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A simple mathematical model of rhegmatogenous retinal detachment

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ABSTRACT

The conditions under which rhegmatogenous retinal detachment occurs are poorly understood, which hampers the success rates of surgery. Fluid dynamical effects play a major role, and in this paper we analyse the tendency for the retina to detach further in both the case of a free flap giant retinal tear (GRT) and in the case of a retinal hole (RH). For this purpose we use a mathematical model to investigate the interaction between the fluid flow and the detached retina during saccadic eye movements. The governing equations are solved numerically using a code developed ad hoc. An idealised two-dimensional geometry is used and realistic values of almost all governing parameters are taken from the literature. For the cases of both GRT and a RH we investigate the tendency for the detachment to progress, analysing two different saccadic motions, different lengths of the detached retina, different attachment angles and, in the case of a RH, different hole diameters. In both cases we find that increasing the length of the detached retina increases the tendency for further detachment, while in the RH case, changing its diameter has little or no effect. We also find the existence of an attachment angle that maximises the tendency to detach, and the model indicates that RHs are more prone to detach further than GRTs. In spite of the fact that the model is highly idealised the results agree qualitatively well with the available clinical evidence.

1. Introduction

Rhegmatogenous retinal detachment (RRD) occurs in approximately 10: 100 000 of the population (Mitry et al., 2009). It is caused by the appearance of a retinal break or breaks in the peripheral retina, which are associated with the accumulation of subretinal fluid, causing detachment of the neurosensory retina. Traction on the retina from separation of the posterior vitreous is thought to create the retinal break. However, traction alone cannot explain the development of the retinal break into full RRD. For this reason it has been postulated that saccadic eye movements create currents in the liquefied vitreous, which cause the retina to lift away. This process is poorly understood and has not been extensively investigated from the mechanical point of view. Unchecked retinal detachment results in blindness. Although surgical interventions lead to successful reattachment in many cases, there is often uncertainty surrounding the mechanism of action of these surgical methods, resulting in suboptimal success rates. It should be noted that both the typical clinical presentation and the rate of

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Table 1
Parameter values used for the simulations and corresponding references when available.

Quantity	Value	Reference
Properties of the retinal flap		
Density ρ_S^*	1300 kg/m^3	
Length L^*	1.5–2.5 mm	
Thickness h^*	70 μm	Alamouti and Funk, 2003; Foster et al., 2010; Ethier et al., 2004; Bowd et al., 2000; Wollensak and Eberhard, 2004; Dogramaci and Williamson, 2013
Young's modulus E^*	$1.21 \cdot 10^3$ N/m^2	Jones et al., 1992; Wollensak and Eberhard, 2004; Reichenbach et al., 1991; Sigal et al., 2005
Bending stiffness $K_b^* = E^*h^{*3}/12$	$3.46 \cdot 10^{-11}$ Nm^2	
Properties of the fluid		
Density ρ_F^*	1000 kg/m^3	Foster et al., 2010
Dynamic viscosity μ^*	$1.065 \cdot 10^{-3}$ kg/ms	Foster et al., 2010

progress of a retinal detachment vary amongst different subjects. The risk of total retinal detachment is important as this affects the anatomical and visual outcome (Williamson et al., 2013, 2014).

In the present study, we model the effects of fluid flow due to saccadic eye motion on a two-dimensional construct of retinal detachment. Various parameters are examined to determine their effects on the elevation of the retina and improve our understanding of what causes or increases the tendency of the retina to detach. As in similar works (Peskin, 2002; Zhu and Peskin, 2002; Kim and Peskin, 2007; Natali et al., 2016), an immersed boundary (IB) method has been used to model elastic bodies interacting with a viscous incompressible fluid. Such a method has been used in various applications, such as cardiac valves (Kovacs et al., 2001) and animal locomotion (Fauci and Peskin, 1988), but this is the first time, to the authors knowledge, it has been used in the context of retinal detachment modelling. Previous works regarding the retina include calculating the shear stress on the retinal surface (Angunawela et al., 2011; Eames et al., 2010; Repetto et al., 2010a; Meskauskas et al., 2012; Abouali et al., 2012; Modarreszadeh and Abouali, 2014), gas diffusion in the vitreous cavity (Shunmugam et al., 2011), silicone oil usage (Dogramaci and Williamson, 2013; Isakova et al., 2014), retinal tractions (Repetto et al., 2010b) and peeling of membranes from the retinal surface (Dogramaci and Williamson, 2013; Bottega et al., 2013), just to mention a few. In order to study the tendency of the retina to further detach from the underlying choroid, due to the combined actions of the forces and moment at the attachment point(s) arising from the interaction between the detached retina and the surrounding fluid, we borrow a simple model from geotechnics of a structure on an elastic foundation (Winkler, 1867). The model assumes that the foundation can be described as a system of identical, mutually independent, closely spaced, discrete and linearly elastic springs. The model allows us to evaluate the displacement of the foundation, which is then analysed as a function of the parameters of interest. We believe that this study, first of its kind in that a fully coupled fluid–structure interaction model has been applied, despite the various approximations it is based on, gives insight on how the tendency of RRD progress depends on parameters, such as amplitude of the saccade, length of the detached retina, detachment angle, and hole diameter (in the case of a RH).

The paper is organised as follows. Section 2 describes the geometry and mechanical properties of the retina and the surrounding fluid as well as the saccadic eye motion. In Section 3 the governing equations for the fluid and the structure are presented along with the elastic foundation model. The numerical results are presented in Section 4 and conclusions are drawn in Section 5.

2. Geometry and mechanical properties

In this work we use simplified geometrical models to study the dynamics of detached retinal flaps induced by rotations of the eye. Specifically, we consider the two different cases depicted in Fig. 1a,b, and we use mathematical models of these simplified geometries to determine the effect of fluid flow on detachment progression. In particular, we use a two-dimensional approximation of the geometry and of the fluid flow, neglecting three-dimensional effects. Within our two-dimensional context the retinal flap is described as a slender, massive, inextensible, one-dimensional structure, with a fixed bending stiffness. In reality a retinal flap with length $L^* = 2$ mm, which is the baseline value used in this work, has an aspect ratio (thickness to length ratio) of approximately 1/30, justifying the slender-body assumption. Geometrical and mechanical properties of the retinal flap are presented in Table 1. The bending stiffness of the retina K_b^* is obtained from the value of the Young's modulus E^*, which has been computed by several authors (Jones et al., 1992; Wollensak and Eberhard, 2004; Reichenbach et al., 1991; Sigal et al., 2005) and the thickness h^*, on the basis of the relationship: $K_b^* = E^*h^{*3}/12$. Note that here superscript $*$ denotes dimensional variables and parameters. The inextensibility of the retina is an approximation and justified by the fact that no data regarding stretching of the detached retina can be found in the literature.

We model the retinal surface as a flat rigid wall, and neglect curvature effects. Moreover, we assume that the region occupied by the liquefied vitreous extends to infinity in the direction orthogonal to the retinal plane. The above assumptions are acceptable if the length of the flap is much smaller than the radii of curvature of the wall. In the present case the radius r^* of the vitreous chamber is approximately 12 mm, and the corresponding ratio L^*/r^* is between 0.125 and 0.21,