We define a boundary condition of $C = 0$ at the hyaloid membrane's surface based on the idea that the aqueous humor mass transfer rate is fast compared to the rate at which the drug reaches the anterior segment. Therefore, the drug is cleared as soon as it reaches the anterior segment. Moreover, a portion of the aqueous can permeate through the vitreous[23]. Our models consider this to be an input velocity through the hyaloid membrane.

2.3.2. Impermeable surfaces: Lens and anterior portion of the vitreous outer surface

The lens and the anterior portion of the vitreous outer surface ($z \geq 0$ and r_v) are assumed to be impervious to fluids and drugs. Therefore, no-flux boundary conditions (Equations (5) and (6)) are applied at these tissues implying that there is no velocity ($u = 0$) across these boundaries, and no drug can leave the lens and anterior portion of the vitreous outer surface.

2.3.3. Posterior elimination: Posterior portion of the vitreous outer surface

We consider the posterior portion of the vitreous outer surface ($z < 0$ and r_v) as the boundary for the posterior elimination route. Given that the blood can be regarded as a perfect sink and that the retinal layer surrounding this tissue is thin, a concentration of $C = 0$ is considered for cases (described in Section 2.4) with posterior elimination. Furthermore, a reference pressure of $p = 0$ Pa is set as the outflow boundary condition for the fluid flow (Figure 1b). No-flux boundary conditions are used for cases without posterior elimination.

2.4. Case studies

We investigate four cases with our models to explore different combinations of convection and drug elimination routes. Table 2 summarizes the four case studies.

The vitreous is modeled as a porous viscoelastic material for the cases where convection is accounted for (denoted by "1"). The aqueous humor fluid produced from the ciliary body permeates the vitreous through the hyaloid membrane, and we consider it as an inlet fluid velocity in our models following another published model that considered convection[40] (Figure 1b). Other

Table 2: Summary of case studies.

	Convection	Anterior elimination ($C = 0$)	Posterior elimination ($C = 0$)
Case 1a	✓	✓	X
Case 1b	✓	✓	✓
Case 2a	X	✓	X
Case 2b	X	✓	✓

models have also considered convection in the vitreous and point to the importance of this transport mechanism for slow diffusing macromolecules[26]. Slow convection is considered for the three injection locations studied, and fast convection is also considered at the middle vitreous position. The resulting flow from Equations (3) and (4) at steady-state is coupled to the convection-diffusion equation (Equation (1)) for the drug transport.

Another common assumption is that there is no fluid flow in the vitreous when modeling transport across the vitreous[24,55]. In the cases denoted by "2", we consider zero inlet velocity ($u = 0$) in the vitreous, meaning there is no convection and only diffusion across the vitreous.

The mechanism for drug clearance in the eye is not fully understood. High molecular weight compounds are usually eliminated via the anterior route[10,31,56]. A recent study observed the elimination routes of anti-VEGF therapeutics in both human and rabbit vitreous[46]. The results suggested that the anterior elimination route is dominant compared to the posterior route for bevacizumab and other anti-VEGF drugs in both human and rabbit eyes. This dominance also depends on the eye's aqueous humor flow rate. However, monoclonal antibodies such as bevacizumab are lipophilic compounds[57,58]. Lipophilicity allows molecules to cross the retina and be eliminated through the posterior route[10].

In our simulations, we consider two elimination routes. Only anterior elimination is considered in the cases denoted by "a" ($C = 0$ at the hyaloid membrane surface and no-flux boundary conditions on all the other boundaries). In the cases denoted by "b", both anterior and posterior elimination ($C = 0$ boundary conditions at the hyaloid membrane and the posterior portion of the vitreous outer surface) are considered. We do not consider a posterior elimination route alone, given that experimental results point towards the prevalence of the anterior elimination route.

We combine the two cases for convective flow modeling in the vitreous with the two elimination cases for a total of four case studies. We study convection in the vitreous with anterior elimination only (Case 1a), convection with both anterior and posterior elimination (Case 1b), no convection with anterior elimination only (Case 2a), and no convection flow with both anterior and posterior elimination (Case 2b).

2.5. Solution methods and meshing

The rabbit and human eye geometries were created, and model equations were formulated and solved in COMSOL Multiphysics 6.1[59]. The Transport of Diluted Species interface was used for

the mass transport of bevacizumab. The Darcy's Law interface was used for fluid flow through the vitreous.

The mesh was generated using the "extra fine" physics-controlled mesh option in COMSOL. The rabbit model consisted of 162,750 elements and 7,252 boundary elements, and the human model consisted of 185,119 elements and 7,076 boundary elements. A mesh independence test was performed using drug concentration results at different mesh sizes. The results were determined to be independent of the mesh settings (Figures S1 and S2).

2.6. Concentration and half-life calculations

From our 3D PK model, we calculate drug concentration in the vitreous and at the fovea for the different case studies described. Concentration in the vitreous is calculated as the volume average in the vitreous domain for both the rabbit and human models using a volume probe in COMSOL.

Bevacizumab concentration at the fovea for Case 1a and Case 2a is calculated using a point probe at the locations specified as (x_f, y_f, z_f) (Table 1). This method cannot be applied for Cases 1b and 2b since $C = 0$ is an established boundary condition in these cases. Therefore, we determine the bevacizumab flux using a point probe in the same locations (x_f, y_f, z_f). Then we use the diameter and volumetric information of the macula (Table 1) to calculate a rolling daily average concentration assuming that the fovea is just on the outside of the point on the vitreous boundary (Figures S3–S6).

There is no clearly defined macula in the rabbit eye[60]; rabbits have a horizontal area with higher cell density called a visual streak[61]. However, we are interested in comparing the amount of drug leaving the vitreous and reaching the retina near the macula region in both species, so we assumed a rabbit "macula" proportional to the scale of a human macula. Table 1 contains the parameters used for the human macula and the rabbit macula approximation. The center point of the macula is taken to be the fovea in both species.

To control the endothelial cell growth to inhibit VEGF completely, the minimum concentration of the therapeutic antibody bevacizumab needs to be 500 ng/mL (0.5 μg/mL)[62]. After calculating the bevacizumab concentration at the fovea with each model, the results determine the number of days when the bevacizumab concentration is above this threshold, which is defined as "duration of action".

Half-lives were calculated by interpolating concentration results. Starting from an arbitrary base concentration at time points of 3 days for rabbits and 5 days for humans, the time at which the concentration reduced by half was obtained through interpolation of the concentration results.

2.7. Validation

WebPlotDigitizer[63] was used to extract data from plots in previously published experimental studies on rabbit and human eyes to validate the model. These experiments measured bevacizumab concentration in the vitreous, but none measured the drug concentration at the macula in human eyes or at the visual streak in rabbit eyes. The experiments followed a similar methodology. Briefly, 1.25 mg/0.05 mL of bevacizumab was injected 1–4 mm behind the surgical limbus in the vitreous

supertemporal quadrant using 30G needles. Model simulations were performed under the same conditions as these experiments.

2.8. Code availability

We have provided the COMSOL codes in a repository at `https://github.com/ashleefv/PBPKHumanRabbitEyes`[64].

3. Results and discussion

3.1. Effects of injection location on bevacizumab distribution after intravitreal injection

Figure 3 shows the normalized concentration profiles of bevacizumab when the injection dose is given at the anterior (a), middle (b), and posterior (c) of the rabbit vitreous and at the anterior (d), middle (e), and posterior (f) of the human vitreous. Regardless of injection location, the slowest clearance in the vitreous happens when considering no convection and anterior elimination only (Case 2a). The fastest clearance from the eye is obtained when considering both anterior and posterior elimination with or without convection (Case 1b and Case 2b, respectively). Intermediate clearance and bevacizumab concentrations are obtained when considering convection through the vitreous and anterior elimination (Case 1a). Spatial distribution plots of bevacizumab concentration at different times in the human vitreous are available for each case in Figures S7–S10.

In rabbits, the concentration results for Case 1a and Case 2a are closer to the experimental data in all three injection locations (Figure 3a–c). These results suggest that drug clearance in the rabbit eye is mainly driven by anterior elimination and that some limited convection might also play a role. Bevacizumab concentration in the rabbit vitreous drops rapidly when considering Case 1b and Case 2b, independently of the injection location. Even though experimental data is sparse, the data[11–15] still show a longer residence time in the vitreous than predicted by these two cases. This suggests posterior elimination is not the main route of drug clearance in rabbit vitreous, which is consistent with other published results[46].

In humans, Case 1b and Case 2b predict similar results, with these two cases being the closest to the experimental data. This suggests that the posterior and the anterior elimination routes play significant roles in drug clearance from the human vitreous. Regardless of the injection location, Case 2a significantly underestimates drug clearance in the human vitreous. Bevacizumab concentration in Case 1a is slightly closer to the experimental data than in Case 2a, but neither fits the limited data[17] exactly. This suggests that the anterior elimination route, even with slow convection, is not enough to explain bevacizumab clearance in the human vitreous. Furthermore, deeper injections result in slower drug clearance in the eye and larger deviations from the experimental data. Case 1b and Case 2b predict faster drug clearance in the eye after a few days compared to the data[16,17]. Therefore, the boundary condition $C = 0$ might be too extreme. This suggests that the human boundary conditions are likely a combination of anterior elimination and somewhat limited posterior elimination compared to the $C = 0$ boundary condition.

The calculated bevacizumab vitreous half-lives for the simulated cases at each injection location are tabulated in Table 3. Our calculated half-lives agree with the PK profiles obtained in the

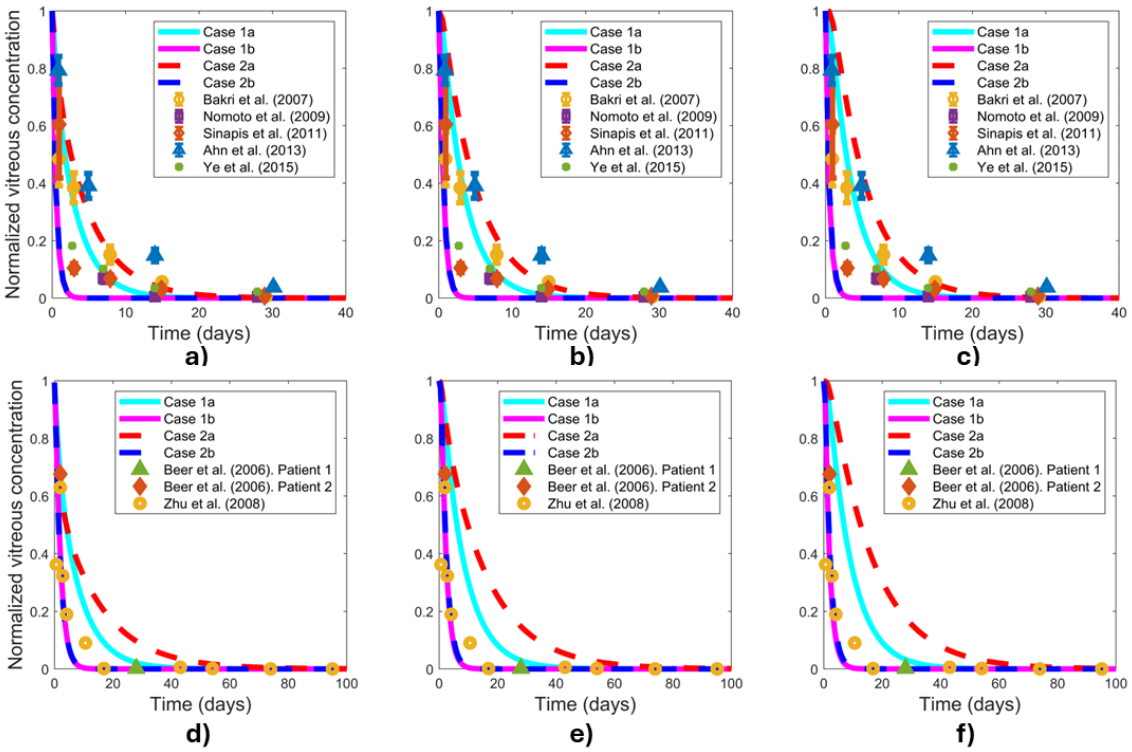

Figure 3: Normalized vitreous concentration in the rabbit and human eye. Injection locations: a) rabbit anterior vitreous, b) rabbit middle vitreous, c) rabbit posterior vitreous, d) human anterior vitreous, e) human middle vitreous, and f) human posterior vitreous. Case 1a: slow convective flow with anterior elimination only, Case 1b: slow convective flow with both anterior and posterior elimination, Case 2a: no convective flow with anterior elimination, and Case 2b: no convective flow with both anterior and posterior elimination. Model results for each case are shown as curves. Experimental data (markers) from Bakri et al.[11], Nomoto et al.[12], Sinapis et al.[13], Ahn et al.[14], Ye et al.[15], Beer et al.[16], and Zhu et al.[17].

rabbit vitreous and are closer to the lower end of the reported range of 3.51–7.06 days[65] when considering Case 2a in rabbits (Case 1a is also reasonable). The half-lives for the human vitreous are near the expected range of 5.8 $\pm$ 1.27 days[66], which matches Case 1a most closely although the concentration profiles for the data[16,17] fall between the profiles for Case 1a and for Cases 1b and 2b (Figure 3). If the human boundary conditions were to be adjusted to be a combination of anterior elimination and somewhat limited posterior elimination, then the resulting half-life would be between that of Case 1a and of Cases 1b and Case 2b. Another source that calculated vitreal elimination half-lives based on a retrospective literature survey has the bevacizumab half-lives as 5.5 days for rabbit and 10.1 days for human[46], which is most consistent with Case 2a calculated for rabbit and for human here.

Bevacizumab half-life increases when injections are nearer to the posterior segment of the eye without posterior elimination. This is expected as the farther the injection site from the anterior segment, the slower the clearance of bevacizumab. In the larger human eye for cases where both anterior and posterior elimination are considered (Case 1b and Case 2b), injections at the anterior of the vitreous may provide marginally longer half-lives due to the relatively smaller surface area for anterior elimination proximal to the dose (Table 3).

Table 3: Calculated bevacizumab vitreous half-lives in days.

Injection location	Case 1a	Case 1b	Case 2a	Case 2b
Rabbit				
Anterior vitreous	2.12	0.38	3.26	0.38
Middle vitreous (slow convection)	2.12	0.38	3.27	0.38
Middle vitreous (fast convection)	1.00	0.32	3.27	0.38
Posterior vitreous	2.14	0.38	3.27	0.38
Human				
Anterior vitreous	5.29	1.20	10.00	1.27
Middle vitreous (slow convection)	5.36	1.19	10.25	1.27
Middle vitreous (fast convection)	1.62	0.68	10.25	1.27
Posterior vitreous	5.46	1.19	10.56	1.27

Our model results when considering anterior elimination only better describe drug concentration in the vitreous after intravitreal injection in rabbits for the Bakri et al.[11] data when compared to previously published models[35,67] (results not shown here). One possible reason for this is that the published models used a bevacizumab diffusion coefficient of 4×10^{-7} [35] and 5.21×10^{-7} [67] cm^2/s, which are significantly lower than our value of 1.2×10^{-6} cm^2/s. Another advantage of our model is the relative computational simplicity. Both these models involved an entire eye geometry, with a mesh of over 1.5 million elements in the model by Sibak et al.[35]. In contrast, our rabbit model involved only the vitreous, with proper boundary conditions and a mesh of 162,750 elements.

Our model results when also considering posterior elimination better predict vitreous bevacizumab concentration after intravitreal injection in human eye for the Zhu et al.[17] data compared to the model by Missel and Sarangapani[67] (results not shown here), particularly at early time points. Their model results and our model results for the case of anterior elimination only are similar despite differences in the diffusion coefficients used (5.21×10^{-7} cm^2/s in their model compared to 9.13×10^{-7} cm^2/s in our model). Additionally, while their model involves a detailed human eye geometry, our model focuses specifically on the human vitreous, making the calculations less computationally expensive.

Figure 4 shows bevacizumab concentration in the rabbit "fovea" when the injection dose is given at the anterior (a), middle (b), and posterior (c) of the rabbit vitreous and in the human fovea for injections placed at the anterior (d), middle (e), and posterior (f) of the human vitreous. The results agree with the bevacizumab concentration profiles in the vitreous obtained in Figure 3. When posterior elimination is considered (Case 1b and Case 2b) for all drug locations, a rapid initial increase in the bevacizumab concentration at the fovea is observed, followed by a sharp decrease. When posterior elimination is not considered (Case 1a and Case 2a), the maximum concentration achieved at the fovea is lower, but clearance is also slower.

A minimum concentration of 0.5 μg/mL is likely required to completely prevent angiogenesis[62]. Table 4 summarizes the predicted bevacizumab duration of action for the study cases at the different injection locations. As expected, calculated half-lives in the human vitreous were longer than the ones in the rabbit vitreous. The drug's duration of action in the human fovea is longer than in the rabbit "fovea" since bevacizumab clearance in the smaller rabbit eye is faster than in the larger human eye. For both Case 1b and Case 2b, our rabbit model predicts that the concentration of bevacizumab goes below the threshold after six days, independently of the injection position. In Case 1a, bevacizumab concentration above the threshold is maintained at the rabbit "fovea" for about 24, 24.5, and 25 days for injections located at the anterior, middle, and posterior vitreous, respectively. Case 2a maintains a duration of action of bevacizumab for 36–37.5 days in rabbits, depending on the injection location. In humans, depending on the injection location, Case 1b bevacizumab concentration goes below the 0.5 μg/mL threshold after 14–14.5 days. Similarly, the duration of action for Case 2b for humans varies in the range of 14.5–15.0 days. For Case 1a in humans, the predicted duration of action is in the range of 51.5–54.5 days. Case 2a predicts a duration of action greater than three months in humans. Note that no case shown for the human vitreous is within the expected duration of action interval of 28–42 days, which is usually the dosing interval for bevacizumab in humans. Instead, the simulated cases bound the actual human data[16,17]. This is further consistent with the idea that the human boundary conditions are likely a combination of anterior elimination and somewhat limited posterior elimination, which would generate an intermediate value of the duration of action between the values of the simulated cases.

Khoobyar et al.[40] calculated a pressure distribution in the human eye considering the vitreous divided into a liquefied and a gel-type region. They calculated the pressure distribution throughout the vitreous and obtained a pressure drop below 50 Pa[40]. Our model calculated the spatial pressure in the vitreous domain and found a much smaller pressure drop, around 2 Pa for slow convection cases (Figure S11 a) and below 10 Pa for fast convection cases (Figure S11 b). This is consistent

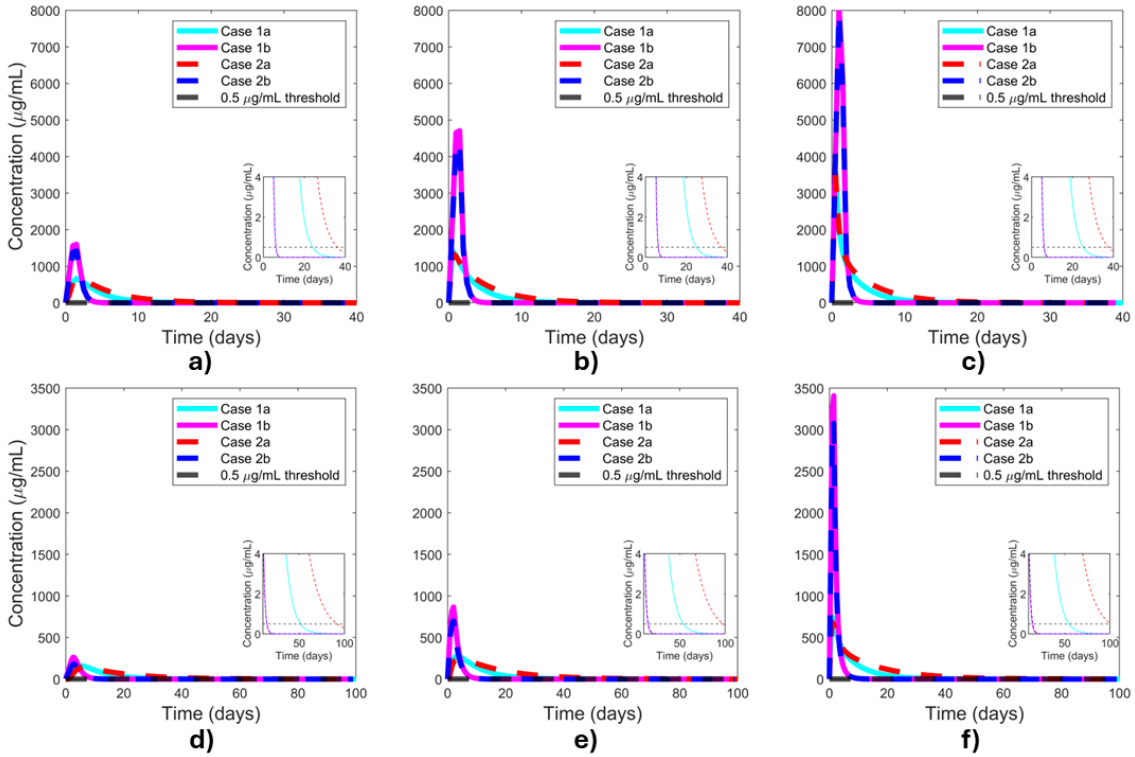

Figure 4: Drug concentration at the rabbit "fovea" and human fovea. Injection locations: a) rabbit anterior vitreous, b) rabbit middle vitreous, c) rabbit posterior vitreous, d) human anterior vitreous, e) human middle vitreous, and f) human posterior vitreous. Case 1a: slow convective flow with anterior elimination only, Case 1b: slow convective flow with both anterior and posterior elimination, Case 2a: no convective flow with anterior elimination, and Case 2b: no convective flow with both anterior and posterior elimination.

with other publications that report pressure drops below 2 Pa in the vitreous[23,26,49].

3.2. Effects of convection on bevacizumab distribution after intravitreal injection in the middle vitreous

We compared the cases of slow and fast aqueous humor inlet at the rabbit and human eyes when the injection was placed in the middle vitreous. The velocity profiles are shown in Figure S12. Figure S13 shows the normalized concentration profiles of the drug bevacizumab in the rabbit vitreous when the injection dose is given at the middle vitreous for slow (a) and fast (b) convection and in the human vitreous when the injection dose is given at the middle vitreous for slow (c) and fast (d) convection. The cases of interest are Case 1a and Case 1b, since Case 2a and Case 2b do not consider convection and therefore present no differences between the plots. For Case 1a, increasing convection results in a significantly faster bevacizumab clearance than for slow convection. For Case 1b for rabbits, the increase in convection produces a relatively small increase in bevacizumab

Table 4: Calculated bevacizumab duration of action at the fovea in days.

Injection location	Case 1a	Case 1b	Case 2a	Case 2b
Rabbit				
Anterior vitreous	24.0	6.0	36.0	6.0
Middle vitreous (slow convection)	24.5	6.0	37.0	6.0
Middle vitreous (fast convection)	12.0	5.5	37.0	6.0
Posterior vitreous	25.0	6.0	37.5	6.0
Human				
Anterior vitreous	51.5	14.0	91.5	14.5
Middle vitreous (slow convection)	53.5	14.5	97.5	15.0
Middle vitreous (fast convection)	18.5	10.0	97.5	15.0
Posterior vitreous	54.5	14.0	>100	14.5

clearance from the eye. By considering a fast inlet of aqueous humor through the hyaloid membrane, the predicted bevacizumab concentrations deviate significantly from the experimental data in rabbit vitreous. This supports the idea that, in rabbit vitreous, convection effects are essentially negligible, and the anterior route of elimination is the dominant route. For Case 1b in humans, considering a fast inlet of aqueous humor through the hyaloid membrane results in bevacizumab concentrations closer to the experimental data in human vitreous. This supports the idea that vitreous convection can be present in humans, and both the anterior and posterior routes of elimination play significant roles in drug clearance. Bevacizumab vitreous half-lives for the cases of slow and fast convection are reported in Table 3.

The bevacizumab concentration profiles in the rabbit "fovea" and the human fovea are shown in Figure S14 for the different convection scenarios, and the duration of action of bevacizumab is tabulated in Table 4. A faster aqueous humor inlet reduces the duration of drug action compared to a slow aqueous humor inlet for cases where convection is considered. Case 1a with fast convection keeps the concentration above the 0.5 μg/mL concentration threshold in rabbits for 12 days (compared to 24.5 days for slow aqueous humor inlet) and in humans for 18.5 days (as compared to 53.5 days with slow aqueous humor inlet). For Case 1b in rabbits with fast convection, the concentration above the threshold lasts 5.5 days (compared to 6 days when considering slow convection) and in humans for 10 days (as opposed to 14.5 days for slow convection). The duration of action for Case 1a is not within the expected range for frequency of administration (28–42 days) for either slow convection (too long) or fast convection (too short). Considering an intermediate convection velocity in human vitreous might help predict better bevacizumab duration of action, in addition to considering adjusted boundary conditions mentioned above.

4. Conclusions

The drug transport mechanisms in the vitreous are not entirely understood and depend on several factors, including species, vitreous properties, age, boundary conditions, and individual ocular anatomy. These factors help explain the variations found in the experimental results where, under the same conditions, researchers obtained different PK profiles.

Our PK models provide realistic estimates of bevacizumab transport in rabbit and human vitreous. The models were validated with published experimental data. Both our models' results are close to the experimental data despite the high variability in the experimental data due to the difference in the vitreous' physiological and material properties among individuals of the same species.

Model results suggest that in rabbit vitreous, one of the most commonly used PK animal models, the effect of the anterior elimination route is dominant over the posterior elimination route. Differently, the results obtained for bevacizumab concentration in human vitreous suggest that the posterior elimination route is more relevant than in rabbit vitreous clearance. Posterior elimination plays a significant role alongside the anterior elimination route in drug clearance from the human eye.

Furthermore, the modeling results show that drug injection location influences vitreous half-life when only anterior elimination is considered. In smaller rabbit vitreous, where anterior elimination dominates, injections at the posterior vitreous maintain higher bevacizumab concentrations for longer. In the larger human vitreous, where both anterior and posterior elimination are important, injections at the middle vitreous provide a marginally longer duration of action at the fovea, and doses at the anterior vitreous provide slightly longer half-lives.

Bevacizumab concentration in the fovea followed a behavior comparable to the vitreous concentration profiles. An initial sharp increase in bevacizumab concentration followed by a rapid decrease is observed when convection is considered. Considering anterior elimination only (Case 2a) resulted in the drug's most extended duration of action, followed by anterior elimination and convection (Case 1a). Cases that considered posterior elimination with (Case 1b) or without (Case 2b) convection resulted in the shortest duration of action.

Our PK models successfully capture drug absorption and distribution in the vitreous, considering the elimination routes from published data. We used our PK models to predict drug concentration in the vitreous of rabbit and human eyes and the duration of action of an intravitreal injection. Such simulation results can be used to gain insight into different dosing regimes. One limitation of our human model is the scarcity of available experimental data to better interpret and validate our results.

Another limitation of the current work is that it focuses only on intravitreal injection. Others have considered modeling controlled-release formulations for intravitreal delivery (reviewed by Chacin Ruiz et al.[9]). This is a direction the current work could be extended towards.

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