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The roles of maturation delay and vaccination on the spread of dengue virus and optimal control. (English) Zbl 1422.92161

Adv. Difference Equ. 2017, Paper No. 278, 19 p. (2017).

Summary: A mathematical model of Dengue virus transmission between mosquitoes and humans, incorporating a control strategy of imperfect vaccination and vector maturation delay, is proposed in this paper. By using some analytical skills, we obtain the threshold conditions for the global attractiveness of two disease-free equilibria and prove the existence of a positive equilibrium for this model. Further, we investigate the sensitivity analysis of threshold conditions. Additionally, using the Pontryagin maximum principle, we obtain the optimal control strategy for the disease. Finally, numerical simulations are delivered to verify the correctness of the theoretical results, the feasibility of a vaccination control strategy, and the influences of the controlling parameters on the control and elimination of this disease. Theoretical results and numerical simulations show that the vaccination rate and effectiveness of vaccines are two key factors for the control of Dengue spread, and the manufacture of the Dengue vaccine is also architecturally significant.

MSC:

92D30 Epidemiology
92C60 Medical epidemiology
37N25 Dynamical systems in biology
49N90 Applications of optimal control and differential games
49J15 Existence theories for optimal control problems involving ordinary differential equations

Keywords:

Dengue vaccination; maturation delay; disease-free equilibrium and endemic equilibrium; attractiveness and bifurcation; sensitivity; optimal control

Full Text: DOI

References:

[1] \textit{Dengue and dengue haemorrhagic fever}. WHO factsheets No. 117 (2009)
[2] Jousset, FX, Geographic \textit{aedes aegypti} strains and dengue-2 virus: susceptibility, ability to transmit to vertebrate and transovarial transmission, Ann. Inst. Pasteur., Virol., 132, 357-370, (1981)
[3] Aldila, D; Götz, T; Soewono, E, An optimal control problem arising from a dengue disease transmission model, Math. Biosci., 242, 9-16, (2013) · Zbl 1316.92079
[4] Kooi, BW; Maira, A; Nico, S, Analysis of an asymmetric two-strain dengue model, Math. Biosci., 248, 128-139, (2014) · Zbl 1310.92055
[5] Coutinho, FAB; Burattini, MN; Lopez, LF; Massad, E, Threshold conditions for a non-autonomous epidemic system describing the population dynamics of dengue, Bull. Math. Biol., 68, 2263-2282, (2006) · Zbl 1296.92226
[6] Esteva, L; Vargas, C, Analysis of a dengue disease transmission model, Math. Biosci., 150, 131-151, (1998) · Zbl 0930.92020
[7] Wang, WD; Zhao, XQ, A nonlocal and time-delayed reaction-diffusion model of dengue transmission, SIAM J. Appl. Math., 71, 147-168, (2011) · Zbl 1228.35118
[8] Garba, SM; Gumel, AB; Bakar, MRA, Backward bifurcations in dengue transmission dynamics, Math. Biosci., 215, 11-25, (2008) · Zbl 1156.92036
[9] Keeling, MJ, Rohani, P: Modeling Infectious Diseases in Humans and Animals p. 415. Princeton University Press, Princeton (2008) · Zbl 1279.92038
[10] Rodrigues, HS; Monteiro, MTT; Torres, DFM, Vaccination models and optimal control strategies to dengue, Math. Biosci., 247, 1-12, (2014) · Zbl 1282.92022
[11] Scherer, A; McLean, A, Mathematical models of vaccination, Br. Med. Bull., 62, 187-199, (2002)
[12] Kar, TK; Jana, S, Application of three controls optimally in a vector-borne disease: a mathematical study, Commun. Nonlinear

Sci. Numer. Simul., 18, 2868-2884, (2013) · Zbl 1306.92059

[13] Nelson, OO, Determination of optimal vaccination strategies using an orbital stability threshold from periodically driven systems, J. Math. Biol., 68, 763-784, (2014) · Zbl 1282.92020

[14] Murrel, S; Butler, SCW, Review of dengue virus and the development of a vaccine, Biotechnol. Adv., 29, 239-247, (2011)

[15] Clark, DV; Mammen, MPJ; Nisalak, A; Puthimethee, V; Endy, TP, Economic impact of dengue fever/dengue hemorrhagic fever in Thailand at the family and population levels, Am. J. Trop. Med. Hyg., 72, 786-791, (2005)

[16] Shepard, DS; etal., Cost-effectiveness of a pediatric dengue vaccine, Vaccine, 22, 1275-1280, (2004)

[17] Suaya, JA; etal., Cost of dengue cases in eight countries in the americas and Asia: a prospective study, Am. J. Trop. Med. Hyg., 80, 846-855, (2009)

[18] http://www.cdc.gov/ncidod/dvbid/westnile/

[19] Bayoh, MN; Lindsay, SW, Effect of temperature on the development of the aquatic stages of \textit{anopheles gambiae} sensu stricto (diptera: culicidae), Bull. Entomol. Res., 93, 375-381, (2003)

[20] Shaman, J; Spiegelman, M; Cane, M; Stieglitz, M, A hydrologically driven model of swamp water mosquito population dynamics, Ecol. Model., 194, 395-404, (2006)

[21] Zhao, XQ; Zou, XF, Threshold dynamics in a delayed SIS epidemic model, J. Math. Anal. Appl., 257, 282-291, (2001) · Zbl 0988.92027

[22] Fan, GH; Wu, JH; Zhu, HP, The impact of maturation delay of mosquitoes on the transmission of west nile virus, Math. Biosci., 228, 119-126, (2010) · Zbl 1204.92057

[23] Tridip, S; Sourav, R; Joydev, C, A mathematical model of dengue transmission with memory, Commun. Nonlinear Sci. Numer. Simul., 22, 511-525, (2015) · Zbl 1329.92140

[24] Smith, HJ: Monotone Dynamical Systems: An Introduction to the Theory of Competitive and Cooperative Systems. Mathematical Surveys and Monographs, vol. 41. Am. Math. Soc., Providence (1995) · Zbl 0821.34003

[25] Cooke, KL; Driessche, P, Analysis of an SEIRS epidemic model with two delays, J. Math. Biol., 32, 240-260, (1996) · Zbl 0865.92019

[26] Smith, HL: An Introduction to Delay Differential Equations with Applications to the Life Sciences, vol. 57. Springer, New York (2011) · Zbl 1227.34001

[27] Nakul, C; James, MH; Jim, MC, Determining important parameters in the spread of malaria through the sensitivity analysis of a mathematical model, Bull. Math. Biol., 70, 1272-1296, (2008) · Zbl 1142.92025

[28] Cesari, L: Optimization-Theory and Applications, Problems with Ordinary Differential Equations. Applications and Mathematics, vol. 17. Springer, New York (1983) · Zbl 0506.49001

[29] Kamien, MI, Schwartz, NL: Dynamics Optimization: The Calculus of Variations and Optimal Control in Economics and Management. Elsevier, Amsterdam (2000) · Zbl 0709.90001

[30] Nababan, S, A Filippov-type lemma for functions involving delays and its application to time-delayed optimal control problems, J. Optim. Theory Appl., 27, 357-376, (1979) · Zbl 0377.49006

[31] Seierstad, A, Sydsaeter, K: Optimal Control Theory with Economic Applications. Elsevier, Amsterdam (1975) · Zbl 0613.49001

[32] Fleming, WH, Rishel, RW: Deterministic and Stochastic Optimal Control. Springer, New York (1975) · Zbl 0323.49001

[33] Bashier, EBM; Patidar, KC, Optimal control of an epidemiological model with multiple time delays, Appl. Math. Comput., 292, 47-56, (2017)

[34] Chen, LJ; Hattaf, K; Sun, JT, Optimal control of a delayed SLBS computer virus model, Physica A, 427, 244-250, (2015)

[35] Zhu, QY; Yang, XF; Yang, LX; Zhang, CM, Optimal control of computer virus under a delayed model, Appl. Math. Comput., 218, 11613-11619, (2012) · Zbl 1278.49045

[36] Stech, H; Williams, M, Alternate hypothesis on the pathogenesis of dengue hemorrhagic fever (DHF)/dengue shock syndrome (DSS) in dengue virus infection, Exp. Biol. Med., 233, 401-408, (2008)

[37] Chung, KW; Lui, R, Dynamics of two-strain influenza model with cross-immunity and no quarantine class, J. Math. Biol., 73, 1-23, (2016) · Zbl 1354.34080

[38] Esteva, L; Vargas, C, Coexistence of different serotypes of dengue virus, J. Math. Biol., 46, 31-47, (2003) · Zbl 1015.92023

[39] Feng, Z; Velasco-Hernández, JX, Competitive exclusion in a vector-host model for the dengue fever, J. Math. Biol., 35, 523-544, (1997) · Zbl 0878.92025

[40] Hartley, LM; Donnelly, CA; Garnett, GP, The seasonal pattern of dengue in endemic areas: mathematical models of mechanisms, Trans. R. Soc. Trop. Med. Hyg., 96, 387-397, (2002)

[41] Zheng, B; Tang, MX; Yu, JS, Modeling wolbachia spread in mosquitoes through delay differential equations, SIAM J. Appl. Math., 74, 743-770, (2014) · Zbl 1303.92124

[42] Zheng, B, Tang, MX, Yu, JS, Qiu, JX: Wolbachia spreading dynamics in mosquitoes with imperfect maternal transmission. J. Math. Biol. \textbf{2017} (2017, in press). doi:10.1007/s00285-017-1142-5

[43] Huang, MG; Tang, MX; Yu, JS, Wolbachia infection dynamics by reaction-diffusion equations, Sci. China Math., 58, 77-96, (2015) · Zbl 1337.35156

[44] Huang, MG; Yu, JS; Hu, LC; Zhang, B, Qualitative analysis for a wolbachia infection model with diffusion, Sci. China Math., 59, 1249-1266, (2016) · Zbl 1344.35156

[45] Hu, LC; Huang, MG; Tang, MX; Yu, JS; Zheng, B, Wolbachia spread dynamics in stochastic environments, Theor. Popul. Biol., 106, 32-34, (2015) · Zbl 1343.92482

[46] Turelli, M; Bartom, NH, Deploying dengue-suppressing wolbachia: robust models predict slow but effective spatial spread in \textit{aedes aegypti}, Theor. Popul. Biol., 115, 45-60, (2017)