Communication

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On the Role of the Water Hammer Pressure in the Modeling of Hydrodynamics of the Human Eye: A Qualitative Analysis and Its Consequences for Physical Training and Healthy Lifestyle

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Abstract: A qualitative analysis of pressure acting within the human eye is presented. The situation emerging within the human eye in rest and human eye of accelerated/training person should be distinguished. When the person is in rest, the hydrostatic pressure is much larger than the Laplace pressure. The dynamic (Bernoulli pressure) emerging from intraocular flows in this case is negligible. The situation is rather different for accelerated or decelerated person. In this case, the dynamical pressure and the water hammer pressure become dominant. Under certain circumstances, the water hammer pressure may be larger than the ultimate tensile strength of retina, choroid and the Bruch membrane-choroid complex, which may possibly affect the retina. As a recommendation: physical training, which is not accompanied with ultimate acceleration/acceleration of the body, may be performed after posterior vitreous detachment; however, potentially traumatic activities such as boxing or competitive diving should be avoided.

Keywords: retina; hydrostatic pressure; physical training; Laplace pressure; dynamic pressure; water hammer pressure; ultimate tensile strength

1. Introduction

In our paper we report one of the controversial problems related to the interrelation between physical activity and health, namely relationship between physical training and ophthalmology diseases, namely Posterior Vitreous Detachment (PVD), i.e., the condition diagnosed when the gel that fills the eyeball separates from the retina. On one hand there are numerous reports evidencing that physical activity and exercise improve retinal microvascular health [1] On the other hand the direct evidence of the interrelation between the sport trauma (such as suffering impact from balls travelling at high velocity, boxing trauma or competitive diving) and retinal detachment were reported [2-4]. PVD is a natural phenomenon, in which the posterior vitreous cortex separates from the internal limiting membrane of the retina [5-6]. This separation occurs after the gradual liquefaction of the vitreous, and may be associated with symptoms such as flashes and floaters [7-8]. PVD commonly occurs between the ages of 45 and 65 years, but may occur earlier in patients with myopia or following trauma and ocular surgery [6, 9]. In some cases, vitreous traction on the retina due to the PVD process causes retinal tears, which may progress to retinal detachment. The occurrence of retinal tears in patients with symptomatic acute PVD has been reported to vary between 8% to 22% [6,9]. Of these cases complicated by retinal tears, up to 5% may progress to retinal detachment [10-11].

Many ophthalmologists recommend patients with acute PVD to refrain from physical activity. Although there are no formal guidelines supporting this recommendation. It is possible that the roots of this practice are in previous works from the early days of retinal surgery, in which patients

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recovering from retinal detachment surgery were instructed to avoid physical activity for one to three months following surgery [12-13].However, later works have shown that physical activity does not influence the rate of retinal reattachment following surgery, nor the final visual acuity [14-17]. Review of the literature revealed a paucity of research attention focused on this issue. Therefore, we developed a qualitative mathematical model of the intraocular forces that are correlated to the vitreous' effect on the retina. This model enables a rough estimation of rescues arising from a variety of factors related to the physical activity.

The human eye is a complex physicochemical system with a range of biomechanical and chemical processes occurring in various physiological as well as pathological conditions. Fluid flow inside different domains of the eye is one of the most significant biomechanical processes that tend to perform a wide variety of functions and when combined with other biophysical processes play a crucial role in ocular drug delivery. Numerous mechanical models were suggested for the study of the physical properties of the biological tissues constituting human eye [18-20] and modeling of the processes occurring within human eye [21-27]. Continuity and the Navier–Stokes equations were involved to model the aqueous humor flow in the anterior and vitreous chambers of the eye [21-27]. Thermal effect on the aqueous humor flow was considered [22]. The system of equations describing of the aqueous humor flow is non-linear and may be solved only with the sophisticated computer simulation methods [27]. We suppose that the qualitative analysis of physical factors constituting the hydrodynamics of liquids filling the human eye will be useful. Rather surprisingly such a qualitative analysis is not found in the literature devoted the hydrodynamics of the human eye.

In our communication we focus on one of the factors which from our point of view is underestimated when hydrodynamics of the aqueous humor is analyzed; namely the effect of the "water hammer pressure", which emerges when abrupt stop of the human eye filled with aqueous humor occurs (this may take place when running or working person encounters an obstacle). Our communication reports the qualitative analysis of the problem only.

2. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

2.1. Dimensional Analysis of the Hydrodynamics of a Human Eye

Let us start from the analysis of the dimensionless numbers describing the hydrodynamics of the human eye. We consider the isothermal flows in the eye; thermal effects introduce additional complications in the analysis of the PVD [22].The main physical factors defining the intraocular flows are inertia, gravity, viscosity η and surface tension γ of vitreous humor [28-29]. The relevant dimensionless numbers are the Reynolds, capillary and Bond numbers, defined by Equations 1-2:

$$Re = \frac{\rho v R}{\eta} \quad (1)$$

$$Ca = \frac{\eta v}{\gamma}, \quad (2)$$

$$Bo = \frac{\rho g R^2}{\gamma} \quad (3)$$

where *Re*, *Ca* and *Bo* are the Reynolds and capillary numbers, ρ, η and γ and the density, viscosity and surface tension of vitreous humor correspondingly, L and v are the characteristic dimension and velocity of the vitreous humor respectively [28-29]. The set of these dimensionless numbers arises from the seminal Buckingham theorem [28]. Assuming $\rho = 1.0053 - 1.0089\,\frac{\mathrm{g}}{\mathrm{cm}^3}$ (see ref. 19), $\gamma \cong 47.8 - 65.9 \pm 1.2\,\frac{\mathrm{mJ}}{\mathrm{m}^2}$ is the surface tension of the aqueous humor[19-20], $\eta \cong 3.0 \times 10^{-3}\,\mathrm{Pa \cdot s}$ (see ref. 20), $R \cong 1.2$ cm and $v \cong 6.0 \times 10^{-4}\,\frac{\mathrm{m}}{\mathrm{s}}$ (see ref. 21) gives rise to the following estimations: $Re \cong 2.4, Ca \cong 3.0 \times 10^{-5} - 4.0 \times 10^{-5}$ and $Bo \cong 50.0$ for the person in rest. This means that for the person in rest

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the flows in the eye are laminar ($Re \cong 1$), the processes due to the surface tension dominate those emerging from viscosity ($Ca \ll 1$); gravity, in turn dominates the surface tension ($Bo \gg 1$). Now let us describe the hydrodynamics of intraocular processes in terms of pressures. Two separate cases should be considered, namely the person in rest (or, alternatively, the person moving with the constant velocity) and accelerated/decelerated individual.

2.2. Analysis of Pressures Acting in the Eye of the Person in Rest

When the person is in rest (or moving with the constant velocity) the pressure P exerted by intraocular liquid on the retina is given by Eq. 4:

$$P = P_h + P_L + P_D, \tag{4}$$

where P_h, P_L and P_D are the hydrostatic, Laplace and dynamic pressures respectively. Let us estimate the components of the resulting pressure P. Hydrostatic pressure P_h is given by Eq. 5:

$$P_h \cong \rho g h, \tag{5}$$

where $\rho = 1.0053 - 1.0089 \frac{g}{\text{cm}^3}$ is the density of aqueous humor[20] and $h \cong 24$ mm is the characteristic height of the vitreous chamber. Calculation of the hydrostatic pressure P_h with Eq. 5 yields $P_h \cong 235$ Pa. The Laplace pressure is reasonably estimated with Eq. 6:

$$P_L \cong \frac{2\gamma}{R}, \tag{6}$$

where $\gamma \cong 47.8 - 65.9 \pm 1.2 \frac{mJ}{m^2}$ is the surface tension of the aqueous humor[19,20] and $R \cong \frac{h}{2} \cong 12$ mm. Calculation of the Laplace pressure P_L with Eq. 6 yields $P_L \cong 10.0 - 11.0$ Pa. It is easily seen that the effect of the Laplace is negligible; this conclusion is easily understood, when we consider that the characteristic length of the problem $R \cong \frac{h}{2} \cong 12$ mm is much larger than the capillary length of the aqueous humor $l_{ca} = \sqrt{\frac{\gamma}{\rho g}} \cong 2.6$ mm; thus, the interrelation $R \gg l_{ca}$ takes place and the effects due to the Laplace pressure are negligible [28]. In other words, the Bond number $Bo = \frac{\rho g R^2}{\gamma} \gg 1$, and the effects due to gravity prevail on those inspired by the surface tension.

The maximal dynamic (Bernoulli) pressure is estimated, in turn, with Eq. 7

$$P_D = \frac{\rho v^2}{2} \tag{7}$$

where $\rho = 1.0053 - 1.0089 \frac{\text{g}}{\text{cm}^3}$ is the density of aqueous humor [18-19] and $v \cong 6.0 \times 10^{-4} \frac{\text{m}}{\text{s}}$ is the maximal velocity of the vitreous humor of a person in rest [21]. Estimation of the dynamic pressure P_D with Eq. 7 yields $P_D \cong 1.8 \times 10^{-4}$ Pa. This estimation yields the following hierarchy of pressures for a person in rest (or moving with the constant velocity):

$$P_h \gg P_L \gg P_D \tag{8}$$

Thus, the influence of the dynamic pressure is negligible for a person in rest/person moving with the constant velocity. It should be emphasized that all of the pressures appearing in Eq. 8 are much smaller than the vascular pressure $P_{vasc} \cong 15 - 25$ mm Hg $\cong 2000 - 3300$ Pa, which drives fluid flow from the choriocapillaris to the inner eye in the absence of other active processes [30]. These pressures are also smaller than the typical values of the intraocular pressure $P_{intr} \cong 10 - 20$ mm Hg $\cong 1300 - 2700$ Pa [30].

2.3. Analysis of Pressures Acting in the Eye of the Accelerated Person

Let us develop the simplest qualitative physical model of the accelerated eye exerted to physical training (labor, whatever). The entire pressure exerted by intraocular liquid on the retina P in this case is given by:

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$$P = P_h + P_L + P_D + P_{WH}, \tag{9}$$

where P_h, P_L, P_D and P_{WH} are hydrostatic, Laplace, dynamic and water hammer pressures respectively [31-32]. The hydrostatic and Laplace pressures were already estimated in Section 2.2.

The maximal dynamic (Bernoulli) pressure is estimated, in turn, with Eq. 7 $P_D = \frac{\rho v_{max}^2}{2}$, where $\rho = 1.0053 - 1.0089 \frac{g}{cm^3}$ is the density of aqueous humor and $v_{max} \cong 10 \frac{m}{s}$ is the maximal realistic velocity of running/training person. Estimation of the dynamic pressure P_D yields $P_D \cong 5 \times 10^4\ Pa$.

The water hammer pressure P_{WH}, in turn, is estimated with Eq. 10:

$$P_{WH} = \rho c v, \tag{10}$$

where $c \cong 1480 \frac{m}{s}$ is the velocity of sound in the intraocular liquid. Estimation of the water hammer pressure with Eq. 10 yields: $P_{WH} \cong 1.5 \times 10^7 Pa$. The water hammer pressure arises when a fluid in motion is forced to stop or change direction suddenly [31-33]. Flowing liquid has momentum. If the moving liquid is suddenly stopped (such as by closing a valve downstream of the flowing water), the pressure can rise suddenly with a resulting shock wave, which pressure is estimated with Eq. 10 [31-33]. The effect takes place when a running or training person suddenly stops his motion. It commonly occurs when a valve closes suddenly at an end of a pipeline system, and a pressure wave propagates in the pipes, as established by Nikolai Joukowsky [31]. Actually, Eq. 10 was derived first by Thomas Young [33]. And this water hammer pressure is much larger than the hydrodynamic, hydrostatic, Laplace and dynamic ones. Analysis of Equations 5-10 gives rise to the following hierarchy of pressures emerging in the eye of the running/training and suddenly accelerated human person:

$$P_{WH} \gg P_D \gg P_h \gg P_L \tag{11}$$

This hierarchy means that just water hammer pressure is the main mechanical factor acting on the retina of a rapidly moving, accelerated person. This pressure arises when a training person is accelerated or decelerated very rapidly. If physical activity can indeed cause retinal detachment or any damage, it is due to the water hammer pressure and not the motion of the training person or effort themselves.

Let us compare the obtained estimations of the pressures with the ultimate tensile strength (UTS) of retina, denoted σ_{UTS}. The maximal (most optimistic) values of retina, choroid and Bruch's membrane-choroid complex are $\sigma_{UTS} \sim 0.3\ \mathrm{MPA} = 3.0 \times 10^5\ \mathrm{Pa}$ [34-36]. It is seen that interrelation $P_{WH} \gg \sigma_{UTS} > P_D$ takes place. Thus, we conclude that the water hammer pressure is the most dangerous factor, which may be responsible for the mechanical damage of human retina and choroid. The water hammer pressure effect necessarily takes place at the conditions inherent for extremal physical training, associated with abrupt decelerations (and even stops) due to direct trauma to the head, such as boxing or competitive diving [3-4]. Rapid acceleration/deceleration inherent for these extremal kinds of physical training produce the conditions necessary for propagation of shock waves in the vitreous humor [37].

3. Discussion: How a Human Eye Withstands the Water Hammer Pressure?

Ultimate accelerations/decelerations are ubiquitous for physical training, thus, the effect of the water hammer pressure may be inevitable. The reasonable question is: how human eye withstands the very high pressures arising from the water hammer effect? We propose the following physical mechanisms enabling human retina to withstand the water hammer pressures. They are: i) the skin friction effect; ii) viscoelasticity of retina [38]. Address first the skin friction effect. The water hammer pressure calculated with Eq. 10 is applicable for atomically smooth surfaces; however, the surface of retina is rough as demonstrated in ref. 39. And it should be emphasized that retina, being the representative of the "soft matter bio-tissue" demonstrates the pronounced viscoelastic properties as demonstrated in ref. 40. Both of these effects enable to decrease the harmful effects of the water hammer pressure, as discussed in ref. 38.

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4. Conclusions

Impact of the physical activity on the posterior vitreous detachment remains a highly controversial topic. Many ophthalmologists recommend patients with acute PVD to refrain from all physical activity, even though such a recommendation has not been scientifically validated or formally recommended. Our analysis demonstrates that the actual situation has a "fine structure": the "regular physical" activity and an "extremal physical activity" giving rise to the ultimate acceleration/deceleration, should be distinguished. Our research leads to the conclusion that acute acceleration/deceleration of a human person under training or labor represents the maximal danger in a view of mechanical detachment damage of retina, choroid or the Bruch retina-choroid complex. The qualitative analysis reported in the paper demonstrates that under extreme conditions, a water hammer dynamic pressure may be much larger than the ultimate tensile strength inherent for retina, choroid or the Bruch membrane-choroid complex. The water hammer pressure emerges when the moving liquid is suddenly stopped; in this case the dynamic pressure can rise suddenly with a resulting shock wave, which pressure scales as $P_{WH} = \rho c v$, where $c \cong 1480\,\frac{\mathrm{m}}{\mathrm{s}}$ is the velocity of sound in the intraocular liquid, and v is the velocity of the training person. Estimation of the water hammer pressure yields: $P_{WH} \cong 1.5 \times 10^7\,\mathrm{Pa}$, which is more than sufficient for detaching the retina. It should be emphasized, that the role of the water hammer pressure is usually underestimated in the research, devoted to the hydrodynamic processes occurring within a human eye. Thus, an acceleration and not motion/training itself, is a main factor, which may be dangerous for the tissues constituting the human eye. Roughness and viscoelastic properties of retina mitigate the harmful effect of the water hammer pressure. The situation is rather different for a human eye in rest. In this case, the hydrostatic pressure is much larger than the Laplace pressure, which is in turn much larger than the dynamic (Bernoulli pressure) emerging from intraocular flows. Actually, the dynamic pressures are negligible for a human eye in rest.

Physical activity, which is not accompanied with rapid acceleration/acceleration of the body, may be definitely recommended in patients with PVD. Walking, running, lifting weights, swimming and most forms of physical activity do not represent any risk for retinal detachment in patients with acute PVD, and this is also true in patients without PVD, as these activities are not considered as causes for PVD. The forces created in the eye during most forms of physical activities are not dangerous, and therefore physical activity should not be avoided. However, under extreme situations, physical activity may create forces in the eye that may be capable of detaching the retina. As shown, these conditions occur under ultimate acceleration or deceleration, where a high velocity motion is suddenly stopped or force is transferred to the eye. This can occur in falls (such as falling from a speeding bicycle or diving from a height to the pool) or direct trauma (such as boxing or getting hit by a ball travelling at high velocity). Such conditions may cause the retina to detach – both in the presence and absence of PVD. Therefore, since regular physical activity is an important factor in preventing cardiovascular risk and improving patients' well-being, it should not be avoided in patients with PVD. Potentially traumatic activities such as boxing or competitive diving should be avoided, or performed with proper protective gear, as a precaution.

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