



Modeling the impact of campaign program on the prevalence of anemia in children under five

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Abstract

Anemia, a global health problem, is increasing worldwide and affecting both developed and developing countries. Being a blood disorder, anemia may occur in any stages of life but it is quite common in children under the age of five. Globally, iron deficiency is the supreme contributor towards the onset of anemia. In this paper, a general model based on the dynamics of anemia among children under five is formulated. The population is divided in three classes such as susceptible, affected and treated. A time-dependent control measure namely campaign program is considered. The model has an equilibrium point and the stability of the point is analyzed. Moreover, sensitivity of the equilibrium point is also performed to discover the critical parameters. Numerical simulations are carried out to observe the dynamic behavior of the model. Results show that campaign program is effective in minimizing the disease progression. The number of child patients and yearly deaths significantly decrease with accelerated campaign program that is implemented earlier whereas termination of the applied measure may upturn the burden. Findings also reveal that application of control measure helps to reduce the prevalence of anemia but may not eliminate the disease.

Keywords: Anemia, Iron deficiency anemia, Campaign program.
2010 MSC: 34A12, 34A30, 93A30.

1. Introduction

Prevalence of anemia (anaemia) in children under the age of five (6 to 59 months) is high and frequently multi-factorial particularly in the developing countries [1]. Anemia in children means that a child is living with inadequate red blood cells or hemoglobin (Hb) level below the threshold for which there is deficiency in providing sufficient oxygen to the tissues. The threshold of Hb level for children under five to be non-anemic is generally 11.0 gram per deciliter (g/dL) [2]. The factors that work behind anemia are lack of hematinics (iron, folic acid, copper, vitamin A, vitamin B-12 and vitamin C). The production of red blood cells may also be disrupted by inflammation or due to serious infections. A child may suffer from anemia for any of these factors but iron deficiency anemia (associated with malnutrition in children) is mostly common among children under five [3] as

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it is liable for 25%-50% of all global cases [4]. Moreover, case fatality in children under five due to iron deficiency anemia varies from 2%-29.3% which suggests to adopt primary prevention policies [5].

Considering the risk factors of anemia in children, prevention strategies with integrated approaches are important to combat the disease [6]. Treatment of anemia requires iron supplementation accompanied by vitamin A [7], vitamin C [8] or even blood transfusion [9] for severe cases. Iron deficiency anemia can be prevented by exclusive breastfeeding, early iron supplementation, adequate nutritional status with iron rich foods [10]. Such dietary diversification, feeding practice and knowledge about nutrition can help to improve Hb concentration in children. Besides breastfeeding, addition of infant formula or milk powder decreases the risk of anemia [11]. Increase of Hb by 1 g/dL could avoid nearly 1.8 million deaths among children under five each year [12]. Thus, communication campaign regarding health education is necessary which can effectively decrease the risk of iron deficiency anemia [13].

Mathematical models can help understanding the disease dynamics better [14]. Several models exist which described the critical factors about infectious diseases with preventive measures [15, 16, 17, 18, 19, 20, 21, 22]. However, modeling blood disorder disease like anemia may seem to be a bit different (as anemia is not infectious type) compared to that of infectious diseases but the insights from mathematical point of view is same. For example, a model on a special type of genetic blood disorder anemia known as thalassemia reveals that prevention measures contribute in reducing the prevalence for short term but cannot eradicate thalassemia in long term [23].

The present paper deals with a Kermack-McKendrick type [24] mathematical model on the dynamics of anemia. The main aim is to reveal the impact of campaign program in minimizing the risk of the disease prevalence. Since campaign program can spread knowledge to the parents regarding the risk factors of anemia, healthy nutrition, feeding practice and iron supplementation, it is important to incorporate campaign program as a control measure in the designed anemia model. With this point of view, the rest of the paper is structured as follows: in Section 2, the model formulation is presented. In Section 3, a precise description based on the numerical findings is given. Section 4 signifies the important summary of the present study with limitations.

2. Materials and methods

2.1. Model

The total children under the age of five is considered as the total population $N(t)$ which is divided into three compartments or classes: susceptible $S(t)$, affected $A(t)$ and treated $T(t)$. Susceptible children become affected by anemia in course of time. Affected children thus require treatment and move to the treated class. Therefore, the dynamics of anemia (Figure 1) can be modeled as follows:

$$\begin{cases} \dot{S} = b - (ef(t) + \mu)S \\ \dot{A} = ef(t)S - (\tau + \delta_1 + \mu)A \\ \dot{T} = \tau A - (\delta_2 + \mu)T \end{cases} \quad (2.1)$$

where b is the birth rate and μ is the natural mortality rate of children under five. The

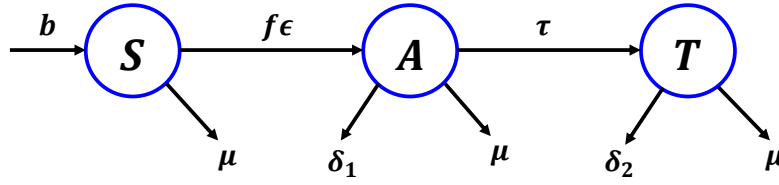


Figure 1: Model of anemia in children under the age of five.

Table 1: Variables corresponding to anemia model (2.1).

Variable	Description
S	Susceptible children
A	Affected children
T	Treated children
N	Total children under the age of five

parameters ϵ and τ denote anemic rate and treatment rate, respectively. It is assumed that deaths of children due to anemia can occur in A and T compartments with rates δ_1 and δ_2 , respectively. Thus, yearly deaths of children under five due to anemia can easily be calculated from $\delta_1 A + \delta_2 T$. It is important to note that the parameter f is denoting the fraction of susceptible children who are likely to be affected by anemia. Thus, susceptible class will increase if the fraction f decreases. It is assumed that the change of the parameter f largely depends on time which is influenced by the campaign program rate $m(t)$. Therefore, the time-dependent parameter f is defined as follows:

$$f(t) = 1 - m(t)$$

Hence, $f(t)$ will be a decreasing function of time provided that the campaign program rate is increased. However, the nature of the time-dependent parameter $m(t)$ can be switched at any time to reflect the acceleration or termination of campaign program. Let $m_0 = m(t)$ be the baseline campaign program rate. For model (2.1), the description of associated state variables and parameters are summarised in Table 1 and Table 2, respectively.

Model (2.1) is a linear nonhomogeneous system which can be written in a compact form as follows:

$$\dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{F} \quad (2.2)$$

Table 2: Parameters corresponding to anemia model (2.1).

Parameter	Description
b	Birth rate of children
μ	Natural mortality rate of children
f	Fraction of susceptible children who are likely to become affected
$m(t)$	Time-dependent campaign program rate
ϵ	Anemic rate or rate at which susceptible children become affected
τ	Treatment rate
δ_1	Death rate in A class due to anemia
δ_2	Death rate in T class due to anemia

The matrices in (2.2) are

$$\mathbf{X} = \begin{pmatrix} S(t) \\ A(t) \\ T(t) \end{pmatrix}, \quad \mathbf{A} = \begin{pmatrix} -k_1 & 0 & 0 \\ \epsilon f & -k_2 & 0 \\ 0 & \tau & -k_3 \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} b \\ 0 \\ 0 \end{pmatrix}$$

where $k_1 = \epsilon f + \mu$, $k_2 = \tau + \delta_1 + \mu$ and $k_3 = \delta_2 + \mu$.

2.2. Analysis

2.2.1. Well-posedness

For biological purpose, positivity and boundedness of the solutions of model (2.1) is needed to investigate [15, 16]. To check the positivity of $S(t)$, the first equation of model (2.1) is

$$\dot{S} = b - k_1 S$$

It follows that

$$S(t) = \frac{b}{k_1} + \left[S(0) - \frac{b}{k_1} \right] e^{-k_1 t}$$

It is clear that as long as $S(0) \geq 0$, $S(t)$ is non-negative. Similarly, $A(t)$ and $T(t)$ can be shown non-negative provided $A(0) \geq 0$ and $T(0) \geq 0$, respectively. Thus, for $S(0) \geq 0$, $A(0) \geq 0$ and $T(0) \geq 0$, model (2.1) has a unique non-negative solution $\forall t > 0$.

Now, for the boundedness of the solutions, all the equations of model (2.1) are added as follows:

$$\dot{S} + \dot{A} + \dot{T} = b - (\epsilon f + \mu)S + \epsilon f S - (\tau + \delta_1 + \mu)A + \tau A - (\delta_2 + \mu)T.$$

Hence

$$\dot{N} \leq b - \mu N$$

which implies

$$\limsup_{t \rightarrow \infty} N \leq \frac{b}{\mu}.$$

Thus, $\frac{b}{\mu}$ is a threshold for $N(t)$ which means that $N(t)$ is bounded $\forall t > 0$. This suggests a biological feasible region for our model (2.1) as follows:

$$\Omega = \left\{ (S, A, T) : S, A, T \geq 0, N \leq \frac{b}{\mu} \right\}.$$

Therefore, it is obvious that the unique solution of model (2.1) exists globally.

2.2.2. Equilibrium

For model (2.1), let $\zeta(\bar{S}, \bar{A}, \bar{T})$ be the equilibrium point. Determination of ζ requires to set \dot{S}, \dot{A} and \dot{T} to zero [25] as follows:

$$\begin{cases} b - k_1 \bar{S} = 0 \\ \epsilon f \bar{S} - k_2 \bar{A} = 0 \\ \tau \bar{A} - k_3 \bar{T} = 0 \end{cases} \quad (2.3)$$

Solution of (2.3) is given by

$$\zeta(\bar{S}, \bar{A}, \bar{T}) \equiv \zeta \left(\frac{b}{k_1}, \frac{bf\epsilon}{k_1 k_2}, \frac{bf\epsilon\tau}{k_1 k_2 k_3} \right)$$

Table 3: Parameter values applied for simulating the model (2.1).

Parameter	Value	Unit	Source
b	0.039	per year	Estimated
μ	0.039	per year	[26, 27]
m(t)	0.20	per year	Assumed
ϵ	0.427	per year	[2, 28, 29]
τ	0.20	per year	Assumed
δ_1	0.03	per year	[5]
δ_2	0.02	per year	[5]

2.2.3. Stability

Following [25], the Jacobian matrix J at $\zeta(\bar{S}, \bar{A}, \bar{T})$ is given as follows:

$$J(\zeta) = \begin{pmatrix} -k_1 & 0 & 0 \\ \epsilon f & -k_2 & 0 \\ 0 & \tau & -k_3 \end{pmatrix} \tag{2.4}$$

The characteristic equation of (2.4) is

$$\det \begin{pmatrix} -k_1 - \lambda & 0 & 0 \\ \epsilon f & -k_2 - \lambda & 0 \\ 0 & \tau & -k_3 - \lambda \end{pmatrix} = 0 \tag{2.5}$$

The solutions of (2.5) (known as eigen values) are $\lambda = -k_1, -k_2, -k_3$. Since the eigen values of (2.4) are real, distinct and most importantly negative, therefore $\zeta(\bar{S}, \bar{A}, \bar{T})$ is asymptotically stable.

2.3. Initial values of the variables and parameters

The state variables of model (2.1) are normalized by the total population $N(t)$. Thus, $N = S + A + T = 1$. The initial values of the state variables are set as: $S(0) = 1, A(0) = 0$ and $T(0) = 0$. Global mortality rate of children under the age of five varies from 3.8% to 3.9% [26, 27]. Therefore, μ is set to be 0.039. Following [17], b is calculated as 0.039. Data reveal that 42%-43% of children under five are anemic [2, 28, 29]. Hence, ϵ is calculated as 0.427 which is the average of the prevalence percentage from the year 2000 to 2019 [28]. Percentage of deaths for children under five due to anemia shows a variation from 2%-29.3% [5]. Based on this information, δ_1 and δ_2 are fixed as 0.03 and 0.02, respectively. The values of the rest two parameters m(t) and τ are assumed. The associated values of the parameters for model (2.1) are listed in Table 3.

2.4. Sensitivity analysis of equilibrium point

We target for determining the sensitivity of each parameter involved in the equilibrium point $\zeta(\bar{S}, \bar{A}, \bar{T})$ of model (2.1). Through sensitivity indices, the change of any variable can be measured [30]. Such indices reveal the importance of parameters for a disease progression. The sensitivity indices of \bar{S}, \bar{A} and \bar{T} are listed in Table 4 using the following definition:

Definition 2.1. Let u be any state variable that is differentiable in terms of a parameter p, then the normalized forward sensitivity index of u is defined as follows:

$$\gamma_p^u := \frac{\partial u}{\partial p} \frac{p}{u}$$

Table 4: Sensitivity of equilibrium point.

Parameter	Sensitivity index of \bar{S}	Sensitivity index of \bar{A}	Sensitivity index of \bar{T}
b	+1.00	+1.00	+1.00
μ	-0.10	-0.25	-0.91
$m(t)$	+0.22	-0.03	-0.03
ϵ	-0.90	+0.10	+0.10
τ		-0.74	+0.26
δ_1		-0.11	-0.11
δ_2			-0.34

The details of the sensitivity of $\zeta(\bar{S}, \bar{A}, \bar{T})$ will be explored in Section 3.

2.5. Interventions

For model (2.1), 10 years of observation period is considered. Let t_i ; $i = 0, 1, 2, \dots, 10$ be the time points (in years) of the whole observation period where t_0 is the initial time and t_{10} is the ending time. In order to reflect the impact of time-dependent campaign program rate, the profile of $m(t)$ is altered at different time. For model (2.1), let t_2 and t_4 be the crucial timings when actions on campaign program are initiated (accelerated or terminated).

For baseline case, the initial value of the campaign program rate m_0 is maintained throughout the whole observation period. That means, $m(t)$ is considered as follows:

$$m(t) = m_0 \quad ; \quad t_0 \leq t \leq t_{10}.$$

Depending on the severity of the disease, campaign program can be accelerated earlier. To understand the effectiveness of early acceleration of campaign program, the time-dependent parameter $m(t)$ is initiated as:

$$m(t) = \begin{cases} m_0 & ; \quad t_0 \leq t \leq t_2 \\ 4m_0 & ; \quad t_2 < t \leq t_{10} \end{cases} \quad \text{and} \quad m(t) = \begin{cases} m_0 & ; \quad t_0 \leq t \leq t_4 \\ 4m_0 & ; \quad t_4 < t \leq t_{10}. \end{cases}$$

Campaign program can be terminated at anytime during the disease period. Keeping the withdrawn fact of campaign program in mind, the nature of $m(t)$ is as follows:

$$m(t) = \begin{cases} m_0 & ; \quad t_0 \leq t \leq t_2 \\ 4m_0 & ; \quad t_2 < t \leq t_4 \\ 0 & ; \quad t_4 < t \leq t_{10}. \end{cases}$$

3. Results and Discussion

3.1. Outcomes of sensitivity analysis

From Table 4 and Figure 2, it is understood that other than birth and all mortality type rates (i.e., b, μ, δ_1 and δ_2), campaign program rate $m(t)$, anemic rate ϵ and treatment rate τ are the most crucial parameters to the equilibrium point $\zeta(\bar{S}, \bar{A}, \bar{T})$ which indicates that an increase (decrease) of such parameters will cause to alter the value of the equilibrium point. If campaign program rate is increased, \bar{S} will increase by 22% whereas both \bar{A} and \bar{T} will decrease by 3%. Similarly, an increase of the anemic rate ϵ will cause to decrease \bar{S} by 90% and increase \bar{A} and \bar{T} by 10%. Moreover, an increase of the treatment rate τ will reduce \bar{A} by 74% and upturn \bar{T} by 26%.

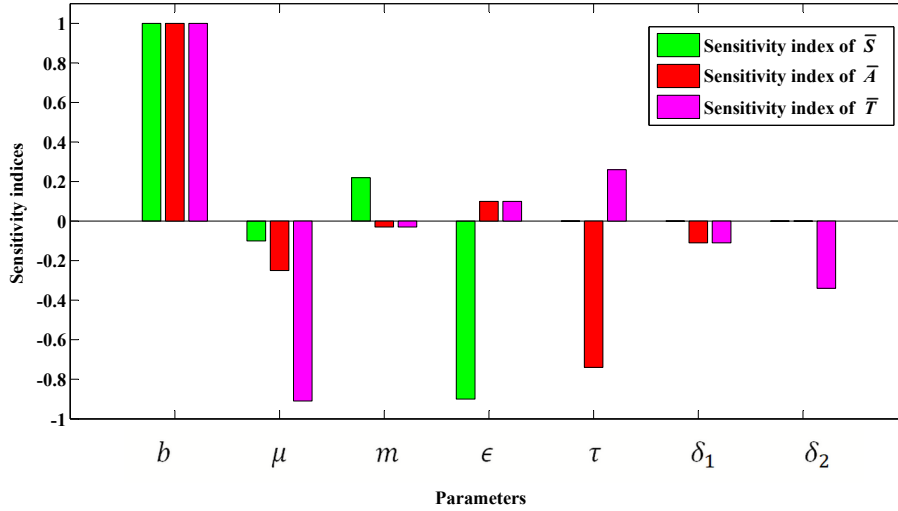


Figure 2: Sensitivity of equilibrium point $z(\bar{S}, \bar{A}, \bar{T})$. The bars in green, red and magenta correspond to \bar{S} , \bar{A} and \bar{T} , respectively.

3.2. Baseline case

Model baseline case (Figure 3) shows that with 20% effectiveness of campaign program, the peak of the affected class occurs in 3 years. Nearly 42% of children are found to be affected during the peak time. Within 10 years, 12% of children are left as susceptible, 24% are as affected and 49% of children need medical treatment. Moreover, average percentage of death due to the disease ranges in between 0.015%-0.02%. From Figure 4, it is understood that the disease would remain endemic as the solution set of the model (2.1) converges to the equilibrium point.

3.3. Impact of anemic rate

Figure 5 represents that with the increase of anemic rate by two times than baseline, susceptible class is decreased by 56% whereas affected and treated classes are increased by 14% and 36%, respectively. Average increase of death is observed to be nearly 22%. On the other hand, if anemic rate becomes one half compared to the baseline, then susceptible class will increase at least by 93%. As a result, disease induced death will decrease by 28% along with 23% reduction from affected class and 35% from treated class.

3.4. Impact of campaign program with constant rates

It is observed from Figure 6 that compared to baseline case, susceptible class is increased by 35% (on average) whereas affected and treated classes are decreased by 8% and 15%, respectively due to 40% effectiveness of campaign program. Moreover, the average reduction of death due to anemia is seen to be 11%. Campaign program with 80% effectiveness results in 50% and 61% decrease in affected and treated classes, respectively compared to the baseline scenario. As a result, disease induced death can be reduced by 55% and susceptible class is increased by twofold.

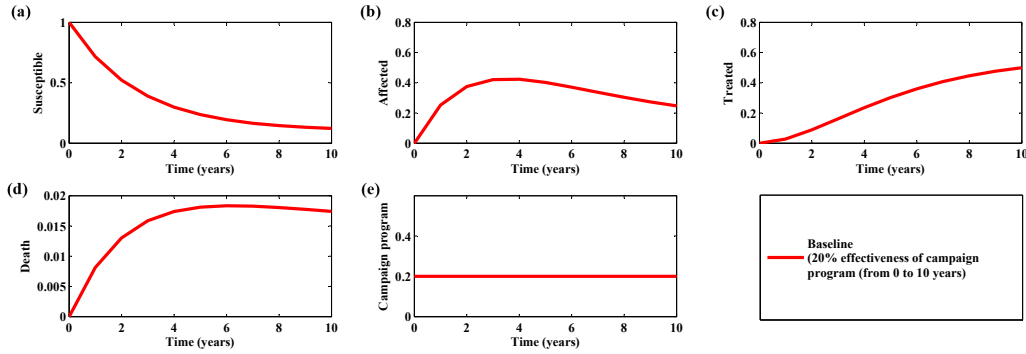


Figure 3: Baseline case of model (2.1) shows the dynamics of (a) susceptible, (b) affected, (c) treated, (d) death and (e) campaign program for a period of 10 years. The simulation is carried out using the baseline values of the parameters listed in Table 3.

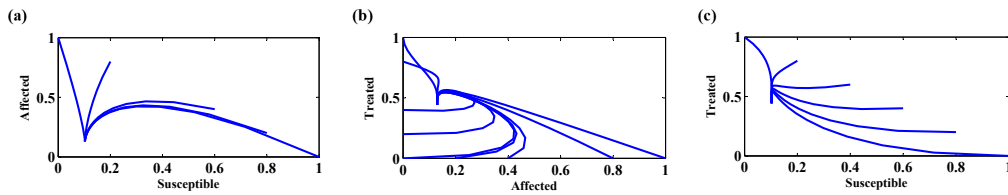


Figure 4: Phase portrait of model (2.1) near the equilibrium point $\zeta(\bar{S}, \bar{A}, \bar{T}) \equiv \zeta(0.1024, 0.1301, 0.4411)$ represents (a) susceptible vs affected, (b) affected vs treated and (c) susceptible vs treated. The simulations are carried out with different starting of the state variables S, A and T followed by the baseline values of the parameters listed in Table 3.

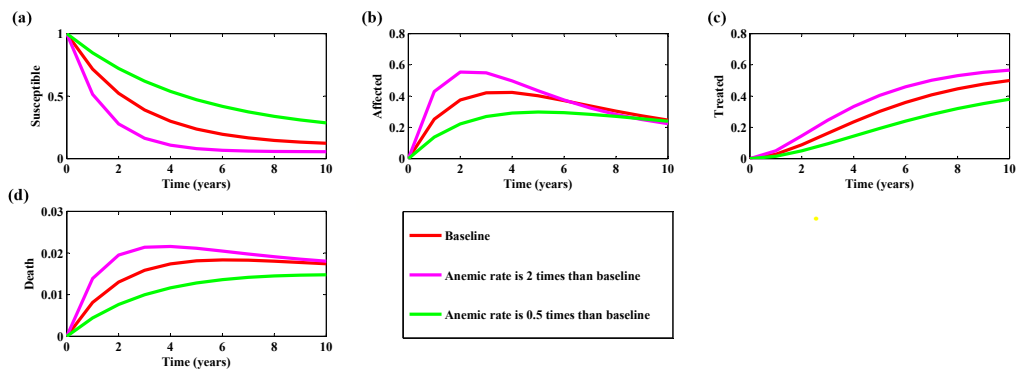


Figure 5: Case due to the change in anemic rate. Simulations of model (2.1) show the dynamics of (a) susceptible, (b) affected, (c) treated and (d) death for a period of 10 years with $\epsilon = 0.427$ (in red color), $\epsilon = 0.854$ (in magenta color) and $\epsilon = 0.2135$ (in green color). Other than anemic rate, the simulations are carried out using the baseline values of the rest parameters listed in Table 3.

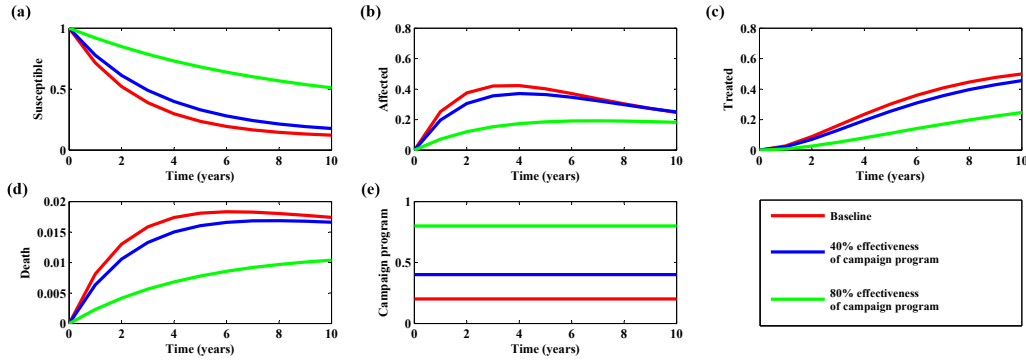


Figure 6: Case for campaign program with constant rates. Simulations of model (2.1) show the dynamics of (a) susceptible, (b) affected, (c) treated, (d) death and (e) campaign program for a period of 10 years due to 20% (in red color), 40% (in blue color) and 80% (in green color) effectiveness of campaign program rate. Other than campaign program rate, the simulations are carried out using the baseline values of the rest parameters listed in Table 3.

3.5. Impact of early acceleration of campaign program

Figure 7 reveals that if campaign program rate is upturned with an effectiveness of 80% after 4 years, then susceptible class will increase nearly by 55% compared to the baseline case. Therefore, affected, treated and death curves will decrease by 17%, 6% and 12%, respectively. If campaign program is implemented just 2 years earlier with the same level of effectiveness, susceptible class will be doubled than the baseline case. Owing to this strategy, on average 30% decline in affected class and 20% in treated class are observed. Moreover, 26% of death could be avoided for such scenario.

3.6. Impact of termination of campaign program

Figure 8 reveals that campaign program is conducted with 80% effectiveness from 2 to 4 years and terminated just after 4 years. Due to this, average decrease in susceptible class is about 8% in last two years of the observation period whereas affected class will increase by 12% within 6 to 10 years and death will rise by 3% soon after 6 years. At the end of the observation period, treated class is comparably same as the base case.

4. Conclusions

A general model on anemia in children under five has been proposed in terms of ordinary differential equations with a view to examining the impact of campaign program. The model is discussed through analytical reasoning along with numerical simulations. It is observed that susceptible population will increase if campaign program rate is accelerated. As a result, the number of children who are anemic and under treatment reduces significantly. Better outcome can be achieved through early implementation of campaign program with a moderate level of effectiveness. The model shows a positive impact of the control measure in reducing the yearly deaths of children under five. Moreover, prevalence of the disease can be controlled with low anemic rate. The model also reveals that anemia will remain endemic but with proper strategies, the burden can be minimized.

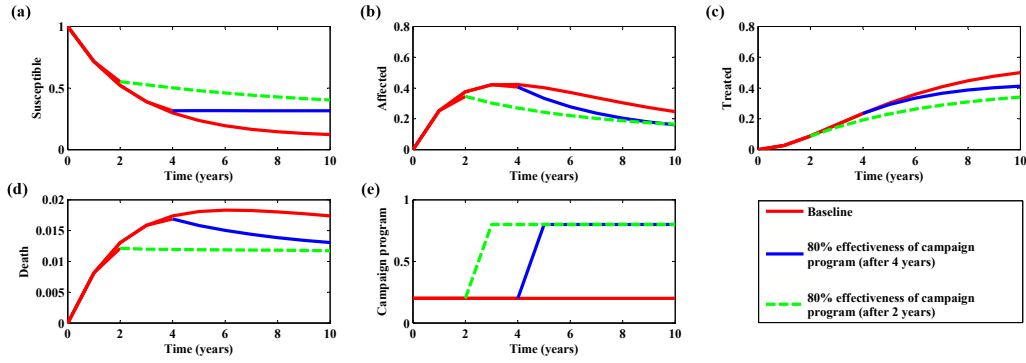


Figure 7: Case for early acceleration of campaign program. Simulations of model (2.1) show the dynamics of (a) susceptible, (b) affected, (c) treated, (d) death and (e) campaign program for a period of 10 years due to 20% effectiveness of campaign program throughout the observation period (in red color), 80% effectiveness of campaign program after 4 years (in blue color) and 80% effectiveness of campaign program after 2 years (in green color). Other than campaign program rate, the simulations are carried out using the baseline values of the rest parameters listed in Table 3.

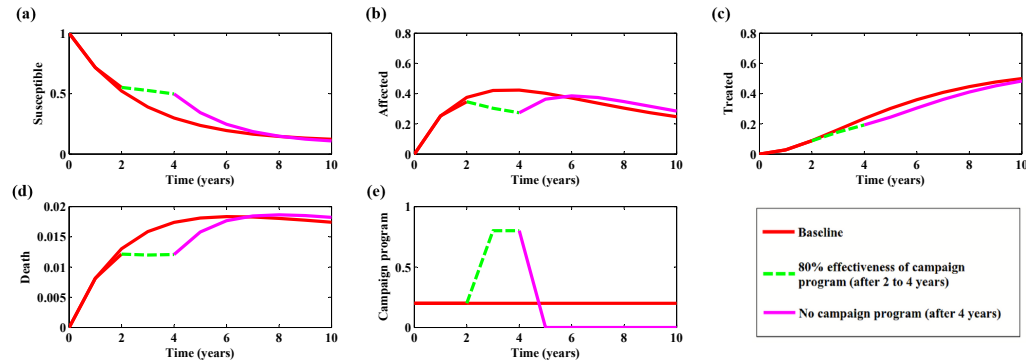


Figure 8: Case for termination of campaign program. Simulations of model (2.1) show the dynamics of (a) susceptible, (b) affected, (c) treated, (d) death and (e) campaign program for a period of 10 years due to 20% effectiveness of campaign program throughout the observation period (in red color), 80% effectiveness of campaign program after 2 to 4 years (in green color) and no campaign program after 4 years. Other than campaign program rate, the simulations are carried out using the baseline values of the rest parameters listed in Table 3.

The present model can be applied to predict the future scenario of the disease by fitting the anemia prevalence data of any region or country which is one of the future goals of this study. It can also be applied to reexamine the case prevalence of a certain region or country. Although the model is explored with its possible insights, it has limitations. For example, the simulation results might not reflect the real world situation as the values of the model parameters are taken from several sources and by assumptions. In reality, there may be uncertainty in the parameters for which results may slightly vary. The model needs to be modified with several other factors which act behind anemia. The function that is considered for the time-dependent campaign program rate in this model can also be replaced by other similar type of functions. Due to such replacement or modification of the control measure, there may be a slight variation in the results. However, the findings found from the model might help to understand the impact of campaign program in reducing the risk of anemia in children under the age of five. Such findings can be the contributors in reducing child mortality and malnutrition which is one of the targets of Sustainable Development Goals (SDGs) [31].

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