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A Deterministic Modeling Approach in Identifying the Optimal Screening for Human Immunodeficiency Virus Management

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Abstract

The enormous success made in the development of drugs for Human Immunodeficiency Virus (HIV) infection to suppress the viral load of the disease, avert death and suffering due to the disease, no HIV individual is supposed to experience morbidity or death due to the disease. However, most affected people only avail themselves for HIV test at symptomatic stage which leads to morbidity and mortality due to Acquired Immune Deficiency Syndrome (AIDS). In the absence of HIV vaccine for the prevention against HIV infection, HIV screening test would be the next close to vaccination. This aim of this study was to developed a model that determine the optimal HIV screening sequence as intervention for HIV in a population. The concept of screening was brought into system of non-linear differential equations to obtain the deterministic model. The screening sequence and the varying population proportions were used in determining the optimal screening. The findings were that; when the systematic HIV screening of the population was done in six years, mortality and morbidity occurrences were reduced, and subsequent systematic screening reduced morbidity and mortality more in the population; and screening thirty percent of the population every year saved the

lives of ninety percent HIV individuals and forestalled ninety percent of them from experiencing morbidity. It was noted also that screening fifty percent of the population three times within six years produced the same effect.

Keywords: HIV/AIDS, Modeling, Deterministic, Systematic Screening, Morbidity and Mortality

INTRODUCTION

Human Immunodeficiency Virus (HIV), a subgroup called lentiviruses in a group of viruses called retroviruses, slowly leads to Acquired Immune Deficiency Syndrome (AIDS) (Sharp and Hahn, (2011); Avert (2020); Arbeitskreis (2016)). There are four main groups of HIV strains, each strain is different a little from others in it make up genetically. HIV-1 of M strain has spread the infection the most in the world while HIV-2 is far lesser in its spread and commonly found in West Africa (Avert (2019); Yebra et al. (2018)). HIV is an infectious disease, and among other modes of transmission, the virus is predominantly transferred through sexual activity (UNICEF (2020); HIV.gov (2019); CDC (2019); Champredon et.al. (2013)). There has not been cure for HIV but there is therapy called antiretroviral therapy (ART) that forestalled the further copies of the retrovirus in an infected individual. As long as this infected individual will stay on ART for life, HIV can be managed such that the infected individual will live a life as normal as an HIV uninfected individual. By the therapy, morbidity and then mortality in a population can be reduced (Ogunmola and Jolayemi (2020)). When adherence to the therapy by an individual is well achieved, the viral load of the infection can be suppressed such that the risk of transmission of the infection is greatly reduced once viral suppression is achieved (Bukenya et.al., 2019).

HIV testing is the way by which an HIV infected individual who is not aware of his/her HIV positive status becomes aware, receive care and treatment, learn how to prevent others from being infected as while prevent himself or herself from contracting another strand of the disease, and eventually bring the infection to undetectable state by remaining on treatment (Obermeyer and Osborn (2007)). It is also a way by which an HIV uninfected individual who is not aware of his/her HIV status becomes aware and then access HIV prevention services (Fonner et. al. (2019)). By it also, an individual who now becomes

aware of his/her HIV status, after receiving prevention services, reduces or eliminate risky behaviours. So, it is very necessary for individuals to be all screened for HIV infection.

Ogunmola and Jolayemi (2020), have used deterministic modeling to experiment effect of HIV testing and treatment when positioned in search of asymptomatic HIV infected individuals in a population. Results showed a great reduction of morbidity and mortality due to HIV/AIDS will be experienced far more than when testing and treatment is focused on symptomatic HIV individuals. Also, results showed that the higher the percentage of HIV asymptomatic individuals sought and placed on treatment, the higher the reduction of morbidity and mortality due to HIV/AIDS that would be experienced in the population. It is upon the results of the work of Ogunmola and Jolayemi (2020) that this research work is built on.

There is the need to experiment and determine the effects of randomly screening in search of varying proportions of HIV asymptomatic individuals in the population and how frequent should the population be screened to determine the optimal in the presence of cost of screening. What will be the impacts on morbidity and mortality due to HIV/AIDS. Indeed, to harness the overall good effects of searching for HIV individuals in the asymptomatic stage of the disease, the entire population or the driving key population will need to be screen for HIV. The central point of this research work is conceptualization of screening a population for HIV (or an infectious disease) using systems of non-linear ordinary differential equations to obtain a deterministic estimate with the aim of identifying an optimal HIV screening point as intervention for HIV/AIDS. By screening the population, HIV individuals are identified and set on treatment immediately.

METHODOLOGY

A population of heterosexual active individuals is considered for the presence of HIV infection and to be screened and place on treatment immediately after detection of the disease. This population of individuals is classified into Susceptible class (No HIV infection but can be acquired) $S(t)$, Unscreened Infective class $I(t)$ at asymptomatic stage of HIV infection, Undiagnosed Pre-AIDS stage $P(t)$ of the infection, AIDS stage $A(t)$, Screened and under treatment HIV Infective at the asymptomatic stage $T_I(t)$, Diagnosed and under treatment Pre-AIDS $T_P(t)$, and Deaths $D(t)$ due to AIDS infection. The population is to

be screened for HIV infection seeking for HIV individuals in the asymptomatic stage of the disease, that is, $I(t)$ class. Therefore, both $S(t)$ class and the $I(t)$ class individuals are to be screened 'k number of times' before the emergence of $P(t)$ class individuals from the $I(t)$ class. At the first population screening for HIV infection, $S(t)$ and $I_1(t)$ are screened for HIV; at the second population screening for HIV infection, $S(t)$ and $I_2(t)$ are screened for HIV; continuously up to the kth population screening for HIV infection, $S(t)$ and $I_k(t)$ are screened for HIV. This means the $I(t)$ class is divided into $I_1(t), I_2(t)$, …, $I_k(t)$ subclasses based on number of times the population is screened for HIV before symptomatic stage of the disease.

The Assumptions of the Model

The underlying assumptions of this model are:

1. The population is assumed to be only sexually active individuals.
2. The number of individuals in each compartment are not random, but a function of constant time.
3. At the first HIV screening of the population, $S(t)$ and $I_1(t)$ are screened for HIV at the rate τ and $I_1(t)$ found are set on treatment immediately, while $1-\tau$ of $I_1(t)$ not found move into $I_2(t)$ class. At the second HIV screening of the population, $S(t)$ and $I_2(t)$ are screened for HIV at the rate τ and $I_2(t)$ found are set on treatment immediately, while $1-\tau$ of $I_2(t)$ not found move into $I_3(t)$ class. At the kth HIV screening of the population, $S(t)$ and $I_k(t)$ are screened for HIV at the rate τ and $I_k(t)$ found are set on treatment immediately, while those of $I_k(t)$ not found move into $P(t)$ (symptomatic) class at the rate natural rate σ_1. An HIV asymptomatic individual who was found in a previous HIV screening scheme of the population must be dropped and replaced with one who has never been found to complete the constant proportion τ that must be screened.
4. The proportion of the population sampled is the same as the proportion of HIV asymptomatic individuals successfully captured for screening.

5. Each time the population is screened, we will assume it to be an intervention preventing morbidity and mortality.
6. Every individual found in the HIV screening scheme are moved into T_I class. An individual in the T_I class may experience fail treatment due to failure in following treatment modalities and move into the A class at the rate γ_1. An individual in the Pre-AIDS stage, $P(t)$ progresses naturally into the full symptomatic stage, AIDS stage, $A(t)$ at the rate σ_2, or detected by diagnosis and move into the treatment class T_P at rate ρ. An individual in the T_P class may experience fail treatment due to failure in following treatment modalities and move into the $A(t)$ class at the rate γ_2. An individual in the AIDS stage $A(t)$ dies due to the AIDS infection at the rate δ.
7. Failing to follow treatment modalities is more of an individual behaviour towards adhering to drugs, we will assume that $\gamma_1 = \gamma_2$.
8. There is no recruitment, no immigration or emigration of any compartment in the model and natural mortality is not considered. Exit out of the heterosexual population is death due to AIDS infection which is also a compartment.
9. Screening the population for HIV infection is assumed to be probability one both in sensitivity and predictive.
10. It is assumed that a susceptible acquires HIV infection in an unprotective sexual encounter a rate λ from either an HIV infective at the asymptomatic stage, or an HIV infective at the Pre-AIDS (symptomatic) stage, or an HIV infective at the asymptomatic stage who is screened and under treatment, or an HIV infective at the Pre-AIDS (symptomatic) stage who is screened and under treatment. No sexual contact with the AIDS individual. The respective sexual transmission rates of the HIV infection to an S individual by an individual in each of the I class, P class, T_I class, T_P class is given as $\beta_I, \beta_P, \beta_{T_I}, \beta_{T_P}$ respectively, where $\beta_I > \beta_P > \beta_{T_I} = \beta_{T_P}$.
11. The force of HIV infection, the means by which a susceptible individual can contract the HIV infection in a sexual encounter λ_i is defined as;

$$\lambda_i = \frac{\beta_I \sum_{j=1}^{k} I_j + \beta_P P + \beta_{T_I} T_I + \beta_{T_P} T_P}{S + \sum_{j=1}^{k} I_j + P + A + T_I + T_P}, \; i = 4, 5, \ldots$$

The Schematic Diagram of the model

The schematic diagram of this model is given below in figure 1.

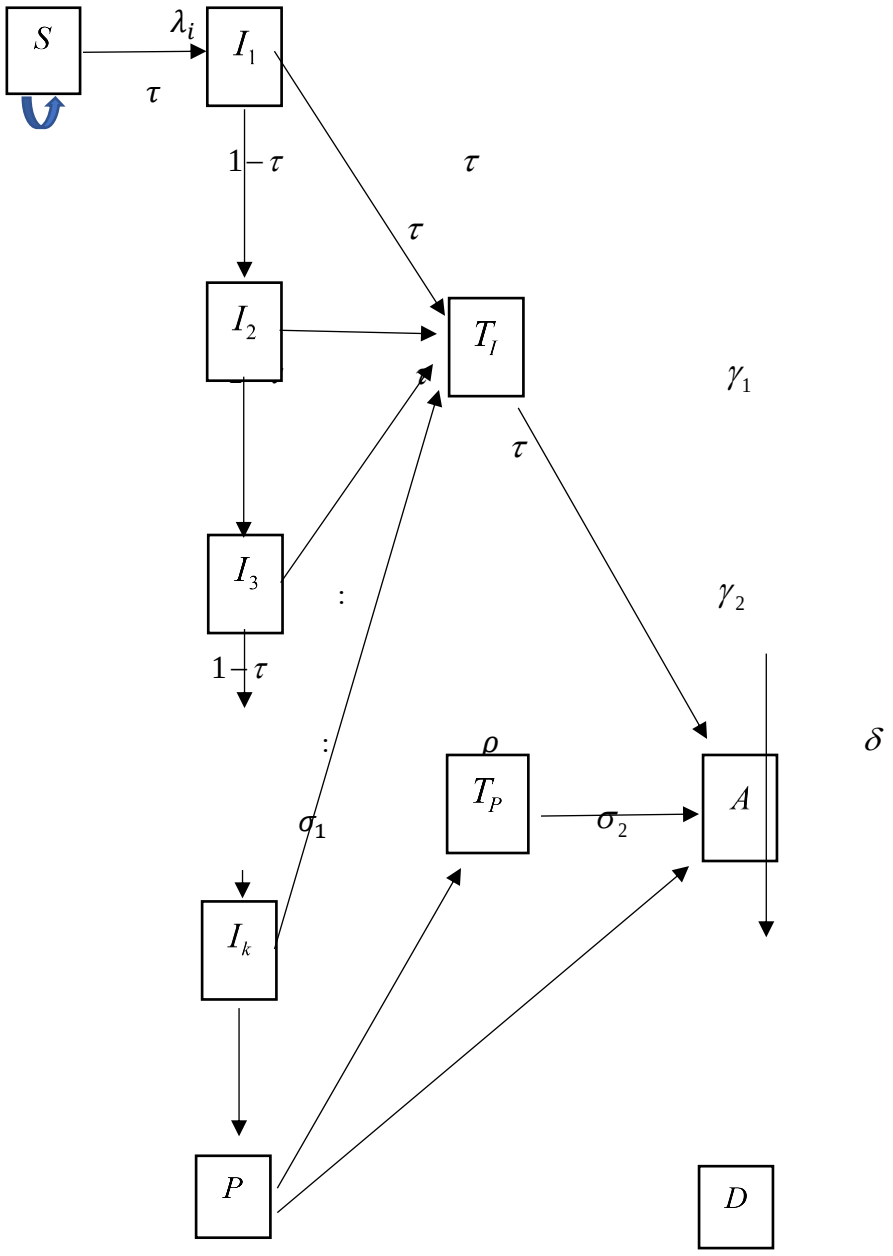

Figure-1: Model Schematic Diagram for Systematic Screening of the Population for HIV Infection

The governing system of non-linear ordinary differential equations of the model are given below in equations (1) – (10):

The system of differential equations is given as follows;

$$\frac{dS}{dt} = -\lambda_i S, \quad (1)$$

$$\frac{dI_1}{dt} = \lambda_i S - I_1, \quad (2)$$

$$\frac{dI_2}{dt} = (1-\tau)I_1 - I_2, \quad (3)$$

$$\frac{dI_3}{dt} = (1-\tau)I_2 - I_3, \quad (4)$$

$$\frac{dI_k}{dt} = (1-\tau)I_{k-1} - \sigma_1 I_k, \quad (5)$$

$$\frac{dP}{dt} = \sigma_1 I_k - \sigma_2 P - \rho P, \quad (6)$$

$$\frac{dT_I}{dt} = \tau\sum_{j=1}^{k} I_j - \gamma_1 T_I, \quad (7)$$

$$\frac{dT_P}{dt} = \rho P - \gamma_2 T_P, \quad (8)$$

$$\frac{dA}{dt} = \sigma_2 P + \gamma_1 T_I + \gamma_2 T_P - \delta A, \quad (9)$$

$$\frac{dD}{dt} = \delta A, \quad (10)$$

where, $\lambda_i = \frac{\beta_I \sum_{j=1}^{k} I_j + \beta_P P + \beta_{T_I} T_I + \beta_{T_P} T_P}{S + \sum_{j=1}^{k} I_j + P + A + T_I + T_P}$, $i = 4, 5, \ldots$

Since it is considered that the median time for full symptomatic stage (AIDS) to set in is usually between 10-15 years (Joint United Nations Programme on HIV/AIDS (UNAIDS) (2015), and Osmond 1998); taking 11 years and then assuming that after 6 years of acquiring HIV infection pre-symptomatic stage (Pre-AIDS) sets in, then maximum of k = 6 years.

When k=1, screening the population once in six years before symptomatic stage sets in, we will consider this as Intervention-2. Then equations (1) to (10) becomes:

$$\frac{dS}{dt} = -\lambda_4 S, \quad (11)$$

$$\frac{dI}{dt} = \lambda_4 S - \tau I - \sigma_1 I, \quad (12)$$

$$\frac{dP}{dt} = \sigma_1 I - \sigma_2 P - \rho P, \quad (13)$$

$$\frac{dT_I}{dt} = \tau I - \gamma_1 T_I, \quad (14)$$

$$\frac{dT_P}{dt} = \rho P + \gamma_1 T_I - \gamma_2 T_P, \quad (15)$$

$$\frac{dA}{dt} = \sigma_2 P + \gamma_2 T_P - \delta A, \quad (16)$$

$$\frac{dD}{dt} = \delta A, \quad (17)$$

where, $\lambda_4 = \frac{\beta_I I + \beta_P P + \beta_{T_I} T_I + \beta_{T_P} T_P}{S + I + P + A + T_I + T_P}$.

When k=2, screening the population the second time, that is, twice in six years before symptomatic stage sets in, we consider as Intervention-3. Equations (1) to (10) becomes:

$$\frac{dS}{dt} = -\lambda_5 S, \quad (18)$$

$$\frac{dI_1}{dt} = \lambda_5 S - I_1, \quad (19)$$

$$\frac{dI_2}{dt} = (1-\tau) I_1 - \sigma_1 I_2 - \tau I_2, \quad (20)$$

$$\frac{dP}{dt} = \sigma_1 I_2 - \sigma_2 P - \rho P, \quad (21)$$

$$\frac{dT_I}{dt} = \tau \sum_{j=1}^{2} I_j - \gamma_1 T_I, \quad (22)$$

$$\frac{dT_P}{dt} = \rho P - \gamma_2 T_P, \quad (23)$$

$$\frac{dA}{dt} = \sigma_2 P - \delta A, \quad (24)$$

$$\frac{dD}{dt} = \gamma_1 T_I + \gamma_2 T_P + \delta A, \quad (25)$$

where, $\lambda_5 = \frac{\beta_I \sum_{j=1}^{2} I_j + \beta_P P + \beta_{T_I} T_I + \beta_{T_P} T_P}{S + \sum_{j=1}^{2} I_j + P + A + T_I + T_P}$.

When k=3, screening the population the third time, that is, HIV screening three times in six years before symptomatic stage sets in, we will also consider as Intervention-4. Equations (1) to (10) becomes:

$$\frac{dS}{dt} = -\lambda_6 S, \tag{26}$$

$$\frac{dI_1}{dt} = \lambda_6 S - I_1, \tag{27}$$

$$\frac{dI_2}{dt} = (1-\tau) I_1 - I_2, \tag{28}$$

$$\frac{dI_3}{dt} = (1-\tau) I_2 - \tau I_3 - \sigma_1 I_3, \tag{29}$$

$$\frac{dP}{dt} = \sigma_1 I_3 - \sigma_2 P - \rho P, \tag{30}$$

$$\frac{dT_I}{dt} = \tau \sum_{j=1}^{3} I_j - \gamma_1 T_I, \tag{31}$$

$$\frac{dT_P}{dt} = \rho P - \gamma_2 T_P, \tag{32}$$

$$\frac{dA}{dt} = \sigma_2 P - \delta A, \tag{33}$$

$$\frac{dD}{dt} = \gamma_1 T_I + \gamma_2 T_P + \delta A, \tag{34}$$

where, $\lambda_6 = \frac{\beta_I \sum_{j=1}^{3} I_j + \beta_P P + \beta_{T_I} T_I + \beta_{T_P} T_P}{S + \sum_{j=1}^{3} I_j + P + A + T_I + T_P}$.

When k=6, screening the population six times (yearly) before symptomatic stage sets in, we consider as Intervention-5. Equations (1) to (10) becomes:

$$\frac{dS}{dt} = -\lambda_9 S \tag{35}$$

$$\frac{dI_1}{dt} = \lambda_9 S - I_1 \tag{36}$$

$$\frac{dI_2}{dt} = (1-\tau) I_1 - I_2, \tag{37}$$

$$\frac{dI_3}{dt} = (1-\tau)I_2 - I_3, \tag{38}$$

$$\frac{dI_4}{dt} = (1-\tau)I_3 - I_4, \tag{39}$$

$$\frac{dI_5}{dt} = (1-\tau)I_4 - I_5, \tag{40}$$

$$\frac{dI_6}{dt} = (1-\tau)I_5 - \tau I_6 - \sigma_1 I_6, \tag{41}$$

$$\frac{dP}{dt} = \sigma_1 I_6 - \sigma_2 P - \rho P, \tag{42}$$

$$\frac{dT_I}{dt} = \tau \sum_{j=1}^{6} I_j - \gamma_1 T_I, \tag{43}$$

$$\frac{dT_P}{dt} = \rho P - \gamma_2 T_P, \tag{44}$$

$$\frac{dA}{dt} = \sigma_2 P - \delta A, \tag{45}$$

$$\frac{dD}{dt} = \gamma_1 T_I + \gamma_2 T_P + \delta A, \tag{46}$$

where, $\lambda_9 = \frac{\beta_I \sum_{j=1}^{6} I_j + \beta_P P + \beta_{T_I} T_I + \beta_{T_P} T_P}{S + \sum_{j=1}^{6} I_j + P + A + T_I + T_P}$.

The number of individuals in all compartments in the population at any time t must be a zero or a positive value. All of the above ordinary differential equations can be solved by numerically simulation using the fourth order Runge Kutta method.

Parameter Estimates

The values of the parameters in the models were obtained from studies of some authors. Table 1 below contains the parameters, their descriptions and values with references.

Table-1: Description of Parameters and their Estimates

Parameters	Description	Values	Reference
β_I	Sexual transmission rate of HIV asymptomatic individual	0.86	Safiel et.al., 2012, Marsudi et.al.,2017
β_P	Sexual transmission rate of Pre-AIDS individual	0.15	Marsudi et.al.,2017
β_{T_I}	Sexual transmission rate of diagnosed and on treatment HIV asymptomatic individual	Assumed equal and value is 0.1	Safiel et.al., 2012
β_{T_P}	Sexual transmission rate of diagnosed and on treatment Pre-AIDS individual		
σ_1	Rate of progression from HIV asymptomatic to Pre-AIDS stage	0.198	Yusuf et.al., 2011, Marsudi et.al.,2017
σ_2	Rate of progression from Pre-AIDS to full AIDS stage	0.4621	Yusuf et.al., 2011, Marsudi et.al., 2017
ρ	Proportion of Pre-AIDS individuals that are screened for HIV and receiving treatment	Experimented at 0.1, 0.3, and 0.5	
τ	Proportion of HIV asymptomatic individuals that are screened for HIV and receiving treatment	Experimented at 0.1, 0.3, and 0.5	
γ_1	Proportion of diagnosed and receiving treatment HIV asymptomatic individuals who failed treatment modalities	Assumed to be equal to γ_2.	
γ_2	Proportion of diagnosed and receiving treatment Pre-AIDS individuals who failed treatment modalities	0.0001	Safiel et.al., 2012, Marsudi et.al.,2017
δ	Mortality rate due to AIDS infection	0.0909	Yusuf et.al., 2011, Huo et.al., 2015, Marsudi et.al.,2017.

Initial Values of Variables

The initial values of all the variables in all the models at time $t = 0$ are given in table 2 below.

Table-2: Description and Initial value of Variables

Variable	Description	Initial Value
S	Susceptible individuals	10,000
I	HIV asymptomatic individuals	2
P	Pre-AIDS individuals	0
A	AIDS individuals	0
T_P	Pre-AIDS individuals who are screened for HIV and are receiving treatment	0
T_I	HIV asymptomatic individuals who are screened for HIV and are receiving treatment	0
D	Mortality due to AIDS	0

RESULTS AND DISCUSSION

Numerical Solution to the Sets of System of Non-linear Ordinary Differential Equations for the Four Interventions (Interventions-2, 3, 4 and 5)

The number of times the population is screened for HIV infection is considered as $k = 1,2,\ldots,6$, whereby, when the population is screened once in 6 years, it is termed Intervention-2. When it is screened twice in 6 years, it is termed as Intervention-3 while when it is screened three times in 6 years, it is termed as Intervention-4. And when the population is screened six times in 6 years, that is every year, it is termed as Intervention-5. The numerical solutions for the sets of the system of non-linear ordinary differential equations given in equations (11) to (46) are expressed in graphical forms. They showed the trends of cumulative numbers of morbidity and mortality for the four interventions: Intervention-2, Intervention-3, Intervention-4 and Intervention-5.

From the previous work of Ogunmola and Jolayemi (2020), the benefits of having HIV screening in the population in search of HIV asymptomatic individuals are many. These includes more lives of HIV individuals are gained rather than lost to mortality due to AIDS. Also includes, the population dying out due to HIV infection is become unlikely as long as the diagnosed HIV individuals remain on treatment and life expectancy is gained more. Also includes more HIV individuals escaped experiencing the suffering of AIDS morbidity. With these benefits with respect to morbidity and mortality due to AIDS, having HIV screening to search for HIV asymptomatic individuals is better than harvesting HIV symptomatic individuals as they come to the health centers for treatment which is the

current situation. So, if an HIV asymptomatic individual is screened for HIV infection and immediately placed in care and treatment, then the individual is not likely to experience morbidity and mortality due to AIDS as long as he/she remains on treatment. On the population level, if the population of HIV individuals can all be screened and kept in care and treatment, the likelihood of the population suffering morbidity and mortality due to AIDS is very unlikely as long as the individuals all remain on treatment. So, there is a great need to bring every one HIV individual to care and treatment before they start emerging into the symptomatic stage of the infection. HIV screening is the way and the HIV individuals must be sought for and be screened before their emergence into the Pre-AIDS stage. But 100 percent screening of the population at once may never be feasible because of the large size of the population to be screen for HIV infection. The enormous time required, the resources required and the overall cost of screening makes 100 percent screening not possible. Then, having a systematic screening of the population in search of HIV asymptomatic individuals in place becomes the objective with the aim to preventing morbidity and mortality in the population. So, instead of the unfeasible 100 percent screening of the population, varied lower percentages of the population will be screened for HIV. When the population is screened once in six years, it is called Intervention-2. When it is screened twice in six years, it is called Intervention-3. When it is screened three times in six years it is called Intervention-4. Lastly, when the population is screened for HIV every in six years, it is called Intervention-5. The results of the interventions, systematic screening of the population, are discussed first for 30 percent screening of the population and then for 50 percent.

Results on Mortality for the Four Interventions when 30 percent of the Population is Screened for HIV Infection

The numerical solutions to the non-linear ordinary differential equations given in equations (11) to (46) for when 30 percent of the population is screened for HIV are expressed in graphical forms showing the trends of mortality for each of the four interventions. Figure 2 below shows the trends of mortality due to AIDS for when there is no HIV screening, the four interventions and for 100 percent HIV screening in the population.

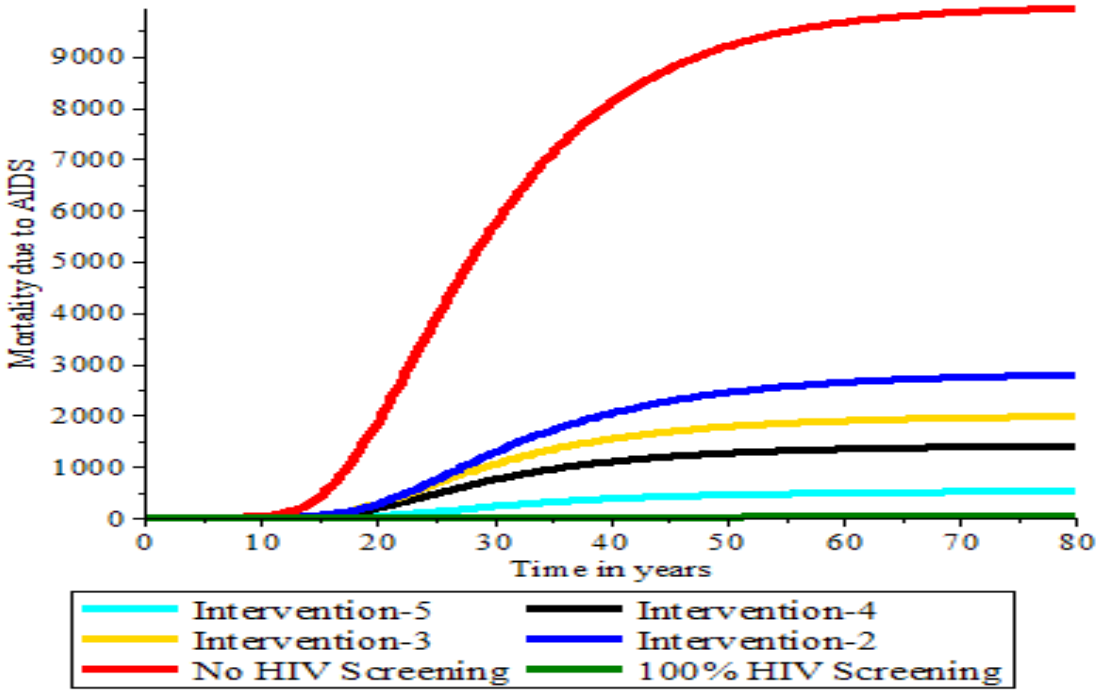

Figure 2: Mortality Trends for the Four Interventions when 30% of the Population is Screened, 100% Screening and No HIV Screening

From the mortality trends, at 10 years of the infection in the population, 0.05 percent, 0.03 percent, 0.02 percent and 0.002 percent mortalities have occurred for Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively. At 20 years of the infection, 2.59 percent, 2.64 percent, 1.78 percent and 0.37 percent mortalities have occurred, for Intervention-2, Intervention-3, Intervention-4 and Intervention-5 in the population, respectively. At 30 years of the infection, 12.65 percent, 10.39 percent, 7.36 percent and 2.15 percent mortalities have occurred, for Intervention-2, Intervention-3, Intervention-4 and Intervention-5 in the population, respectively. At 40 years of HIV in the population, 20.32 percent, 15.30 percent, 10.86 percent and 3.64 percent mortalities are experienced for Intervention-2, Intervention-3, Intervention-4 and Intervention-5 in the population, respectively. At 60 years of the infection, 26.33 percent, 18.83 percent, 13.33 percent and 4.75 percent mortalities have occurred for Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively. At 80 years of the infection, 27.77 percent, 19.67 percent, 13.93 percent and 5.12 percent mortalities have occurred for Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively. At 100 years of the infection in the population, 28.18 percent, 19.67 percent, 14.19 percent and 5.34 percent

mortality have occurred for Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively.

Generally, Intervention-2 performed well by lowering mortality due to AIDS and subsequent interventions performed better. The more the number of times the population is screened for HIV, the lower the mortality experienced in the population.

Taking 73 years to be global life expectancy (WHO (2021a); Roser et. al. (2021)), then at 73 years of HIV infection in the population, table 3 shows the cumulative percentage of mortalities due to AIDS for the four interventions at the 30 percent screening, 100% HIV screening and when there is no HIV screening in the population. And table 4 shows the number of times a subsequent intervention is performed better than previous intervention.

Table-3: Cumulative Percentages of Mortality at 72 Years of HIV Infection when 30% of the Population is Screened

	Interventions				**100% HIV Screening**	**No HIV Screening**
	II	**III**	**IV**	**V**		
% Mortality	27.471	19.488	13.797	5.019	0.266	98.783
Gained of Life	71.312	79.295	84.986	93.764	98.517	
% Gained of Life	72.19	80.27	86.03	94.92	99.73	

From table 4, the performance of the four interventions can be seen. Intervention-5 reduced mortality 5.47 times that of Intervention-2. Intervention-5 also reduced mortality 3.88 times and 2.75 times more than Intervention-3 and Intervention-4, respectively. Intervention-4 reduced mortality 1.99 times and 1.41 times more than Intervention-2 and Intervention-3, respectively. Intervention-3 reduced mortality 1.41 times more than Intervention-2.

Table-4: Number of Times Subsequent Intervention Performed Better than Previous Intervention when 30% of the Population is Screened

Interventions					
V > II	**V > III**	**V > IV**	**IV > II**	**IV > III**	**III > II**
5.47	3.88	2.75	1.99	1.41	1.41

Generally, the effect of Intervention-5 outweighed the effect of other interventions, the least difference is about 2.75 times more the performance of the closest intervention to it. So, if 30 percent of the population is screened for HIV every year, mortality due to AIDS will be reduced as much as 2.75 times the size that would be reduced when the population is screened three times withing six years. It is important to note that all the interventions performed well at 30 percent screening of the population and all HIV asymptomatic individuals screened are placed on treatment. The more frequent 30 percent of the population was screened for HIV asymptomatic individuals, the less mortality due to AIDS was experienced and the more lives of HIV individuals were saved.

Comparing the mortality curves of the four interventions with those of when there is no HIV screening in the population and when there is 100 percent HIV screening, figure 2 still shows the results. Mortality curve for no HIV screening serves as the upper bound, the worst scenario of mortality experienced while 100 percent HIV screening is the lower bound, the best scenario of mortality experienced that can ever be obtained. The mortality curves for the four interventions are found in between these upper and lower bounds and closer to the lower bound more than the higher bound.

From table 3 above, 100% HIV screening of the population and 30 percent HIV screening of the population every year (Intervention-5) screened 99.73 percent and 94.92 percent of HIV asymptomatic individuals in the population. Other interventions screened between 72 percent and 86 percent of HIV asymptomatic individuals. The HIV asymptomatic individuals are screened and placed on treatment. According to the World Health Organisation target on HIV screening and treatment; "90: 90: 90", meaning 90 percent of screened HIV individuals, 90 percent of them on treatment and 90 percent attained viral suppression to end the epidemic (Avert (2021); UNAIDS, 2020). Going by the WHO 90:90:90, 100% HIV screening of the population and every year 30 percent screening of the population will meet the target. So, screening 30 percent of the population every year will result into screening and saving the lives of at least 90 percent HIV asymptomatic individuals. These HIV asymptomatic individuals that are saved by this intervention would have been lost if there was no HIV screening in the population

Results on Morbidity for the Four Interventions when 30 Percent of the Population is Screened for HIV Infection

The numerical solutions to the non-linear ordinary differential equations given in equations (11) to (46) for when 30 percent of the population is screened for HIV are expressed in graphical forms showing the trends of morbidity for the four interventions. Figure 3 below shows the trends of morbidity due to AIDS for when there is no HIV screening, the four interventions and for 100 percent HIV screening in the population.

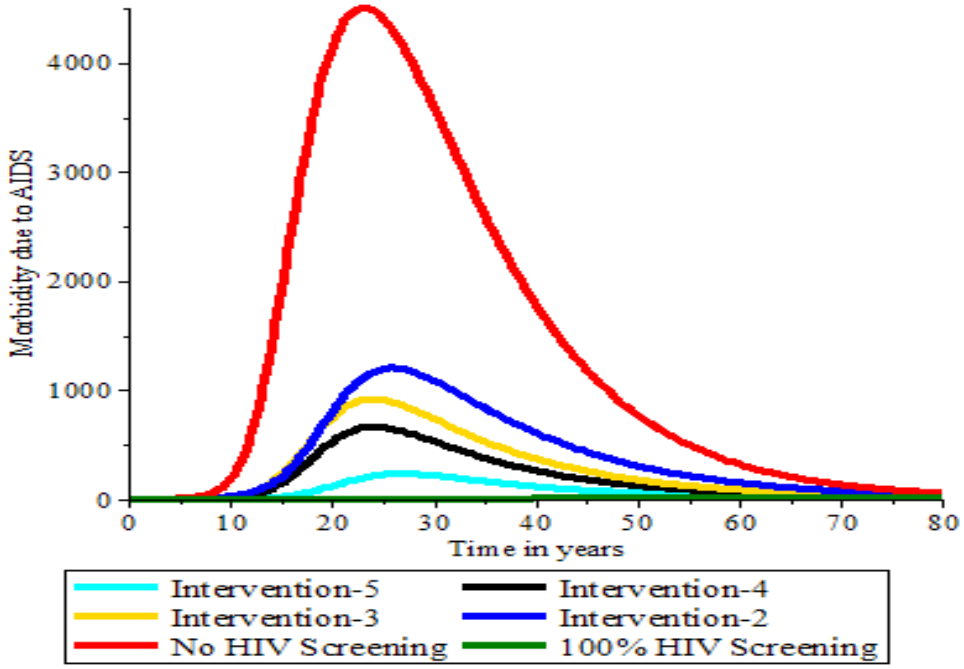

Figure 3: Morbidity Trends for the Four Imterventions when 30% of the Population is Screening, 100% Screening and No HIV Screening

At 10 years of HIV infection in the population, 0.24 percent, 0.20 percent, 0.11 percent and 0.01 percent of morbidities have occurred in the population for Intervention-2, Intervention-3 Intervention-4 and Intervention-5, respectively. At 20 years of the infection, 7.98 percent, 7.48 percent, 5.27 percent and 1.19 percent of morbidities are experienced for Intervetion-2, Intervention-3, Intervention-4 and Intervention-5, respectively. Each of the intervention's morbidity curve peaked at 21.82 percent, 8.55 percent, 6.45 percent and 2.68 percent, respectively, at 26 years, 24 years, 24 years, and 27 years of the infection, respectively, for Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively. At 40 years of the infection, 6.10 percent, 3.72 percent, 2.62 percent and 1.14

percent of morbidities are experienced for Intervetion-2, Intervention-3, Intervention-4 and Intervention-5, respectively. At 60 years of HIV infection, 1.49 percent, 0.85 percent, 0.60 percent and 0.30 percent of morbidities are experienced for Intervetion-2, Intervention-3, Intervention-4 and Intervention-5, respectively. At 80 years, 0.37 percent, 0.24 percent, 0.19 percent and 0.14 percent of morbidities have occurred for when Intervetion-2, Intervention-3, Intervention-4 and Intervention-5, respectively, were in place in the population.

Morbidity due to AIDS is lowered for all the curves. Intervention-5 reduced morbidity the most and have the lowest peak, followed by Intervention-4, and then Intervention-3. Each of the morbidity curves decreases after their peak slowly and the slowest decrease is seen in Intervention-5 curve, followed by Intervention-4 curve, then Intervention-3.

Comparing the AIDS morbidity curves of the four interventions with those of when there is no HIV screening in the population and when there is 100 percent HIV screening is shown in figure 3, Morbidity curve for no HIV screening serves as the upper bound, the worst scenario of morbidity while the morbidity curve for 100 percent is the lower bound, the best scenario of morbidity in the population. The morbidity curves for the four interventions are found in between the upper and lower bounds. The AIDS morbidity curves for each of the interventions are closer to the lower bound and far away from the upper bound. The more frequent the HIV screening, the closer the outcome of AIDS morbidity to the best scenario, 100 percent HIV screening in search of HIV asymptomatic individuals.

Table 5 below shows the morbidity peaks in percentage for the interventions, 100% HIV screening and no HIV screening in the population. The table also shows the amount of morbidity and percentage of forestalled morbidity by each of the interventions. Intervention-2 forestalls 51.52%, Intervention-3 forestalls 81 percent, Intervention-4 forestalls 85.67 percent and Intervention-5 forestalls 94.04 percent of the morbidity that would have occurred if there is no HIV screening. Again, going by the WHO target of 90:90:90, Intervention-5 can meet this target since it forestalls above 90 percent of morbidity due to AIDS. Screening 30 percent of the population every year would results into forestalling morbidity of at least 90 percent of HIV asymptomatic individuals.

Table 5: Morbidity Peaks from the Four Interventions when 30% of the Population is Screened, 100% HIV Screening and No HIV Screening

	Interventions				100% HIV Screening	No HIV Screening
	II	**III**	**IV**	**V**		
Peak (%)	21.82	8.55	6.45	2.68	No Peak	45.011
Forestalled Morbidity	23.191	36.461	38.561	42.331		
Forestalled Morbidity (%)	51.52	81.00	85.67	94.04		

Results on Mortality for the Four Interventions when 50 Percent of the Population is Screened for HIV Infection

When 50 percent of the population is screened for HIV infection, the numerical solutions to the non-linear ordinary differential equations given in equations (11) to (46) are expressed in graphical forms showing the AIDS mortality trends for the four interventions.

Figure 4 below shows the trends of the AIDS mortality under the impact of the four interventions in the population, 100% HIV screening and no HIV screening. For the four interventions, at 10 years of HIV infection in the population, 0.02 percent, 0.01 percent, 0.004 percent and 0.0002 percent mortalities are experienced under the impact of Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively. At 20 years of the infection, about 0.63 percent, 0.59 percent, 0.28 percent and 0.02 percent mortalities have occurred under the impact of Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively, in the population. At 30 years of HIV infection in the population, 5.19 percent, 3.79 percent, 1.95 percent and 0.22 percent mortalities are experienced for Intervention-2, Intervention-3, Intervention-4 and Intervention-5 in the population, respectively. At 40 years of the infection, 11.40 percent, 6.80 percent, 3.51 percent and 0.49 percent mortalities are experienced for Intervention-2, Intervention-3, Intervention-4 and Intervention-5 in the population, respectively. At 60 years of the infection, 17.85 percent, 9.42 percent, 4.88 percent and 0.85 percent mortalities have occurred under Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively, in the population. At 80 years, 19.68 percent, 10.17 percent, 5.33 percent and 1.08 percent mortalities have occurred under Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively, in the population. At 100 years of HIV infection in the population, 20.20 percent, 10.46 percent, 5.57 percent and 1.29 percent mortalities have

occurred under Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively, in the population.

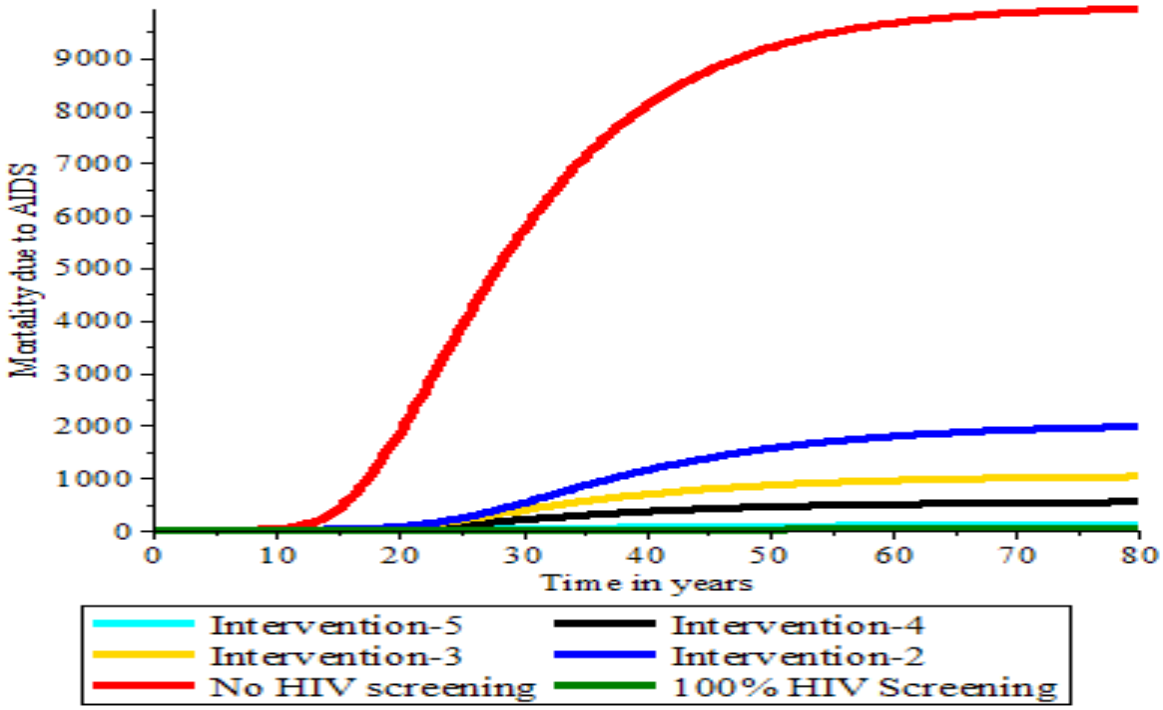

Figure 4: Mortality trends for the Four Interventions when 50% of the Population is Screened, 100% HIV Screening and No HIV Screening

Again at 73 years of HIV infection in the population, table 6 shows the cumulative percentage of mortalities due to AIDS for the four interventions when 50 percent HIV asymptomatic individuals are screened, 100% HIV asymptomatic individuals are screened and when there is no HIV screening in the population. Table 7 also, shows the number of times a subsequent intervention is performed better than previous intervention.

Table 6: Cumulative Percentages of Mortality at 73 Years of HIV Infection when 50% of the Population is Screened

	Interventions				**100% HIV Screening**	**No HIV Screening**
	II	**III**	**IV**	**V**		
% Mortality	19.290	9.999	5.215	1.004	0.266	98.783
Gained of Life	79.493	88.784	93.568	97.779	98.517	
% Gained of Life	80.47	89.88	94.72	98.98	99.73	

Table 7 below, shows the performance of the four interventions. Intervention-5 reduced mortality due to AIDS 19.21 times, 9.96 times and 5.19 times than those of Intervention-2, Intervention-3 and Intervention-4, respectively. While Intervention-4 reduced mortality 3.70 times and 1.92 times than those of Intervention-2 and Intervention-3, respectively. Intervention-3 reduced mortality 1.93 times that of Intervention-2.

Table 7: Number of Times Subsequent Intervention Performed Better than Previous Intervention when 50% of the Population is Screened

Interventions					
V > II	**V > III**	**V > IV**	**IV > II**	**IV > III**	**III > II**
19.21	9.96	5.19	3.70	1.92	1.93

Generally, at 50 percent screening of HIV asymptomatic individuals, the effect of Intervention-5 far outweighed the effect of other interventions. If 50 percent of the population is screened for HIV infection every year, mortality due to AIDS will be reduced 5.19 times the size that would be reduced when the population is screened three times withing six years. Also, screening three times within six years (Intervention-4) will reduce 1.94 times the size of mortality that would be reduced if screening is twice within six years (Intervention-3). It is important to note that all the interventions performed better than at 30 percent screening of the population. All HIV asymptomatic individuals screened are placed on treatment.

Comparing the mortality curves of the four interventions with when there is no HIV screening in the population and when there is 100 percent HIV screening, figure 4 shows the results. Mortality curve for no HIV screening is the upper bound and 100 percent HIV screening is the lower bound. The four interventions mortality curves are closer to the lower bound than when 30 percent of HIV asymptomatic individuals are screened.

From table 6, apart from 100% HIV screening, Intervention-5 and Intervention-4 will saved the lives of 98.98 percent and 94.72 percent, respectively, of HIV asymptomatic individuals in the population that would have died if there was no HIV screening in the population. While Intervention-3 and Intervention-2 would save the lives of 89.88 percent and 80.41 percent of HIV asymptomatic individuals, respectively. According to the WHO 90:90:90 target, aside 100% HIV screening of the population, 50% screening of the

population every year and three times within six years will meet the target of saving the lives of at least 90% of HIV asymptomatic individuals.

Results on Morbidity for the Four Interventions when 50 percent of the population is screened for HIV infection

The numerical solutions to the non-linear ordinary differential equations given in equations (11) to (46) when 50 percent of the population is screened for HIV are expressed in graphical forms showing the trends of morbidity for the four interventions. Figure 5 below shows the trends of morbidity due to AIDS for when there is no HIV screening, the four interventions and for 100 percent HIV screening in the population.

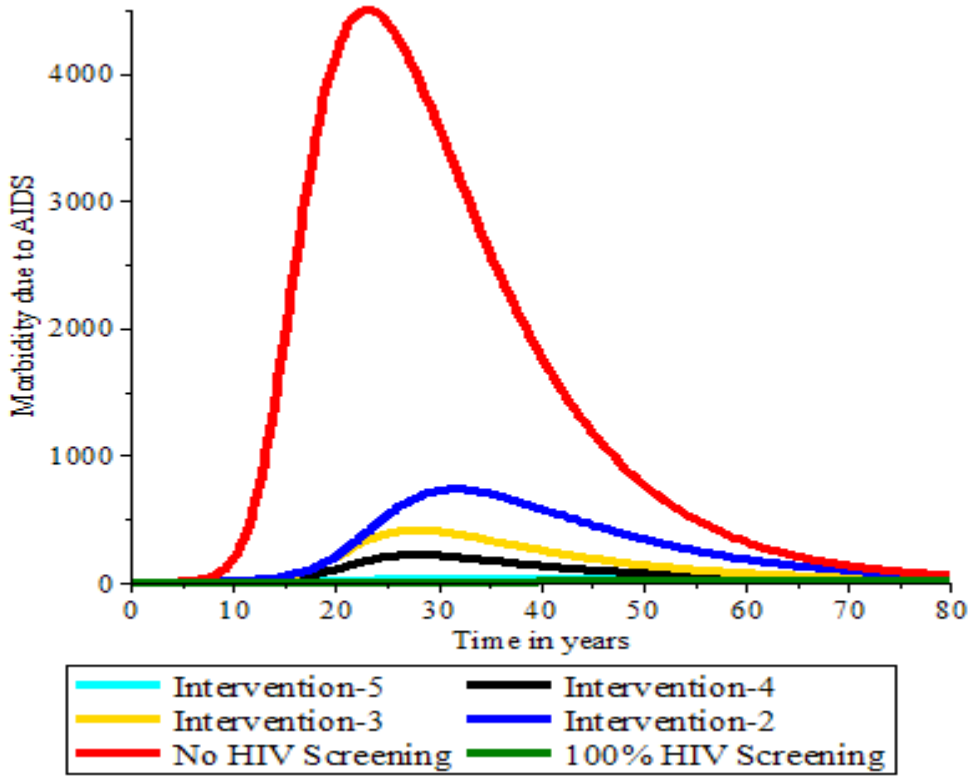

Figure 5: Morbidity Trends for the Four Interventions when 50% of the Population is Screemed, 100% Screening and No HIV Screening

At 10 years of HIV infection in the population, 0.089 percent, 0.056 percent, 0.028 percent and 0.0012 percent of morbidities have occurred in the population for Intervention-2, Intervention-3 Intervention-4 and Intervention-5, respectively. At 20 years, 2.062 percent, 1.982 percent, 1.008 percent and 0.075 percent of morbidities are experienced for

Intervetion-2, Intervention-3, Intervention-4 and Intervention-5, respectively. Peak of the morbidity curves were experienced at 7.308 percent, 4.115 percent, 2.154 percent and 0.324 percent, respectively, at 32 years, 28 years, 28 years, and 32 years of the infection, respectively, for Intervention-2, Intervention-3, Intervention-4 and Intervention-5, respectively. At 40 years of the infection, 11.395 percent, 2.534 percent, 1.303 percent and 0.264 percent of morbidities are experienced for Intervetion-2, Intervention-3, Intervention-4 and Intervention-5, respectively, in the population. At 60 years of HIV infection, 17.853 percent, 0.706 percent, 0.389 percent and 0.147 percent of morbidities are experienced for Intervetion-2, Intervention-3, Intervention-4 and Intervention-5, respectively. At 80 years, 0.484 percent, 0.226 percent, 0.162 percent and 0.116 percent of morbidities have occurred for Intervetion-2, Intervention-3, Intervention-4 and Intervention-5, respectively, in place the population.

Morbidity due to AIDS is lowered for all the curves more than when 30 percent of the population is screened for HIV infection. Intervention-2 reduced morbidity and subsequent interventions reduced morbidity more.

Comparing the AIDS morbidity curves of the four interventions with those of when there is no HIV screening and when there is 100 percent HIV screening in the population is shown in figure 5. Morbidity curve for no HIV screening serves as the upper bound while 100 percent is the lower bound and the morbidity curves for the four interventions are found in between the upper and lower bounds. The AIDS morbidity curves for each of the interventions are closer to the lower bound more than when 30 percent of the population are screened for HIV infection. The more the frequent of HIV screenings, the closer the AIDS morbidity to the lower bound.

Table 8 below shows the morbidity peaks in percentage for the interventions, 100% HIV screening and no HIV screening in the population. The table also shows the amount of morbidity and percentage of forestalled morbidity by each of the interventions. Intervention-2 forestalls 83.76%, Intervention-3 forestalls 90.86, Intervention-4 forestalls 95.21% and Intervention-5 forestalls 99.28% of the morbidity that would have occurred if there is no HIV screening. Again, going by the WHO target of 90:90:90, Intervention-5, Intervention-4 and Intervention-3 will meet this target since they forestalled at least 90 percent of morbidity due to AIDS. So, screening 50 percent of the population for HIV

infection at least twice in six years will forestall HIV asymptomatic individuals from becoming morbid. All HIV asymptomatic individuals screened are placed on treatment.

Table 8: Morbidity Peaks from the Four Interventions when 50% of the population is Screened, 100% Screening and No HIV Screening

	Interventions				**100% HIV Screening**	**No HIV Screening**
	II	**III**	**IV**	**V**		
Peak (%)	7.308	4.115	2.154	0.324	No Peak	45.011
Forestalled Morbidity	37.703	40.896	42.857	44.687		
Forestalled Morbidity (%)	83.76	90.86	95.21	99.28		

CONCLUSION

This study was motivated by the fact that there was no systematic HIV screening in Nigeria and in Africa to forestall morbidity and mortality due to AIDS. Most persons with HIV infection would never go to a health centre for HIV screening except when they are sick and are asked to go through an HIV test. The conclusions made in this study are as follows:

1. The flow of HIV symptomatic individuals into the health centres for treatment reduced mortality due to AIDS but the individuals are already experiencing morbidity.
2. Treating identified HIV asymptomatic individuals would reduce both morbidity and mortality more than for the HIV symptomatic individuals. The higher the proportion of identified and treated HIV individuals the lesser the morbidity and mortality.
3. Introducing HIV systematic screening into the population in search of HIV asymptomatic individuals impacted more on morbidity and mortality due to AIDS. The higher the proportion of the population screened and the more frequent it is screened the more morbidity and mortality were reduced in the HIV population.
4. Thirty percent screening of the population every year, fifty percent screening of the population every three times within six years or fifty percent screening of the population every year saved 90% HIV individuals from morbidity and mortality.
5. Thirty percent screening of the population every year is the optimal HIV screening.

The following are recommendations from the study:

1. Screening a population for asymptomatic HIV individuals is essential.
2. Thirty percent of the population should be screened for HIV every year to forestall morbidity and save the lives of about ninety percent HIV persons in the population.

The model is applicable to other infectious disease with asymptomatic stage where there is no vaccination.

Data Availability Statement

This research is a product of the simulation of mathematical deterministic models, with specified parameters drawn from the literature as described in Table 1 of this manuscript. The values of the parameters used in the models and where they are drawn from in the literature are displayed in the table below. The hypothetical data produced are then plotted in graphs for interpretation.

Parameters	**Description**	**Values**	**Reference**
β_I	Sexual transmission rate of HIV asymptomatic individual	0.86	Safiel et.al., 2012, Marsudi et.al.,2017
β_P	Sexual transmission rate of Pre-AIDS individual	0.15	Marsudi et.al.,2017
β_{T_I}	Sexual transmission rate of diagnosed and on treatment HIV asymptomatic individual	Assumed equal and value is 0.1	Safiel et.al., 2012
β_{T_P}	Sexual transmission rate of diagnosed and on treatment Pre-AIDS individual		
σ_1	Rate of progression from HIV asymptomatic to Pre-AIDS stage	0.198	Yusuf et.al., 2011, Marsudi et.al.,2017
σ_2	Rate of progression from Pre-AIDS to full AIDS stage	0.4621	Yusuf et.al., 2011, Marsudi et.al., 2017
γ_2	Proportion of diagnosed and receiving treatment Pre-AIDS individuals who failed treatment modalities	0.0001	Safiel et.al., 2012, Marsudi et.al.,2017
δ	Mortality rate due to AIDS infection	0.0909	Yusuf et.al., 2011, Huo et.al., 2015, Marsudi et.al.,2017.

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