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Formulation of a Mathematical Model for Transmission and Control of Zika Virus Fever Dynamics

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ABSTRACT: We formulated a mathematical model for the transmission and control of zika virus fever dynamics, incorporating controls; and mosquito bite, sexual contact, vertical transmission blood transfusion as medium of transmissions. Based on our previous findings that the model is mathematically well posed for analysis, the state variables at the endemic state are expressed in terms of parameters and forces of infection, substitution and simplifying led to a polynomial. Invoking Descartes sign rule of polynomial confirmed the existence of a unique endemic equilibrium point of the model if and only if the effective reproduction number is greater than one ($R_e > 1$).

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Zika virus derives its name from zika forest in Uganda where it was first discovered in monkey in 1947, in a female mosquito in 1948 and in human in 1952; the infection caused by zika virus is called zika virus fever which does not kill but is linked with Microcephaly and Neurological anomalies (WHO, 2016). Zika virus lives longer in the semen than in the blood or virginal fluid (CDC, 2016). The virus is transmitted through mosquito bite, sexual contact, vertical transmission and blood transfusion (ECDC, 2016). (Funk *et al.,* 2016) worked on comparative analysis of Zika and Dengue by setting the viruses. (Kucharski *et al,* 2016) worked on the outbreaks of zika in French Polynesia between 2013 and 2014. Gao *et al.*, (2016) and Augusto *et al*., (2017) modeled zika virus as mosquito borne and sexually transmitted disease. The aim of this paper is to establish the condition for the existence of the endemic state and also determine the number of the endemic points of our improved model equations.

MATERIALS AND METHODS

Total female population (N_1) is split into: Susceptible female compartment (S_1), Exposed female compartment (E_1), Symptomatic female compartment (I_{11}), Asymptomatic female compartment (I_{12}) and the Removed female compartment (R_1). The male population (N_2) is similarly partitioned into sub –populations as given in equation (15); and mosquito population is split into mosquitoes without zika virus (S_3) and mosquitoes with zika virus (I_3) as in (14).

MODEL EQUATIONS

$$\frac{dS_1}{dt} = \theta_1\omega_1\Lambda_1 - \frac{S_1}{N_1}\{\alpha_1\phi_3 I_3 + \alpha_{21}\phi_{21}I_{21}(1-\epsilon_c\,\tau_c) + \alpha_{22}\phi_{22}I_{22}(1-\epsilon_c\,\tau_c)\} - \mu_1 S_1 \quad (1)$$

$$\frac{dE_1}{dt} = (1-\theta_1)\omega_1\Lambda_1 + \frac{S_1}{N_1}\{\alpha_1\phi_3 I_3 + \alpha_{21}\phi_{21}I_{21}(1-\epsilon_c\,\tau_c) + \alpha_{22}\phi_{22}I_{22}(1-\epsilon_c\,\tau_c)\} - (\gamma_1 + \sigma_{11} + \sigma_{12} + \mu_1)E_1 \quad (2)$$

$$\frac{dI_{11}}{dt} = \sigma_{11}E_1 - (\gamma_{11} + \mu_1)I_{11} \quad (3)$$

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$$\frac{dI_{12}}{dt} = \sigma_{12}E_1 - (\gamma_{12} + \mu_1)I_{12} \quad (4)$$

$$\frac{dR_1}{dt} = (1-\omega_1)\Lambda_1 + \gamma_1 E_1 + \gamma_{11}I_{11} + \gamma_{12}I_{12} - \mu_1 R_1 \quad (5)$$

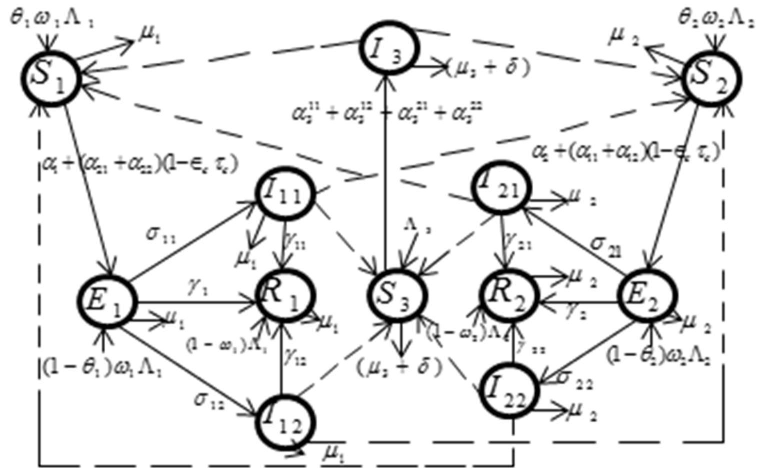

Fig 1: Model graph

$$\frac{dS_3}{dt} = \Lambda_3 - \frac{S_3}{N_3}(\alpha_3^{11}\phi_{11}I_{11} + \alpha_3^{12}\phi_{12}I_{12} + \alpha_3^{21}\phi_{21}I_{21} + \alpha_3^{22}\phi_{22}I_{22}) - (\mu_3+\delta)S_3 \quad (6)$$

$$\frac{dI_3}{dt} = \frac{S_3}{N_3}(\alpha_3^{11}\phi_{11}I_{11} + \alpha_3^{12}\phi_{12}I_{12} + \alpha_3^{21}\phi_{21}I_{21} + \alpha_3^{22}\phi_{22}I_{22}) - (\mu_3+\delta)S_3 \quad (7)$$

$$\frac{dS_2}{dt} = \theta_2\omega_2\Lambda_2 - \frac{S_2}{N_2}\{\alpha_2\phi_3 I_3 + \alpha_{11}\phi_{11}I_{11}(1-\in_c \tau_c) + \alpha_{12}\phi_{12}I_{12}(1-\in_c \tau_c)\} - \mu_2 S_2 \quad (8)$$

$$\frac{dE_2}{dt} = (1-\theta_2)\omega_2\Lambda_2 + \frac{S_2}{N_2}\{\alpha_2\phi_3 I_3 + \alpha_{11}\phi_{11}I_{11}(1-\in_c \tau_c) + \alpha_{12}\phi_{12}I_{12}(1-\in_c \tau_c)\} - (\gamma_2 + \sigma_{21} + \sigma_{22} + \mu_2)E_2 \quad (9)$$

$$\frac{dI_{21}}{dt} = \sigma_{21}E_2 - (\gamma_{21} + \mu_2)I_{21} \quad (10)$$

$$\frac{dI_{22}}{dt} = \sigma_{22}E_2 - (\gamma_{22} + \mu_2)I_{22} \quad (11)$$

$$\frac{dR_2}{dt} = (1-\omega_2)\Lambda_2 + \gamma_2 E_2 + \gamma_{21}I_{21} + \gamma_{22}I_{22} - \mu_2 R_2 \quad (12)$$

$$N_1 = S_1 + E_1 + I_{11} + I_{12} + R_1 \quad (13)$$

$$N_3 = S_3 + I_3 \quad (14)$$

$$N_2 = S_2 + E_2 + I_{21} + I_{22} + R_2 \quad (15)$$

Table 1: Parameters of the Model

Parameter	Description
Λ_1	Number of recruitment into female population
ω_1	Proportion of births without microcephaly into female population
$(1-\omega_1)$	Proportion of female births with microcephaly
θ_1	Proportion of susceptible female births without microcephaly

$(1-\theta_1)$	Proportion of exposed female births without Microcephaly
μ_1	Natural death rate of females
Λ_2	Number of recruitment into male population
ω_2	Proportion of births without microcephaly into male population
$(1-\omega_2)$	Proportion of male births with microcephaly
θ_2	Proportion of susceptible female births without microcephaly
$(1-\theta_2)$	Proportion of exposed female births without Microcephaly
μ_2	Natural death rate of males
Λ_3	Number of recruitment into the population of mosquitoes without zika virus
μ_3	Natural death rate of mosquitoes
δ	Death rate of mosquitoes due to insecticides
α_1	Transmission rate of infection through mosquito bite to the susceptible females
α_2	Transmission rate of infection through mosquito bite to the susceptible males
α_{21}	Transmission rate of infection through sex from symptomatic infectious males to susceptible females
α_{22}	Transmission rate of infection through sex from asymptomatic infectious males to susceptible females
α_{11}	Transmission rate of infection through sex from symptomatic infectious females to susceptible males
α_{12}	Transmission rate of infection through sex from symptomatic infectious females to susceptible males
α_3^{11}	Transmission rate of virus from symptomatic infectious females to mosquitoes without virus through mosquito bite
α_3^{12}	Transmission rate of virus from asymptomatic infectious females to mosquitoes without virus through mosquitoes bite
α_3^{21}	Transmission rate of virus from symptomatic infectious males to mosquitoes without virus through mosquito bite
α_3^{22}	Transmission rate of virus from asymptomatic infectious males to mosquitoes without virus through mosquito bite
σ_{11}	Progression rate of exposed females to the symptomatic infectious compartment
σ_{12}	Progression rate of exposed females to the asymptomatic infectious compartment
σ_{21}	Progression rate of exposed males to the symptomatic infectious compartment
σ_{22}	Progression rate of exposed males to the asymptomatic infectious compartment
γ_1	Rate of recovery from the compartment of exposed females to the removed compartment
γ_2	Rate of recovery from the compartment of exposed males to the removed compartment
γ_{11}	Rate of recovery from the compartment of symptomatic, infectious, females to the removed compartment
γ_{12}	Rate of recovery from the compartment of asymptomatic, infectious, females to the removed compartment
γ_{21}	Rate of recovery from the compartment of symptomatic, infectious, males to the removed compartment
γ_{22}	Rate of recovery from the compartment of asymptomatic, infectious, males to the removed compartment
ϕ_3	Is measuring the reduction in effectiveness of mosquito activities in transmitting virus by creating non conducive environment for the mosquitoes through the use of air conditioner
ϕ_{11}	Is measuring the reduction in effectiveness of sexual transmission through adherence to the preventive instructions
ϕ_{12}	Is measuring the reduction in effectiveness of sexual transmission through adherence to the preventive instructions
ϕ_{21}	Is measuring the reduction in effectiveness of sexual transmission through adherence to the preventive instructions
ϕ_{22}	Is measuring the reduction in effectiveness of sexual transmission through adherence to the preventive instructions
$(1-\in_c \tau_c)$	Reflects the impact of condom usage which is enhanced by public campaign (efficacy and compliance) on sexual transmission where $0 < \in_c, \tau_c < 1$

RESULTS AND DISCUSION

Theorem 1: The Zika transmission model (1) – (12) has endemic equilibrium point if $R_e > 1$.

Proof

$\varepsilon_E = (S_1^{**}, E_1^{**}, I_{11}^{**}, I_{12}^{**}, R_1^{**}, S_3^{**}, I_3^{**}, S_2^{**}, E_2^{**}, I_{21}^{**}, I_{22}^{**}, R_2^{**})$ is assumed to be the endemic point of (2) – (12) then the respective compartments are expressed in terms of parameters and forces of infection,

$$S_1^{**}=\frac{\theta_1\omega_1\Lambda_1}{\eta\lambda_H^{**}+\mu_1} \quad (16)$$

$$E_1^{**}=\frac{\omega_1\Lambda_1\eta\lambda_H^{**}+(1-\theta_1)\omega_1\Lambda_1\mu_1}{k_1(\eta\lambda_H^{**}+\mu_1)} \quad (17)$$

$$I_{11}^{**}=\frac{\sigma_{11}\omega_1\Lambda_1\eta\lambda_H^{**}+(1-\theta_1)\sigma_{11}\omega_1\Lambda_1\mu_1}{k_1k_2(\eta\lambda_H^{**}+\mu_1)} \quad (18)$$

$$I_{12}^{**}=\frac{\sigma_{12}\omega_1\Lambda_1\eta\lambda_H^{**}+(1-\theta_1)\sigma_{12}\omega_1\Lambda_1\mu_1}{k_1k_3(\eta\lambda_H^{**}+\mu_1)} \quad (19)$$

$$R_1^{**}=\frac{(k_2k_3\gamma_1+k_3\gamma_{11}\sigma_{11}+k_2\gamma_{12}\sigma_{12})\{\omega_1\Lambda_1\eta\lambda_H^{**}+(1-\theta_1)\omega_1\Lambda_1\mu_1\}}{k_1k_2k_3(\eta\lambda_H^{**}+\mu_1)} \quad (20)$$

$$S_3^{**}=\frac{\Lambda_3}{\lambda_3^{**}+k_4} \quad (21)$$

$$I_3^{**}=\frac{\Lambda_3\lambda_3^{**}}{k_4(\lambda_3^{**}+k_4)} \quad (22)$$

$$S_2^{**}=\frac{\theta_2\omega_2\Lambda_2}{(1-\eta)\lambda_H^{**}+\mu_2} \quad (23)$$

$$E_2^{**}=\frac{\omega_2\Lambda_2(1-\eta)\lambda_H^{**}+(1-\theta_2)\omega_2\Lambda_2\mu_2}{k_5[(1-\eta)\lambda_H^{**}+\mu_2]} \quad (24)$$

$$I_{21}^{**}=\frac{\sigma_{21}\omega_2\Lambda_2(1-\eta)\lambda_H^{**}+(1-\theta_2)\sigma_{21}\omega_2\Lambda_2\mu_2}{k_5k_6[(1-\eta)\lambda_H^{**}+\mu_2]} \quad (25)$$

$$I_{22}^{**}=\frac{\sigma_{22}\omega_2\Lambda_2(1-\eta)\lambda_H^{**}+(1-\theta_2)\sigma_{22}\omega_2\Lambda_2\mu_2}{k_5k_7[(1-\eta)\lambda_H^{**}+\mu_2]} \quad (26)$$

$$R_2^{**}=\frac{(k_6k_7\gamma_2+k_7\gamma_{21}\sigma_{21}+k_6\gamma_{22}\sigma_{22})\{\omega_2\Lambda_2(1-\eta)\lambda_H^{**}+(1-\theta_2)\omega_2\Lambda_2\mu_2\}}{k_5k_6k_7[(1-\eta)\lambda_H^{**}+\mu_2]} \quad (27)$$

$$\lambda_1^{**}=\eta\lambda_H^{**} \quad (28)$$

$$\lambda_2^{**}=(1-\eta)\lambda_H^{**} \quad (29)$$

$$\lambda_H^{**}=\frac{\beta_8I_3^{**}+\beta_2I_{21}^{**}+\beta_3I_{22}^{**}+\beta_9I_{11}^{**}+\beta_{10}I_{12}^{**}}{N_H^{**}} \quad (30)$$

$$\lambda_3^{**}=\frac{\beta_4I_{11}^{**}+\beta_5I_{12}^{**}+\beta_6I_{21}^{**}+\beta_7I_{22}^{**}}{N_3^{**}} \quad (31)$$

λ_H represents the force of infection from mosquitoes and infectious humans to susceptible humans. λ_3^{**} is the force of transmitting virus from infected humans to the vectors.

Substitute for $I_{11}^{**}, I_{12}^{**}, I_{21}^{**}, I_{22}^{**}$ and I_3^{**} in (30) and (31) and simplify, then with $a_i's$ definitions, for $i=1,2,\ldots 14$, equations (30) and (31) become

$$\lambda_3^{**} = \frac{a_1 \lambda_H^{**^3} + a_2 \lambda_H^{**^2} + a_3 \lambda_H^{**} + a_4}{a_5 \lambda_H^{**^3} + a_6 \lambda_H^{**^2} + a_7 \lambda_H^{**} + a_8} \quad (32)$$

$$\lambda_3^{**} = \frac{a_9 \lambda_H^{**^2} + a_{10} \lambda_H^{**} + a_{11}}{a_{12} \lambda_H^{**^2} + a_{13} \lambda_H^{**} + a_{14}} \quad (33)$$

$$a_1 = k_1 k_2 k_3 k_4^2 k_5 k_6 k_7 N_H^{**} (1-\eta) \quad (34)$$

$$a_2 = \left. \begin{aligned} &\{k_1 k_2 k_3 k_4^2 k_5 k_6 k_7 N_H^{**} [(1-\eta)\mu_1 + \eta\mu_2] - k_1 k_2 k_3 k_4^2 \omega_2 \Lambda_2 (1-\eta)\eta (k_7 \beta_2 \sigma_{21} + k_6 \beta_3 \sigma_{22}) - \\ &k_4^2 k_5 k_6 k_7 \omega_1 \Lambda_1 (1-\eta)\eta (k_3 \beta_9 \sigma_{11} - k_2 \beta_{10} \sigma_{12})\} \end{aligned} \right] \quad (35)$$

$$a_3 = \left. \begin{aligned} &\{k_1 k_2 k_3 k_4^2 k_5 k_6 k_7 N_H^{**} \mu_1 \mu_2 - k_1 k_2 k_3 k_4^2 \omega_2 \Lambda_2 [(1-\eta)\mu_1 + (1-\theta_2)\eta\mu_2](k_7 \beta_2 \sigma_{21} + k_6 \beta_3 \sigma_{22}) - \\ &k_4^2 k_5 k_6 k_7 \omega_1 \Lambda_1 [(1-\eta)(1-\theta_1)\mu_1 + \eta\mu_2](k_3 \beta_9 \sigma_{11} + k_2 \beta_{10} \sigma_{12})\} \end{aligned} \right] \quad (36)$$

$$a_4 = k_4^2 \mu_1 \mu_2 [k_1 k_2 k_3 \omega_2 \Lambda_2 (1-\theta_2)(k_7 N_H^{**} \beta_2 \sigma_{21} + k_6 \beta_3 \sigma_{22}) + k_5 k_6 k_7 \omega_1 \Lambda_1 (1-\theta_1)(k_3 \beta_9 \sigma_{11} + k_2 \beta_{10} \sigma_{12})] \quad (37)$$

$$a_5 = -k_1 k_2 k_3 k_4 k_5 k_6 k_7 N_H^{**} (1-\eta)\eta \quad (38)$$

$$a_6 = \left. \begin{aligned} &\{k_1 k_2 k_3 (1-\eta)\eta [k_5 k_6 k_7 (\beta_1 + \beta_8)\Lambda_3 + k_4 \omega_2 \Lambda_2 (1-\eta)\eta (k_7 \beta_2 \sigma_{21} + k_6 \beta_3 \sigma_{22})] + \\ &k_4 k_5 k_6 k_7 \omega_1 \Lambda_1 (1-\eta)\eta (k_3 \beta_9 \sigma_{11} + k_2 \beta_{10} \sigma_{12}) - k_1 k_2 k_3 k_4 k_5 k_6 k_7 N_H^{**} [(1-\eta)\mu_1 + \eta\mu_2]\} \end{aligned} \right] \quad (39)$$

10.

$$a_7 = \left. \begin{aligned} &\{k_1 k_2 k_3 \{k_5 k_6 k_7 (\beta_1 + \beta_8)\Lambda_3 [(1-\eta)\mu_1 + \eta\mu_2] + k_4 \omega_2 \Lambda_2 [(1-\eta)\mu_1 + \eta(1-\theta_2)\mu_2](k_7 \beta_2 \sigma_{21} + k_6 \beta_3 \sigma_{22})\} + \\ &k_4 k_5 k_6 k_7 \omega_1 \Lambda_1 [(1-\theta_1)(1-\eta)\mu_1 + \eta\mu_2](k_3 \beta_9 \sigma_{11} + k_2 \beta_{10} \sigma_{12}) - k_1 k_2 k_3 k_4 k_5 k_6 k_7 N_H^{**} \mu_1 \mu_2\} \end{aligned} \right] \quad (40)$$

$$a_8 = \mu_1 \mu_2 \{k_1 k_2 k_3 [k_5 k_6 k_7 (\beta_1 + \beta_8)\Lambda_3 + k_4 \omega_2 \Lambda_2 (1-\theta_2)(k_7 \beta_2 \sigma_{21} + k_6 \beta_3 \sigma_{22})] + k_4 k_5 k_6 k_7 \omega_1 \Lambda_1 (1-\theta_1)[k_3 \beta_9 \sigma_{11} + k_2 \beta_{10} \sigma_{12}]\} \quad (41)$$

$$a_9 = (1-\eta)\eta [k_5 k_6 k_7 \omega_1 \Lambda_1 (k_3 \beta_4 \sigma_{11} + k_2 \beta_5 \sigma_{12}) + k_1 k_2 k_3 \omega_2 \Lambda_2 (k_7 \beta_6 \sigma_{21} + k_6 \beta_7 \sigma_{22})] \quad (42)$$

$$a_{10} = k_5 k_6 k_7 \omega_1 \Lambda_1 [(1-\theta_1)(1-\eta)\mu_1 + \eta\mu_2](k_3 \beta_4 \sigma_{11} + k_2 \beta_5 \sigma_{12}) + k_1 k_2 k_3 \omega_2 \Lambda_2 [(1-\eta)\mu_1 + \eta(1-\theta_2)\mu_2](k_7 \beta_6 \sigma_{21} + k_6 \beta_7 \sigma_{22}) \quad (43)$$

$$a_{11} = \mu_1 \mu_2 \{k_5 k_6 k_7 \omega_1 \Lambda_1 (1-\theta_1)(k_3 \beta_4 \sigma_{11} + k_2 \beta_5 \sigma_{12}) + k_1 k_2 k_3 \omega_2 \Lambda_2 (1-\theta_2)(k_7 \beta_6 \sigma_{21} + k_6 \beta_7 \sigma_{22})\} \quad (44)$$

$$a_{12} = k_1 k_2 k_3 k_5 k_6 k_7 N_3^{**} (1-\eta)\eta, a_{13} = k_1 k_2 k_3 k_5 k_6 k_7 N_3^{**} [(1-\eta)\mu_1 + \eta\mu_2], a_{14} = k_1 k_2 k_3 k_5 k_6 k_7 N_3^{**} \mu_1 \mu_2 \quad (45)$$

Equating equations (30) and (31) and simplifying the result gives

$$\left. \begin{aligned} &\{(a_1 a_{12} - a_5 a_9)\lambda_H^{**^5} + [(a_1 a_{13} + a_2 a_{12}) - (a_5 a_{10} + a_6 a_9)]\lambda_H^{**^4} + [(a_1 a_{14} + a_2 a_{13} + a_3 a_{12}) - (a_5 a_{11} + a_6 a_{10} + a_7 a_9)]\lambda_H^{**^3} + \\ &[(a_2 a_{14} + a_3 a_{13} + a_4 a_{12}) - (a_6 a_{11} + a_7 a_{10} + a_8 a_9)]\lambda_H^{**^2} + [(a_3 a_{14} + a_4 a_{13}) - (a_7 a_{11} + a_8 a_{10})]\lambda_H^{**} + (a_4 a_{14} - a_8 a_{11})\} \end{aligned} \right] = 0$$

$$\Rightarrow \quad b_5 \lambda_H^{**^5} + b_4 \lambda_H^{**^4} + b_3 \lambda_H^{**^3} + b_2 \lambda_H^{**^2} + b_1 \lambda_H^{**} + b_0 = 0 \quad (46)$$

$\Rightarrow b_5 > 0, b_4 > 0, b_3 > 0, b_2 > 0$ and $b_1 > 0$.

$\Rightarrow \quad b_0 = a - b < c(1 - R_e) - b < 0$ if and only if $R_e > 1$

$$\Rightarrow b_5 \lambda_H^{**^5} + b_4 \lambda_H^{**^4} + b_3 \lambda_H^{**^3} + b_2 \lambda_H^{**^2} + b_1 \lambda_H^{**} + [c(1 - R_e) - b] = 0 \, , \quad (47)$$

QED

Conclusion: Invoking Descartes rule of signs to polynomial, states that if given a polynomial with real coefficients then the number of positive roots or zeros of the polynomial is equal the number of variation in sign of the polynomial (number of sign changes) or less than this by an even number. Applying the above rule of signs to the polynomial (47) shows that there is only one sign change. Hence the system (1) – (12) has a unique endemic equilibrium point, which is a confirmation of the existence of endemic state of the system (1) – (12).

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