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A MODEL ANALYSIS OF THE EFFECT OF PUBLIC ENLIGHTENMENT AND BEHAVIOURAL CHANGE WITH TREATMENT ON *NEISSERIA GONORRHEA* DYNAMICS

AWORTU, IBIFAA SANDRA & GEORGE, ISOBEYE
Ignatius Ajuru University of Education, Rumuolumeni, Port Harcourt, Rivers State.
ibifaaawortu2@gmail.com

Abstract
A simple nonlinear SIR mathematical model describing the use of gonorrhea public enlightenment as a control in the presence of treatment of gonorrhea infectives is considered to assess the contribution of behavioural change among the enlightened gonorrhea susceptible individuals. The enlightenment programme resulted in a change in the behaviour of enlightened gonorrhea susceptible individuals thereby splitting the susceptible class into three. The basic properties of the model are considered and the basic reproduction number (R_0) was determined. It was shown that, a decrease in the rate at which susceptible individuals know their gonorrhea status (ρ), increases the value of the basic reproduction number (R_0), the population of unaware susceptible individuals (S) and aware susceptible individuals (S_1). On the contrary, a decrease in ρ decreases the population of enlightened gonorrhea susceptible individuals who remain faithful to their uninfected sexual partners for life (S_2) as well as infected (I) and recovered (R) individuals. Also, a decrease in the incidence rate of unaware *neisseria gonorrhea* susceptible individuals per unit time (β_1) decreases the basic reproduction number (R_0) and the populations of infected (I) and recovered (R) individuals, while the susceptible populations (S, S_1 and S_2) increase slightly. Finally, decreasing the incidence rate of aware *neisseria gonorrhea* susceptible individuals per unit time (β_2) gradually decreases the basic reproduction number (R_0) and, the populations of infected (I) and recovered (R) individuals, while the susceptible populations (S, S_1 and S_2) increase slightly. It is therefore recommended that, the relevant agencies

should increase the rate of public enlightenment so as to bring the population of susceptible individuals to the barest minimum.

Keywords: Public Awareness, Behavioural Change, Treatment, *Neisseria Gonorrhea*, Model Analysis.

Introduction

Gonorrhea is the most common sexually transmitted disease (STD) caused by infection with the *neisseria gonorrhea bacterium.* It infects the mucous membranes of the reproductive tracts, including the cervix, uterus, fallopian tubes in women, urethra in women and men, and the mucous membranes of the mouth, throat, eyes and rectum (Center for Disease Control (CDC), 2015; Mushayabasa et al 2010). Gonorrhea is strictly human pathogen and is primarily transmitted through sexual contact (Hill et al., 2016).

Gonorrhea was first discovered in 1972 in Edinburg where the surgeon Benjamin Bell clearly separated it from syphilis infectious disease (Benedek, 2005), and has now been a global health challenge that has affected every country in the world. In 1963, the World health organization (WHO) found Lagos State in Nigeria to have the highest gonorrhea infectives in the world (Ogunbajo, 1989).

Gonorrhea is a curable sexually transmitted infection and can be cured with the right treatment, but untreated gonorrhea can cause serious and permanent health problems in both men and women (Bolan et al., 2012). In women, gonorrhea can spread into the uterus or fallopian tubes and cause pelvic inflammatory disease (PID)(Los Olivos women's medical group 2019), while in men, it may be complicated by epididymitis which may lead to infertility (Rowley et al., 2016). A gonorrhea infected pregnant woman may give the infection to her baby during child birth and this can cause blindness, joint infection or a life-threatening blood infection in the baby (Unemo et al., 2019).

Mathematical Formulation

The total population under consideration at time t, represented by $N(t)$, is divided into the following compartments of susceptible individuals to diphtheria $S(t)$, susceptible individuals who are unaware of diphtheria $S_1(t)$, susceptible individuals who are aware of diphtheria $S_2(t)$, individuals infected with diphtheria $I(t)$ and recovered individuals $R(t)$. Hence,

$$N(t) = S(t) + S_1(t) + S_2(t) + I(t) + R(t). \qquad (1)$$

In this work, the model proposed by Udoo (2018) is adopted and is stated as follows:

$$\frac{dS}{dt} = p - (\lambda + \rho + \mu)S, \qquad S(0) > 0 \qquad (2)$$
$$\frac{dS_1}{dt} = (1 - \phi)\rho S - (\tau\lambda_1 + \mu)S_1, \qquad S_1(0) > 0 \qquad (3)$$
$$\frac{dS_2}{dt} = \phi\rho S - \mu S_2, \qquad S_2(0) > 0 \qquad (4)$$
$$\frac{dI}{dt} = \lambda S + \tau\lambda_1 S_1 - (\delta + \alpha + \mu)I, \qquad I(0) \geq 0 \qquad (5)$$
$$\frac{dR}{dt} = \delta I - (v + \mu)R, \qquad R(0) \geq 0 \qquad (6)$$

The model variables and parameter values are presented in Tables 1 and 2 below.

Table 1: Description of parameters in the model (2) – (6)

Parameter	Description	Approximate value
$\boldsymbol{p}$	Recruitment rate	0.029
$\boldsymbol{\beta_1}$	Incidence rate of unaware susceptible individuals	$0 \leq \beta_1 \leq 1$
$\boldsymbol{\beta_2}$	Incidence rate of aware susceptible individuals	$0 \leq \beta_2 \leq 1$
$\boldsymbol{\tau}$	Modification parameter	$0 < \tau < 1$
$\boldsymbol{\rho}$	Rate of susceptible knowing their infectious status	$0 < \rho < 1$
$\boldsymbol{\mu}$	Natural death rate	0.02
$\emptyset$	Proportion of aware susceptible individuals who are vaccinated	$0 < \emptyset < 1$
$\boldsymbol{\delta}$	Treatment rate of gonorrhea infectives	$0 < \delta < 1$
$\boldsymbol{\alpha}$	Disease-induced death rate of infectives	0.10
$\boldsymbol{v}$	Disease-induced death rate of treated gonorrhea infectives	0.02

Table 2: Description of model variables

Parameter	Description
$\boldsymbol{S}$	Population of individuals susceptible to gonorrhea
$\boldsymbol{S_1}$	Population of susceptible individuals unaware of gonorrhea
$\boldsymbol{S_2}$	Population of susceptible individuals aware of gonorrhea
$\boldsymbol{I}$	Population of Infectious individuals
$\boldsymbol{R}$	Population of recovered individuals

It follows from equation (1) that the rate at which the total population is changing is given by

$$\frac{dN(t)}{dt} = p - \mu N - \alpha I - vR \quad (7)$$

The forces of infection for S and S_1 are given as

$\lambda = \beta_1 I$ and $\lambda_1 = \beta_2 I$

Basic Properties of the Model

Since equations (2) – (6) monitor the human population, it is assumed that all the state variables and parameters are non-negative for all time (t). In other words, the solution of the model equations (2) – (6) with positive initial data will remain positive for all $t \geq 0$.

Existence and Uniqueness of Solution

To establish the conditions for the existence and uniqueness of the solution for the model (2) – (6), let

$$f_1(t,x) = p - (\lambda + \rho + \mu)S, \quad (8)$$
$$f_2(t,x) = (1-\phi)\rho S - (\tau\lambda_1 + \mu)S_1, \quad (9)$$
$$f_3(t,x) = \phi\rho S - \mu S_2, \quad (10)$$
$$f_4(t,x) = \lambda S + \tau\lambda_1 S_1 - (\delta + \alpha + \mu)I, \quad (11)$$
$$f_5(t,x) = \delta I - (v + \mu)R. \quad (12)$$

So that

$$\frac{dx}{dt} = f(t,x) = f(x). \quad (13)$$

Theorem 1. Let D' represent the region

$|t' - t'_0| \leq a,\ \|x' - x'_0\| \leq b,\ x = (x'_1, x'_2, \dots, x'_n) = (x'_{10}, x'_{20,} \dots, x'_{n0})$ (14)

and assume that $f(t',x')$ meets the Lipschitz condition

$$\|f(t',x'_1) - f(t'_1,x'_2)\| \leq k\|x'_1 - x'_2\| \quad (15)$$

For (t',x'_1) and (t'_1,x'_2) inD' and $k > 0$. Then, there is a constant $\delta > 0$ such that there is a unique continuous vector solution $\bar{x}'(t)$ of equations (8) – (12) in $|t' - t'_0| \leq \delta$.

$\frac{\partial f_i}{\partial x'_j}$, $i,j = 1,2,\dots,n$ is continuous and bounded in D' and met the condition in equation (15)

Lemma 1. If $f(t',x')$ is continuous and has partial derivative $\frac{\partial f_i}{\partial x'_j}$ on a bounded closed convex domain $\mathbb{R}$, then it satisfies a Lipschitz condition in $\mathbb{R}$.

The region of interest is given by

$$1 \leq \epsilon \leq \mathbb{R} \tag{16}$$

and bounded solution of the form below is sought for:

$$0 < \mathbb{R} < \infty \tag{17}$$

The following existence theorem will be proved:

Theorem 2: If D' represents the region defined in (15) such that (16) and (17) are true, then ∀ a solution of model (8) – (12) is bounded in the region D'.

Proof. Let

$$f_1(t', x') = p - (\lambda + \rho + \mu)S,$$
$$f_2(t', x') = (1 - \phi)\rho S - (\tau\lambda_1 + \mu)S_1,$$
$$f_3(t', x') = \phi\rho S - \mu S_2,$$
$$f_4(t', x') = \lambda S + \tau\lambda_1 S_1 - (\delta + \alpha + \mu)I,$$
$$f_5(t', x') = \delta I - (v + \mu)R.$$

It is sufficient to prove that the continuity of $\frac{\partial f_i}{\partial x'_j}, i = j = 1, 2, 3, 4, 5$ exist. Differentiating f_i partially with respect to the state variables S, S_1, S_2, I and R, yield:

$$\left|\frac{\partial f_1}{\partial S}\right| = |-(\lambda + \rho + \mu)| < \infty \tag{18}$$
$$\left|\frac{\partial f_1}{\partial S_1}\right| = |0| < \infty \tag{19}$$
$$\left|\frac{\partial f_1}{\partial S_2}\right| = |0| < \infty \tag{20}$$
$$\left|\frac{\partial f_1}{\partial I}\right| = |0| < \infty \tag{21}$$
$$\left|\frac{\partial f_1}{\partial R}\right| = |0| < \infty \tag{22}$$

Also,

$$\left|\frac{\partial f_2}{\partial S}\right| = |(1 - \phi)\rho| < \infty \tag{23}$$
$$\left|\frac{\partial f_2}{\partial S_1}\right| = |-(\tau\lambda_1 + \mu)| < \infty \tag{24}$$
$$\left|\frac{\partial f_2}{\partial S_2}\right| = |0| < \infty \tag{25}$$
$$\left|\frac{\partial f_2}{\partial I}\right| = |0| < \infty \tag{26}$$
$$\left|\frac{\partial f_2}{\partial R}\right| = |0| < \infty \tag{27}$$

Similarly,

$$\left|\frac{\partial f_3}{\partial S}\right| = |\phi\rho| < \infty \tag{28}$$

$$\left|\frac{\partial f_3}{\partial S_1}\right| = |0| < \infty \tag{29}$$
$$\left|\frac{\partial f_3}{\partial S_2}\right| = |-\mu| < \infty \tag{30}$$
$$\left|\frac{\partial f_3}{\partial I}\right| = |0| < \infty \tag{31}$$
$$\left|\frac{\partial f_3}{\partial R}\right| = |0| < \infty \tag{32}$$

Furthermore,

$$\left|\frac{\partial f_4}{\partial S}\right| = |\lambda| < \infty \tag{33}$$
$$\left|\frac{\partial f_4}{\partial S_1}\right| = |\tau\lambda_1| < \infty \tag{34}$$
$$\left|\frac{\partial f_4}{\partial S_2}\right| = |0| < \infty \tag{35}$$
$$\left|\frac{\partial f_4}{\partial I}\right| = |-(\delta + \alpha + \mu)| < \infty \tag{36}$$
$$\left|\frac{\partial f_4}{\partial R}\right| = |0| < \infty \tag{37}$$

Finally,

$$\left|\frac{\partial f_5}{\partial S}\right| = |0| < \infty \tag{38}$$
$$\left|\frac{\partial f_5}{\partial S_1}\right| = |0| < \infty \tag{39}$$
$$\left|\frac{\partial f_5}{\partial S_2}\right| = |0| < \infty \tag{40}$$
$$\left|\frac{\partial f_5}{\partial I}\right| = |\delta| < \infty \tag{41}$$
$$\left|\frac{\partial f_5}{\partial R}\right| = |-(v + \mu)| < \infty \tag{42}$$

It has been shown that the partial derivatives (18) – (42) of the right-hand side of (2) – (6) with respect to S, S_1, S_2, I, R are continuously differentiable and bounded. Hence, by Theorem 2, it is locally Lipschitz, therefore, $S(t), S_1(t), S_2(t), I(t), R(t)$ is a unique solution to system (2) – (6) with the initial condition $S_0, S_{10}, S_{20}, I_0, R_0$ in the region D'.

Invariant Region

Lemma 2. The region $D \subset \mathbb{R}_+^5$ is positively invariant for the equation (2) – (6) with zero or positive initial condition in $\mathbb{R}_+^5$.

Proof. From equation (7), it is shown that,

$$\frac{dN}{dt} = p - \mu N - \alpha I - vR$$

$$\Rightarrow \frac{dN}{dt} \leq p - \mu N$$
$$\Rightarrow N(t) \leq N(0)e^{\mu t} + \frac{p}{\mu}(1 - e^{-\mu t})$$

If $N(0) \leq 0$, then $N(t) \leq \frac{p}{\mu}$. Hence, equations (2) – (6) will be studied in the feasible region $D \subset \mathbb{R}_+^5$, with

$$D = \left\{S,\ S_1,\ S_2,\ I,\ R \in \mathbb{R}_+^5 :\ 0 \leq N \leq \frac{p}{\mu}\right\}.$$

Thus, D is a positively invariant set and a global attractor of the system (2) – (6). That is, any phase trajectory initiated anywhere in the non-negative region $\mathbb{R}_+^5$ of the phase space eventually enters region D and remains in D thereafter.

Positivity and Boundedness of Solutions

Lemma 3. The solution of the system (2) – (6), $\{S,\ S_1,\ S_2,\ I,\ R\}$, with initial condition, $\{S_0,\ S_{10},\ S_{20},\ I_0,\ R_0 \geq 0\} \in D$, will remain greater than zero for all time $t \geq 0$.

Proof. From equation (2),

$$\frac{dS}{dt} = p - \lambda S - \rho S - \mu S$$
$$\geq -\lambda S - \rho S - \mu S$$
$$\int \frac{dS}{S} = -\int (\lambda + \rho + \mu)\, dt$$
$$\Rightarrow S \geq S_0 e^{-\int(\lambda+\rho+\mu)dt} \geq 0$$

Similarly, it can be shown that $S_1(t) \geq 0, S_2 \geq 0, I \geq 0, R \geq 0$ for all time $t > 0$.

Critical Points and Basic Reproduction Number (R_0)

Equations (2) – (6) have two critical points: Disease-free equilibrium (DFE) and endemic equilibrium (EE) points. At equilibrium, the right-hand side of the model (2) – (6) is zero (George, 2019). Hence

$$(S^*,\ S_1^*,\ S_2^*,\ I^*,\ R^*) = \left(\frac{p}{\rho+\mu}, \frac{(1-\emptyset)\rho p}{\mu(\rho+\mu)}, \frac{\emptyset \rho p}{\mu(\rho+\mu)}, 0, 0\right) \qquad (43)$$

The basic reproduction number (R_0) is the average number of secondary infections when a typical infective enters a susceptible population. In this study, R_0 is the average number of new gonorrhea infections generated by a single gonorrhea-infected individual throughout infection of the individual in a completely susceptible population (Diekmann et al., 1990; Anderson & May, 1991; Hethcote, 2000; Driessche & Watmough, 2002). The magnitude of R_0 not only indicates the speed of how a disease will spread, but whether it will spread at all.

Using the next-generation matrix, the basic reproduction number (R_0) can be determined. According to Driessche and Watmough (2002), the basic reproduction number (R_0) is given by the dominant eigenvalue of FV^{-1}, where F and V respectively represent the new infection term and the remaining transfer terms. Hence,

$F = \lambda S + \tau\lambda_1 S_1$ and $V = \delta + \alpha + \mu$. So that, $V^{-1} = \frac{1}{\delta+\alpha+\mu}$.

$$\therefore R_0 = FV^{-1}$$

$$= \frac{\lambda S^* + \tau\lambda_1 S_1^*}{(\delta+\alpha+\mu)} = \frac{\beta_1 p}{(\rho+\mu)(\delta+\alpha+\mu)} + \frac{\tau\beta_2(1-\phi)\rho p}{\mu(\rho+\mu)(\delta+\alpha+\mu)} = \frac{\boldsymbol{p}[\mu\beta_1 + \tau\beta_2(1-\phi)\rho]}{(\rho+\mu)(\delta+\alpha+\mu)} \quad (44)$$

Results and Discussion

The simulated results of the analysis are presented in Tables 1 – 3 below to determine the effect of public enlightenment on the population of susceptible individuals. The results are respectively discussed in this session.

Table 1: Assessing the effect of the rate of susceptible individuals knowing their *neisseria gonorrhea* status (ρ) on the spread of the virus, using numerical method

ρ	R_0	S	S_1	S_2	I	R
0.6000	0.0095	0.0204	0.0574	1.1661	1.1038	2.9624
0.5400	0.0096	0.0217	0.0601	1.1612	1.0763	2.8861
0.4800	0.0097	0.0233	0.0636	1.1554	1.0432	2.7951
0.4200	0.0098	0.0253	0.0683	1.1483	1.0026	2.6848
0.3600	0.0100	0.0279	0.0749	1.1393	0.9517	2.5490
0.3000	0.0102	0.0317	0.0844	1.1273	0.8859	2.3788
0.2400	0.0106	0.0377	0.0985	1.1102	0.7985	2.1615
0.1800	0.0111	0.0493	0.1195	1.0836	0.6784	1.8811
0.1200	0.0122	0.0801	0.1481	1.0370	0.5110	1.5228
0.0600	0.0148	0.1982	0.1619	0.9389	0.2901	1.0979

Table 1 reveals that, a decrease in the rate at which susceptible individuals know their gonorrhea status (ρ), while the other parameter are fixed, results in an increase in the value of the basic reproduction number (R_0), the population of unaware susceptible individuals (S) and aware susceptible individuals (S_1). On the contrary, a decrease in ρ decreases the population of enlightened gonorrhea susceptible individuals who remain faithful to their uninfected sexual partners for life (S_2) as well as infected (I) and recovered (R) individuals. The implication is that, increase in the basic reproduction number and a decline in the population of faithful partners will result in an escalation in the population of individuals who are susceptible to the disease. The more susceptible people there are, the faster the disease will spread.

Table 2: Assessing the effect of incidence rate of unaware *neisseria gonorrhea* susceptible individuals per unit time (β_1) on the spread of the virus, using a numerical method

β_1	R_0	S	S_1	S_2	I	R
0.8000	0.0095	0.0204	0.0574	1.1661	1.1038	2.9624
0.7200	0.0094	0.0335	0.2277	1.1937	0.3929	1.4096
0.6400	0.0093	0.0424	0.4038	1.2090	0.1181	0.7883
0.5600	0.0092	0.0457	0.4964	1.2153	0.0292	0.5681
0.4800	0.0091	0.0465	0.5321	1.2179	0.0065	0.4957
0.4000	0.0090	0.0467	0.5452	1.2190	0.0014	0.4711
0.3200	0.0088	0.0468	0.5506	1.2197	0.0003	0.4618
0.2400	0.0087	0.0468	0.5531	1.2202	5.7972×10^{-5}	0.4577
0.1600	0.0086	0.0468	0.5548	1.2206	1.1819×10^{-5}	0.4555
0.0800	0.0085	0.0468	0.5555	1.2209	2.4050×10^{-5}	0.4543

Table 2 shows that a decrease in the incidence rate of unaware *neisseria gonorrhea* susceptible individuals per unit time (β_1) decreases the basic reproduction number (R_0) and the populations of infected (I) and recovered (R) individuals, while the susceptible populations (S, S_1 and S_2) increase slightly.

Table 3: Assessing the effect of incidence rate of aware *neisseria gonorrhea* susceptible individuals per unit time (β_2) on the spread of the virus, using a numerical method

β_2	R_0	S	S_1	S_2	I	R
0.7000	0.0095	0.0204	0.0574	1.1661	1.1038	2.9624
0.6300	0.0086	0.0218	0.0908	1.1708	0.9895	2.6330
0.5600	0.0078	0.0237	0.1384	1.1759	0.8610	2.3016
0.4900	0.0070	0.0260	0.1998	1.1810	0.7218	1.9800
0.4200	0.0061	0.0287	0.2705	1.1862	0.5795	1.6815
0.3500	0.0053	0.0317	0.3423	1.1911	0.4449	1.4181

0.2800	0.0044	0.0347	0.4072	1.1957	0.3277	1.1968
0.2100	0.0036	0.0375	0.4599	1.1996	0.2331	1.0189
0.1400	0.0028	0.0399	0.4992	1.2030	0.1616	0.8806
0.0700	0.0019	0.0418	0.5264	1.2057	0.1099	0.7756

Table 3 shows that decreasing the incidence rate of aware *neisseria gonorrhea* susceptible individuals per unit time (β_2) will gradually decrease the basic reproduction number (R_0) and, the populations of infected (I) and recovered (R) individuals, while the susceptible populations (S, S_1 and S_2) will increase slightly. The smaller the basic reproduction number, less infected people there are and the faster the disease will die out.

Conclusion

An SIR mathematical model describing the use of gonorrhea public enlightenment as a control in the presence of treatment of gonorrhea infectives was considered to assess the contribution of behavioural change among the enlightened gonorrhea susceptible people. The enlightenment programme resulted in a change in the behaviour of enlightened gonorrhea susceptible individuals thereby splitting the susceptible class into three. The basic properties of the model were considered and the basic reproduction number (R_0) was determined. It was discovered that, a decrease in the rate at which susceptible individuals know their gonorrhea status (ρ), results in an increase in the value of the basic reproduction number (R_0), the population of unaware susceptible individuals (S) and aware susceptible individuals (S_1). On the contrary, a decrease in ρ decrease the populations of enlightened gonorrhea susceptible individuals who remain faithful to their uninfected sexual partners for life (S_2) as well as infected (I) and recovered (R) individuals. Also, a decrease in the incidence rate of unaware *neisseria gonorrhea* susceptible individuals per unit time (β_1) decreases the basic reproduction number (R_0) and the populations of infected (I) and recovered (R) individuals, while the susceptible populations (S, S_1 and S_2) increase slightly. Finally, decreasing the incidence rate of aware *neisseria gonorrhea* susceptible individuals per unit time (β_2) will gradually decrease the basic reproduction number (R_0) and, the populations of infected (I) and recovered (R) individuals, while the susceptible populations (S, S_1 and S_2) will increase slightly. It is therefore recommended that, the relevant agencies should increase the rate of public enlightenment so as to keep the population of susceptible individuals at a barest minimum.

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