Ruan, Shigui

Modeling the transmission dynamics and control of rabies in China. (English) Zbl 1366.92130

Math. Biosci. 286, 65-93 (2017).

Summary: Human rabies was first recorded in ancient China in about 556 BC and is still one of the major public-health problems in China. From 1950 to 2015, 130,494 human rabies cases were reported in Mainland China with an average of 1977 cases per year. It is estimated that 95% of these human rabies cases are due to dog bites. The purpose of this article is to provide a review about the models, results, and simulations that we have obtained recently on studying the transmission of rabies in China. We first construct a basic susceptible, exposed, infectious, and recovered (SEIR) type model for the spread of rabies virus among dogs and from dogs to humans and use the model to simulate the human rabies data in China from 1996 to 2010. Then we modify the basic model by including both domestic and stray dogs and apply the model to simulate the human rabies data from Guangdong Province, China. To study the seasonality of rabies, in Section 4 we further propose a SEIR model with periodic transmission rates and employ the model to simulate the monthly data of human rabies cases reported by the Chinese Ministry of Health from January 2004 to December 2010. To understand the spatial spread of rabies, in Section 5 we add diffusion to the dog population in the basic SEIR model to obtain a reaction-diffusion equation model and determine the minimum wave speed connecting the disease-free equilibrium to the endemic equilibrium. Finally, in order to investigate how the movement of dogs affects the geographically inter-provincial spread of rabies in Mainland China, in Section 6 we propose a multi-patch model to describe the transmission dynamics of rabies between dogs and humans and use the two-patch submodel to investigate the rabies virus clades lineages and to simulate the human rabies data from Guizhou and Guangxi, Hebei and Fujian, and Sichuan and Shaanxi, respectively. Some discussions are provided in Section 7.

MSC:

92D30 Epidemiology

Cited in **5** Documents

Keywords:

mathematical modeling; transmission dynamics; rabies; basic reproduction number; seasonality; geographic spread

Full Text: DOI

References:

[1] Allen, L. J.S., An introduction to stochastic processes with applications to biology, (2010), Chapman and Hall/CRC Boca Raton, FL

[2] Allen, L. J.S.; Flores, D. A.; Ratnayake, R. K.; Herbold, J. R., Discrete-time deterministic and stochastic models for the spread of rabies, Appl. Math. Comput., 132, 271-292, (2002) · Zbl 1017.92027

[3] Anderson, R. M.; Jackson, H. C.; May, R. M.; Smith, A. M., Population dynamics of fox rabies in Europe, Nature, 289, 765-771, (1981)

[4] Andersson, H.; Britton, T., Stochastic epidemic models and their statistical analysis, (2000), Springer Verlag New York · Zbl 0951.92021

[5] C.D.C. Anshan, Rabies Knowledge for 20 Questiones, 2011, http://www.ascdc.com.cn/newscontent.asp?lsh=5.

[6] Aronson, D. G.; Weinberger, H. F., Nonlinear diffusion in population genetics, combustion, and nerve pulse propagation, (Goldstein, J. A., Partial Differential Equations and Related Topics, (1975), Springer-Verlag Berlin), 5-49 · Zbl 0325.35050

[7] Artois, M.; Langlais, M.; Suppo, C., Simulation of rabies control within an increasing fox population, Ecol. Model., 97, 23-34, (1997)

[8] Bacaer, N.; Guernaoui, S., The epidemic threshold of vector-borne diseases with seasonality, J. Math. Biol., 53, 421-436, (2006) · Zbl 1098.92056

[9] B. Baike, Rabies, http://baike.baidu.com/view/10630.htm.

[10] Bjornstad, O. N.; Finkenstadt, B. F.; Grenfell, B. T., Dynamics of measles epidemics: estimating scaling of transmission rates using a time series SIR model, Ecol. Monogr., 72, 169-184, (2002)

[11] Carroll, M. J.; Singer, A.; Smith, G. C.; Cowan, D. P.; Massei, G., The use of immunocontraception to improve rabies eradication in urban dog populations, Wildl. Res., 37, 676-687, (2010)

[12] Chen, J.; Zou, L.; Jin, Z.; Ruan, S., Modeling the geographic spread of rabies in China, PLoS Negl. Trop. Dis., 9, 5, e0003772, (2015)

[13] Center for Disease Control and Provention (CDC), 2011, Rabies. http://www.cdc.gov/rabies/. Accessed June 1.

[14] Childs, J. E.; Curns, A. T.; Dey, M. E.; Real, L. A.; Feinstein, L., Predicting the local dynamics of epizootic rabies among raccoons in the united states, Proc. Natl. Acad. Sci. USA, 97, 13666-13671, (2000)

[15] Chinese Center for Disease Control and Prevention (CCDC), National Public Health Statistical Data. 2012. http://www.chinacdc.cn/tjsj/gjwstjsj.

[16] Chinese Center for Disease Control and Provention (CCDC), Questions and Answers About Rabies, 2011, http://www.chinacdc.cn/jkzt/crb/zl/kqb

[17] Clayton, T.; Duke-Sylvester, S.; Gross, L. J.; Lenhart, S.; Real, L. A., Optimal control of a rabies epidemic model with a birth pulse, J. Biol. Dyn., 4, 43-58, (2010) · Zbl 1315.92074

[18] Coleman, P. G.; Dye, C., Immunization coverage required to prevent outbreaks of dog rabies, Vaccine, 14, 185-186, (1996)

[19] Coyne, M. J.; Smith, G.; McAllister, F. E., Mathematic model for the population biology of rabies in raccoons in the mid-atlantic states, Am. J. Vet. Res., 50, 2148-2154, (1989)

[20] Department of Health of Guangdong Province (DOHG), Bulletins, 2010, http://www.gdwst.gov.cn/a/yiqingxx/.

[21] Diekmann, O., Run for your life. A note on the asymptotic speed of propagation of an epidemic, J. Differ. Equ., 33, 58-73, (1979) · Zbl 0377.45007

[22] Diekmann, O.; Heesterbeek, J. A.P.; Roberts, M. G., On the definition and the computation of the basic reproduction ratio R_{0} in models for infectious diseases in heterogeneous populations, J. Math. Biol., 28, 365-382, (1990) · Zbl 0726.92018

[23] Diekmann, O.; Heesterbeek, J. A.P.; Roberts, M. G., The construction of next-generation matrices for compartmental epidemic models, J. R. Soc. Interface, 7, 873-885, (2010)

[24] Dimitrov, D. T.; Hallam, T. G.; Rupprecht, C. E.; Turmelle, A. S.; McCracken, G. F., Integrative models of bat rabies immunology, epizootiology and disease demography, J. Theor. Biol., 245, 498-509, (2007)

[25] Dowell, S. F., Seasonal variation in host susceptibility and cycles of certain infectious diseases, Emerg. Infect. Dis., 7, 369-374, (2001)

[26] Ega, T. T.; Luboobi, L. S.; Kuznetsov, D.; Kidane, A. H., Sensitivity analysis and numerical simulations for the mathematical model of rabies in human and animal within and around addis ababa, Asian J. Math. Appl., 4, 23, (2015)

[27] Evans, N. D.; Pritchard, A. J., A control theoretic approach to containing the spread of rabies, IMA J. Math. Appl. Med. Biol., 18, 1-23, (2001) · Zbl 0985.92035

[28] Fitzpatrick, M. C.; Shah, H. A.; Pandey, A., One health approach to cost-effective rabies control in India, Proc. Natl. Acad. Sci. USA, 113, 14574-14581, (2016)

[29] Fooks, A. R.; Banyard, A. C.; Horton, D. L., Current status of rabies and prospects for elimination, Lancet, 384, 1389-1399, (2014)

[30] Fxxue, Statistics on Annual Birth Populations in China, 2010. http://fxxue.blog.hexun.com/44596551_d.html.

[31] Gao, D.; Ruan, S., A multipatch malaria model with logistic growth populations, SIAM J. Appl. Math., 72, 819-841, (2012) · Zbl 1250.92029

[32] Greenhalgh, D.; Moneim, I. A., SIRS epidemic model and simulations using different types of seasonal contact rate, Syst. Anal. Model. Simul., 43, 573-600, (2003) · Zbl 1057.92046

[33] Grenfell, B., Rivers dam waves of rabies, Proc. Natl. Acad. Sci. USA, 99, 3365-3367, (2002)

[34] Guangdong Statistical Yearbook (GSY), Main Population Indicators, 2010a, http://www.gdstats.gov.cn/tjnj/2010/table/4/c4_1.htm.

[35] Guangdong Statistical Yearbook (GSY), Status of Natural Population Changes, 2010b, http://www.gdstats.gov.cn/tjnj/2010/table/4/c4_3.htm.

[36] Guo, D.; Zhou, H.; Zou, Y., Geographical analysis of the distribution and spread of human rabies in China from 2005 to 2011, PLoS One, 8, 8, e72352, (2013)

[37] Guo, Z.; Tao, X.; Yin, C., National borders effectively halt the spread of rabies: the current rabies epidemic in China is dislocated from cases in neighboring countries, PLoS Negl. Trop. Dis., 7, 1, e2039, (2013)

[38] Hampson, K.; Coudeville, L.; Lembo, T., Estimating the global burden of endemic canine rabies, PLoS Negl. Trop. Dis., 9, 4, e0003709, (2015)

[39] Hampson, K.; Dushoff, J.; Bingham, J.; Bruckner, G.; Ali, Y. H., Synchronous cycles of domestic dog rabies in sub-saharan africa and the impact of control effort, Proc. Natl. Acad. Sci. USA, 104, 7717-7722, (2007)

[40] Hampson, K.; Dushoff, J.; Cleaveland, S.; Haydon, D. T.; Kaare, M., Transmission dynamics and prospects for the elimination of canine rabies, PLoS Biol., 7, 0462-0471, (2009)

[41] He, J.-F.; Kang, M.; Li, L.-H.; Liang, W.-J., Exposure to human rabies and the related risk factors in guangdong, Chin. J. Epidemiol., 30, 532-533, (2009)

[42] Hemachudha, T.; Laothamatas, J.; Rupprecht, C. E., Human rabies: a disease of complex neuropathogenetic mechanisms and diagnostic challenges, Lancet Neurol., 1, 101-109, (2002)

[43] Hou, Q.; Jin, Z.; Ruan, S., Dynamics of rabies epidemics and the impact of control efforts in guangdong province, China, J. Theor. Biol., 300, 39-47, (2012) · Zbl 1397.92638

[44] Hu, R.-L.; Fooks, A. R.; Zhang, S.-F.; Liu, Y.; Zhang, F., Inferior rabies vaccine quality and low immunization coverage in

dogs (\textit{canis familiaris}) in China, Epidemiol. Infect., 136, 1556-1563, (2008)

[45] Hu, R.-L.; Tang, Q.; Tang, J. R.; Fooks, A. R., Rabies in China: an update, Vector-borne Zoonotic Dis., 9, 1-11, (2009)

[46] Hutson, V.; Schmitt, K., Permanence and the dynamics of biological systems, Math. Biosci., 111, 1-71, (1992) · Zbl 0783.92002

[47] Kallen, A., Thresholda and travelling waves in an epidemic model for rabies, Nonlinear Anal., 8, 851-856, (1984) · Zbl 0547.92016

[48] Kallen, A.; Arcuri, P.; Murray, J. D., A simple model for the spatial spread and control of rabies, J. Theor. Biol., 116, 377-393, (1985)

[49] Keeling, M. J.; Eames, K. T.D., Networks and epidemic models, J. R. Soc. Interface, 2, 295-307, (2005)

[50] Knobel, D. L.; Cleaveland, S.; Coleman, P. G., Re-evaluating the burden of rabies in africa and Asia, Bull. WHO, 83, 360-368, (2005)

[51] Kureishi, A.; Xu, L. Z.; Stiver, H. G., Rabies in China: recommendations for control, Bull. WHO, 70, 443-450, (1992)

[52] London, W.; Yorke, J. A., Recurrent outbreaks of measles, chickenpox and mumps. I. seasonal variation in contact rates, Am. J. Epidemiol., 98, 453-468, (1973)

[53] Lozano, R.; Naghavi, M.; Foreman, K., Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: a systematic analysis for the global burden of disease study 2010, Lancent, 380, 2095-2128, (2012)

[54] Ma, J.; Ma, Z., Epidemic threshold conditions for seasonally forced SEIR models, Math. Biosci. Eng., 3, 161-172, (2006) · Zbl 1089.92048

[55] MacDonald, D. W., Rabies and wildlife: A biologist's perspective, (1980), Oxford University Press Oxford

[56] Maidana, N. A.; Yang, H. M., Describing the geographic spread of degue disease by traveling waves, Math. Biosci., 215, 64-77, (2008) · Zbl 1156.92037

[57] Maidana, N. A.; Yang, H. M., Spatial spreading of west nile virus described by traveling waves, J. Theor. Biol., 258, 403-417, (2009) · Zbl 1405.92260

[58] Massei, G.; Fooks, A. R.; Horton, D. L., Free-roaming dogs in Nepal: demographics, health and public knowledge, attitudes and practices, Zoonose Public Health, 64, 29-40, (2017)

[59] Meng, S. L.; Xu, G. L.; Wu, X. F., Transmission dynamics of rabies in China over the last 40 years: 1969-2009, J. Clin. Virol., 49, 47-52, (2010)

[60] Ministry of Health of the People's Republic of China (MOHC), The Status of Prevention and Control of Rabies in China (Zhongguo Kuangquanbing Fangzhi Xiankuang), 2009, http://www.moh.gov.cn/publicfiles/business/htmlfiles/mohbgt/s9513/200909/42937.htm.

[61] Ministry of Health of the People's Republic of China (MOHC), Bulletins, 2010, http://www.moh.gov.cn/publicfiles/business/htmlfiles/mohbgt/pws Accessed June 1, 2011.

[62] Moneim, I., The effect of using different types of periodic contact rate on the behaviour of infectious diseases: a simulation study, Comput. Biol. Med., 37, 1582-1590, (2007)

[63] Murray, J. D.; Seward, W. L., On the spatial spread of rabies among foxes with immunity, J. Theor. Biol., 156, 327-348, (1992)

[64] Murray, J. D.; Stanle, E. A.; Brown, D. L., On the spatial spread of rabies among foxes, Proc. R. Soc. Lond. B, 229, 111-150, (1986)

[65] National Bureau of Statistics of China (NBSC), China Demographic Yearbook of 2009, 2011, http://www.stats.gov.cn/tjsj/ndsj/2009/indexch.htm. Accessed June 1.

[66] National Health and Family Planning Commission of the People's Republic of China (NHFPC), China Health Statistical Yearbook 2012, 2014, http://www.nhfpc.gov.cn/htmlfiles/zwgkzt/ptjnj/year2012/index2012.html. Accessed July 17.

[67] National Health and Family Planning Commission of the People's Republic of China (NHFPC), Bulletins, 2014, http://www.nhfpc.gov.cn/jkj/s3578 Accessed July 17, 2014.

[68] Newman, M. E.J., Spread of epidemic disease on networks, Phys. Rev. E., 66, 016128, (2002)

[69] Ou, C.; Wu, J., Spatial spread on nonlinear dynamics, SIAM J. Appl. Math., 67, 138-163, (2006) · Zbl 1110.35027

[70] Panjeti, V. G.; Real, L. A., Mathematical models for rabies, Adv. Virus Res., 79, 377-395, (2011)

[71] Perko, L., Differential equations and dynamical systems, (2000), Springer-Verlag New York

[72] Rhodes, C. J.; Atkinson, R. P.D.; Anderson, R. M.; Macdonald, D. W., Rabies in zimbabwe: reservoir dogs and the implications for disease control, Philos. Trans. R. Soc. Lond. B, 353, 999-1010, (1998)

[73] Roberts, M. G.; Aubert, M. F.A., A model for the control of echinococcus multilocularis in France, Vet. Parasitol., 56, 67-74, (1995)

[74] Ruan, S.; Wu, J., Modeling spatial spread of communicable diseases involving animal hosts, (Cantrell, S.; Cosner, C.; Ruan, S., Spatial Ecology, (2009), Chapman Hall/CRC Boca Raton, FL), 293-316 · Zbl 1183.92074

[75] Russell, C. A.; Real, L. A.; Smith, D. L., Spatial control of rabies on heterogeneous landscapes, PLoS One, 1, e27, (2006)

[76] Schenzle, D., An age-structured model of pre- and pose-vaccination measles transmission, Math. Med. Biol., 1, 169-191, (1984) · Zbl 0611.92021

[77] Schultz, R. D., Duration of immunity for canine and feline vaccines: a review, Vet. Microbiol., 117, 75-79, (2006)

[78] Schwartz, I., Small amplitude, long periodic out breaks in seasonally driven epidemics, J. Math. Biol., 30, 473-491, (1992) · Zbl 0745.92026

[79] Si, H.; Guo, Z. M.; Hao, Y. T.; Liu, Y. G.; Zhang, D. M., Rabies trend in China (1990-2007) and post-exposure prophylaxis in the guangdong province, BMC Infect. Dis., 8, 113, (2008)

[80] Si, H.; Liu, Y.-G.; Li, G.-W.; Liu, Z.-Y.; Lu, J.-H., Analysis on the characteristic of rabies epidemiology in guangdong province from 1990 to 2005, J. Sun Yat-Sen Univ., 28, 263-264, (2007)

[81] Smith, D. L.; Lucey, B.; Waller, L. A.; Childs, J. E.; Real, L. A., Predicting the spatial dynamics of rabies epidemic on heterogeneous landscapes, Proc. Natl. Acad. Sci. USA, 99, 3668-3672, (2002)

[82] Smith, G. C.; Cheeseman, C. L., A mathematical model for the control of diseases in wildlife populations: culling, vaccination and fertility control, Ecol. Model., 150, 45-53, (2002)

[83] Smith, G. C.; Harris, S., The control of rabies in urban fox populations, (Putman, R. J., Mammals as Pests, (1989), Chapman \& Hall London), 209-224

[84] Song, M.; Tang, Q.; Wang, D. M.; Mo, Z. J.; Guo, S. H., Epidemiological investigations of human rabies in China, BMC Infect. Dis., 9, 210, (2009)

[85] Song, M.; Tang, Q.; Rayner, S., Human rabies surveillance and control in China, BMC Infect. Dis., 14, 212, (2014)

[86] Sterner, R. T.; Smith, G. C., Modelling wildlife rabies: transmission, economics, and conservation, Biol. Conserv., 131, 163-179, (2006)

[87] Tang, X. C.; Luo, M.; Zhang, S. Y.; Anthony, R. F.; Hu, R. L., Pivotal role of dogs in rabies transmission, China, Emerg. Infect. Dis., 11, 1970-1972, (2005)

[88] Tao, X. Y.; Tang, Q.; Li, H., Molecular epidemiology of rabies in southern people's republic of China, Emerg. Infect. Dis., 15, 1192-1198, (2009)

[89] Tao, X.-Y.; Tang, Q.; Yayner, S., Molecular phylodynamic analysis indicates lineage displacement occurred in Chinese rabies epidemics between 1949 to 2010, PLoS Negl. Trop. Dis., 7, 7, e2294, (2013)

[90] Tenzin; Ward, M. P., Review of rabies epidemiology and control in south, south east and east Asia: past, present and prospects for elimination, Zoonoses Public Health, 59, 451-467, (2012)

[91] Tierkel, E. S., Canine rabies, (Baer, G. M., The Natural History of Rabies, (1975), Academic Press London)

[92] Torill, M.; Pal, P., Arctic rabies - a review, Acta Vet. Scand., 45, 1-9, (2004)

[93] van den Driessche, P.; Watmough, J., Reproduction numbers and sub-threshold endemic equilibria for compartmental models of disease transmission, Math. Biosci., 180, 29-48, (2002) · Zbl 1015.92036

[94] Wang, L.; Tang, Q.; Liang, G., Rabies and rabies virus in wildlife in mainland China, 1990-2013, Int. J. Infect. Dis., 25, 122-129, (2014)

[95] Wang, W.; Zhao, X.-Q., Threshold dynamics for compartmental epidemic models in periodic environments, J. Dyn. Differ. Equ.., 20, 699-717, (2008) · Zbl 1157.34041

[96] Wang, X.; Lou, J., Two dynamic models about rabies between dogs and human, J. Biol. Syst., 16, 519-529, (2008) · Zbl 1355.92132

[97] Wang, X. J.; Huang, J. T., Epidemiology, (Yu, Y. X., Rabies and Rabies Vaccine, (2001), Chinese Medicine Technology Press Beijing), 127-144

[98] Wang, Z.-X., WHO position on rabies vaccine, Int. J. Biol., 25, 245-248, (2002)

[99] Wesley, C.; Allen, L., The basic reproduction number in epidemic models with periodic demographics, J. Biol. Dyn., 3, 116-129, (2009) · Zbl 1342.92287

[100] World Health Organization (WHO), 2004, WHO Expert Consultation on Rabies: First Report. Geneva.

[101] World Health Organization (WHO), 2010, Rabies. http://www.who.int/mediacentre/factsheets/fs099/en/. Updated.

[102] Williams, B., Infectious disease persistence when transmission varies seasonally, Math. Biosci., 145, 77-88, (1997) · Zbl 0896.92024

[103] Wu, H.; Wang, L.; Tao, X., Genetic diversity and molecular evolution of the rabies virus matrix protein gene in China, Infect. Genet. Evol., 16, 248-253, (2013)

[104] Wu, X. F.; Hu, R. L.; Zhang, Y. Z.; Dong, G. M.; Rupprecht, C. E., Reemerging rabies and lack of systemic surveillance in people's republic of China, Emerg. Infect. Dis., 15, 1159-1164, (2009)

[105] Wunner, W. H.; Briggs, D. J., Rabies in the 21st century, PLoS Negl. Trop. Dis., 4, 3, e591, (2010)

[106] Yin, C.; Zhou, H.; Wu, H., Analysis on factors related to rabies epidemic in China from 2007-2011, Virol. Sin., 27, 132-143, (2012)

[107] Yin, W.; Dong, J.; Tu, C., Challenges and needs for China to eliminate rabies, Infect. Dis. Poverty, 2, 23, (2013)

[108] Yu, J.; Hao, L.; Tang, Q., The spatial and temporal dynamics of rabies in China, PLoS Negl. Trop. Dis., 6, e1640, (2012)

[109] Yang, W.; Lou, L., The dynamics of an interactional model of rabies transmitted between human and dogs, Boll. UMI, 3, 591-605, (2009) · Zbl 1178.92050

[110] Zhang, F.; Zhao, X.-Q., A periodic epidemic model in a patchy environment, J. Math. Anal. Appl., 325, 496-516, (2007) · Zbl 1101.92046

[111] Zhang, J.; Jin, Z.; Sun, G.; Sun, X.; Ruan, S., Modeling seasonal rabies epidemics in China, Bull. Math. Biol., 74, 1226-1251, (2012) · Zbl 1237.92056

[112] Zhang, J.; Jin, Z.; Sun, G.; Sun, X.; Ruan, S., Spatial spread of rabies in China, J. Appl. Anal. Comput., 2, 111-126, (2012)

· Zbl 1304.92126

[113] Zhang, J.; Jin, Z.; Sun, G.; Zhou, T.; Ruan, S., Analysis of rabies in China: transmission dynamics and control, PLoS One, 6, e20891, (2011)

[114] Zhang, Y.-Z.; Xiao, D.-L.; Sun, Y.-H.; Yang, X.-R.; Yan, Y.-Z., The epidemic situation of human rabies from 1984 to 2002 and its preventive measures in China, Chin. J. Epidemiol., 24, 883-886, (2003)

[115] Zhang, Y.-Z.; Xiong, C.-L.; Xiao, D.-L., Human rabies in China, Emerg. Infect. Dis., 11, 1983-1984, (2005)

[116] Zhao, X.-Q., Dynamical systems in population biology, (2003), Springer-Verlag New York

[117] Zinsstag, J.; Durr, S.; Penny, M. A.; Mindekem, R.; Roth, F., Transmission dynamic and economics of rabies control in dogs and humans in an african city, Proc. Natl. Acad. Sci. USA, 106, 14996-15001, (2009)