Spelman, T. A.; **Stewart, P. S.**

Shock wave propagation along the central retinal blood vessels. (English) Zbl 1437.76057

Proc. R. Soc. Lond., A, Math. Phys. Eng. Sci. 476, No. 2234, Article ID 20190269, 20 p. (2020).

Summary: Retinal haemorrhage is often observed following brain injury. The retinal circulation is supplied (drained) by the central retinal artery (vein) which enters (leaves) the eye through the optic nerve at the optic disc; these vessels penetrate the nerve immediately after passing through a region of cerebrospinal fluid (CSF). We consider a theoretical model for the blood flow in the central retinal vessels, treating each as multi-region collapsible tubes, where we examine how a sudden change in CSF pressure (mimicking an injury) drives a large amplitude pressure perturbation towards the eye. In some cases, this wave can steepen to form a shock. We show that the region immediately proximal to the eye (within the optic nerve where the vessels are strongly confined by the nerve fibres) can significantly reduce the amplitude of the pressure wave transmitted into the eye. When the length of this region is consistent with clinical measurements, the CSF pressure perturbation generates a wave of significantly lower amplitude than the input, protecting the eye from damage. We construct an analytical framework to explain this observation, showing that repeated rapid propagation and reflection of waves along the confined section of the vessel distributes the perturbation over a longer lengthscale.

MSC:

76Z05 Physiological flows
92C35 Physiological flow
76L05 Shock waves and blast waves in fluid mechanics

Keywords:

retinal haemorrhage; retinal blood flow; shock waves; elastic jumps

Full Text: DOI

References:

[1] Aryan HE, Ghosheh FR, Jandial R, Levy ML. (2005) Retinal hemorrhage and pediatric brain injury: etiology and review of the literature. J. Clin. Neurosci. 12, 624-631. (doi:10.1016/j.jocn.2005.05.005)· doi:10.1016/j.jocn.2005.05.005

[2] Harding B, Risdon RA, Krous HF. (2004) Shaken baby syndrome. BMJ 328, 720-721. (doi:10.1136/bmj.328.7442.720)· doi:10.1136/bmj.328.7442.720

[3] Richards PG et al. (2006) Shaken baby syndrome. Arch. Dis. Child. 91, 205-206. (doi:10.1136/adc.2005.090761)· doi:10.1136/adc.2005.090761

[4] Tuerkheimer D. (2014) Flawed convictions: 'shaken baby syndrome' and the inertia of injustice. Oxford, UK: Oxford University Press.

[5] Gilkes M, Mann T. (1967) Fundi of battered babies. Lancet 290, 468-469. (doi:10.1016/S0140-6736(67)90889-6)· doi:10.1016/S0140-6736(67)90889-6

[6] Clarke MP. (2009) Vitreoretinal traction is a major factor in causing the haemorrhagic retinopathy of abusive head injury? - No. Eye 23, 1761-1763. (doi:10.1038/eye.2009.200)· doi:10.1038/eye.2009.200

[7] Levin A. (2011) Eye injuries in child abuse. In Child abuse and neglect, pp. 402-412. Elsevier.

[8] Bonshek R, Cowley S, Jensen O, Pearce P, Ravi A, Stewart P, Whittaker R, Zouache M Understanding patterns of haemorrhage in the eye. Report on the 2014 UK Maths in Medicine Study Group available from www.nc3rs.org.uk/sites/default/files/documents/Maths/un

[9] Singh S, Dass R. (1960a) The central artery of the retina I. Origin and course. Br. J. Ophthalmol. 44, 193. (doi:10.1136/bjo.44.4.193)· doi:10.1136/bjo.44.4.193

[10] Singh S, Dass R. (1960b) The central artery of the retina II. A study of its distribution and anastomoses. Br. J. Ophthalmol. 44, 280. (doi:10.1136/bjo.44.5.280)· doi:10.1136/bjo.44.5.280

[11] Hayreh SS. (1963) The central artery of the retina its role in the blood supply of the optic nerve. Br. J. Ophthalmol. 47, 651. (doi:10.1136/bjo.47.11.651)· doi:10.1136/bjo.47.11.651

[12] Stewart PS, Jensen OE, Foss AJE. (2014) A theoretical model to allow prediction of the CSF pressure from observations of the retinal venous pulse. Invest. Ophthalmol. Vis. Sci. 55, 6319. (doi:10.1167/iovs.14-14331)· doi:10.1167/iovs.14-14331

[13] Stewart PS, Foss AJE. (2019) Self-excited oscillations in a collapsible channel with applications to retinal venous pulsation. ANZIAM J. 61, 320-348. (doi:10.1017/S1446181119000117) · Zbl 1422.76213 · doi:10.1017/S1446181119000117

[14] Cowley SJ. (1982) Elastic jumps on fluid-filled elastic tubes. J. Fluid Mech. 116, 459-473. (doi:10.1017/S002211208200055X) · Zbl 0514.76130 · doi:10.1017/S002211208200055X

[15] Brook BS, Falle SAEG, Pedley TJ. (1999) Numerical solutions for unsteady gravity-driven flows in collapsible tubes: evolution and roll-wave instability of a steady state. J. Fluid Mech. 396, 223-256. (doi:10.1017/S0022112099006084) · Zbl 0971.76052 · doi:10.1017/S0022112099006084

[16] Igra O, Meguro T, Takayama K, Heilig W. (2001) Experimental and theoretical study of shock wave propagation through double-bend ducts. J. Fluid Mech. 437, 255-282. (doi:10.1017/S0022112001004098) · Zbl 1085.76520 · doi:10.1017/S0022112001004098

[17] Whitham GB. (1974) Linear and nonlinear waves. New York, NY: John Wiley \& Sons Inc.

[18] Siviglia A, Toffolon M. (2013) Steady analysis of transcritical flows in collapsible tubes with discontinuous mechanical properties: implications for arteries and veins. J. Fluid Mech. 736, 195-215. (doi:10.1017/jfm.2013.542) · Zbl 1294.76295 · doi:10.1017/jfm.2013.542

[19] Siviglia A, Toffolon M. (2014) Multiple states for flow through a collapsible tube with discontinuities. J. Fluid Mech. 761, 105-122. (doi:10.1017/jfm.2014.635) · Zbl 1308.76347 · doi:10.1017/jfm.2014.635

[20] Woollatt D. (1965) An approximate theory for the transmission and reflection of simple waves at area changes and junctions in pipes. Int. J. Mech. Sci. 7, 777-783. (doi:10.1016/0020-7403(65)90006-8)· doi:10.1016/0020-7403(65)90006-8

[21] Davies P, Dwyer M. (1964) A simple theory for pressure pulses in exhaust systems. Proc. Inst. Mech. Eng. 179, 365-394. (doi:10.1243/PIME_PROC_1964_179_027_02)· doi:10.1243/PIME$_P ROC_1 964_1 79_0 27_0 2$

[22] Guidoboni G et al. (2014) Intraocular pressure, blood pressure, and retinal blood flow autoregulation: a mathematical model to clarify their relationship and clinical relevance. Invest. Ophthalmol. Vis. Sci. 55, 4105-4118. (doi:10.1167/iovs.13-13611)· doi:10.1167/iovs.13-13611

[23] Garhofer G, Werkmeister R, Dragostinoff N, Schmetterer L. (2012) Retinal blood flow in healthy young subjects. Invest. Ophthalmol. Vis. Sci. 53, 698-703. (doi:10.1167/iovs.11-8624)· doi:10.1167/iovs.11-8624

[24] Shapiro A. (1977) Steady flow in collapsible tubes. J. Biomech. Eng. 99, 126-147. (doi:10.1115/1.3426281)· doi:10.1115/1.3426281

[25] Ockendon H, Ockendon J. (2004) Waves and compressible flow. New York, NY: Springer Verlag. · Zbl 1041.76001

[26] Cancelli C, Pedley T. (1985) A separated-flow model for collapsible-tube oscillations. J. Fluid Mech. 157, 375-404. (doi:10.1017/S0022112085002427) doi:10.1017/S0022112085002427

[27] Halpern D, Naire S, Jensen O, Gaver D. (2005) Unsteady bubble propagation in a flexible channel: predictions of a viscous stick-slip instability. J. Fluid Mech. 528, 53-86. (doi:10.1017/S002211200400309X) · Zbl 1163.76332 · doi:10.1017/S002211200400309X

[28] Band L, Hall C, Richardson G, Jensen O, Siggers J, Foss A. (2009) Intracellular flow in optic nerve axons: a mechanism for cell death in glaucoma. Invest. Ophthalmol. Vis. Sci. 50, 3750-3758. (doi:10.1167/iovs.08-2396)· doi:10.1167/iovs.08-2396

[29] Pedley TJ. (1980) The fluid mechanics of large blood vessels. Cambridge, UK: Cambridge University Press. · Zbl 0449.76100

[30] Moghimi S, Hosseini H, Riddle J, Lee GY, Bitrian E, Giaconi J, Caprioli J, Nouri-Mahdavi K. (2012) Measurement of optic disc size and rim area with spectral-domain OCT and scanning laser ophthalmoscopy. Invest. Ophthalmol. Vis. Sci. 53, 4519. (doi:10.1167/iovs.11-8362)· doi:10.1167/iovs.11-8362

[31] Xie X et al. (2013) Noninvasive intracranial pressure estimation by orbital subarachnoid space measurement: the Beijing Intracranial and Intraocular Pressure (iCOP) study. Crit. Care 17, R162. (doi:10.1186/cc12841)· doi:10.1186/cc12841

[32] Snyder RG. (1963) Human survivability of extreme impacts in free-fall. Rep. Civ. Aeromed. Res. Inst. US. Aug:1-29.

[33] Morgan WH, Yu DY, Balaratnasingam C. (2008) The role of cerebrospinal fluid pressure in glaucoma pathophysiology: the dark side of the optic disc. J. Glaucoma. 17, 408-413. (doi:10.1097/IJG.0b013e31815c5f7c)· doi:10.1097/IJG.0b013e31815c5f7c

[34] Love A. (1944) A treatise on the mathematical theory of elasticity. Cambridge, UK: Cambridge University Press. · Zbl 0063.03651

[35] Kotliar K, Hanssen H, Eberhardt K, Vilser W, Schmaderer C, Halle M, Heemann U, Baumann M. (2013) Retinal pulse wave velocity in young male normotensive and mildly hypertensive subjects. Microcirculation 20, 405-415. (doi:10.1111/micc.12036)· doi:10.1111/micc.12036

[36] Kotliar KE, Lanzl I, Eberhardt K, Hanssen H, Halle M, Heemann U, Baumann M. (2012) Does increased blood pressure rather than aging influence retinal pulse wave velocity? Invest. Ophthalmol. Vis. Sci 53, 2119. (doi:10.1167/iovs.11-8815)· doi:10.1167/iovs.11-8815

[37] Li Q, Li L, Fan S, Dai C, Chai X, Zhou C. (2017) Retinal pulse wave velocity measurement using spectral-domain optical coherence tomography. J. Biophotonics 11, e201700163. (doi:10.1002/jbio.201700163)· doi:10.1002/jbio.201700163

[38] Kotliar KE, Baumann M, Vilser W, Lanzl IM. (2011) Pulse wave velocity in retinal arteries of healthy volunteers. Br. J. Ophthalmol. 95, 675-679. (doi:10.1136/bjo.2010.181263)· doi:10.1136/bjo.2010.181263

[39] Spahr H, Hillmann D, Hain C, Pfaffle C, Sudkamp H, Franke G, Huttmann G. (2015) Imaging pulse wave propagation in human retinal vessels using full-field swept-source optical coherence tomography. Opt. Lett. 40, 4771-4774. (doi:10.1364/OL.40.004771)· doi:10.1364/OL.40.004771

[40] Spahr H, Hillmann D, Pfaffle C, Huttmann G. (2018) Comment on 'Retinal pulse wave velocity measurement using spectral-domain optical coherence tomography'. J. Biophotonics 11, e201700347.

[41] Olufsen MS. (1999) Structured tree outflow condition for blood flow in larger systemic arteries. Am. J. Physiol. 276, H257-H268. (doi:10.1152/ajpheart.1999.276.1.h257)· doi:10.1152/ajpheart.1999.276.1.h257

[42] Westerhof N, Bosman F, De Vries CJ, Noordergraaf A. (1969) Analog studies of the human system arterial tree. J. Biomech. 2, 121-134. (doi:10.1016/0021-9290(69)90024-4)· doi:10.1016/0021-9290(69)90024-4

[43] Pries AR, Secomb TW, Gaehtgens P. (1998) Structural adaptation and stability of microvascular networks: theory and simulations. Am. J. Physiol. Heart Circ. Physiol. 275, H349-H360. (doi:10.1152/ajpheart.1998.275.2.H349)· doi:10.1152/ajpheart.1998.275.2.H349

[44] Stewart P, Waters S, Jensen O. (2009) Local and global instabilities of flow in a flexible-walled channel. Eur. J. Mech. B 28, 541-557. (doi:10.1016/j.euromechflu.2009.03.002) · Zbl 1167.76329 · doi:10.1016/j.euromechflu.2009.03.002

[45] Stewart P. (2017) Instabilities in flexible channel flow with large external pressure. J. Fluid Mech. 825, 922-960. (doi:10.1017/jfm.2017.404) · Zbl 1374.76243 · doi:10.1017/jfm.2017.404

[46] Sherwin SJ, Franke V, Peiro J, Parker K. (2003) One-dimensional modelling of a vascular network in space-time variables. J. Eng. Math. 47, 217-250. (doi:10.1023/B:ENGI.0000007979.32871.e2) · Zbl 1200.76230 · doi:10.1023/B:ENGI.0000007979.32871.e2

[47] Chapman CJ. (2000) High speed flow. Cambridge, UK: Cambridge University Press.