Influencing HIV/AIDS Policy in India Through Mathematical Modelling

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Abstract The third phase of the National AIDS Control Programme in India (NACP III) was launched in July 2007. To help the planning team set appropriate targets, we were asked to predict the number of people living with HIV/AIDS (PLHIV) under different intervention protocols. Using a dynamical systems approach to model the time evolution of disease, we predicted that if 50 % of the targets in NACP III were reached, then there would be 2.08 million PLHIV by 2011. This prediction was published in 2009 and compared very well with the 2.089 million PLHIV estimated by the Indian government at the end of 2011. This success of mathematical modelling encouraged the Indian government to integrate mathematical modelling into their decision making process.

Abbreviations

AIDS	Acquired Immunodeficiency Syndrome,
ART	Anti-Retroviral Therapy,
HIV	Human Immunodeficiency Virus,
NACO	National AIDS Control Organization,
NACP	National AIDS Control Programme,
ODE	Ordinary Differential Equation,
PLHIV	People Living with HIV/AIDS.

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Introduction

The first case of HIV in India was detected in 1986 and, since then, there has been a dramatic rise in the number of cases. By 2005, it was estimated that the number of HIV-infected individuals in India accounted for one in eight of all infections worldwide, with a total of over 5 million cases [2]. During our study, the government adjusted their estimate of HIV numbers at national level in India after the third round of the National Family Health Survey (2005–2006) results on HIV prevalence were available and we had to take these new figures into account [3]. To deal with this epidemic, India launched a series of National AIDS Control Programmes, the third of which (NACP III) was initiated in early 2007. In a major strategy advance over the previous programmes, one of us (Rao) was asked by the National AIDS Control Organization (NACO) to use mathematical modelling to help develop planning for NACP III. This led to the study [3] which we summarise in this chapter.

Mathematical Model

We followed the standard approach for building models for spread of infection (see, for example, [1]). Our model consisted of a set of coupled ordinary differential equations (ODEs) which took into account the spread of HIV via heterosexual encounters and male homosexual encounters, as well as spread amongst injecting drug users. The sub-models for these different modes of transmission are all formulated using mass action type kinetics. For illustrative purposes, here we consider only the model equations for HIV spread in the general population. Let $S_i(t)$, $G_i(t)$, $I_i(t)$ and $D_i(t)$ denote, respectively, the numbers of susceptibles, individuals with STI (sexually transmitted infection, excluding HIV), HIV infected individuals, and AIDS infected individuals of gender i at time t. Then the model equations take the form:

$$\frac{dS_i}{dt} = r_i S_i - f(S_i, G_j, I_j; \lambda_{ij}, \beta_{ij}) + \Phi G_i \tag{1}$$

$$\frac{dG_i}{dt} = f'(S_i, G_j; \lambda_{ij}) - g(G_i, I_j; \alpha_{ij}) - \mu G_i - \Phi G_i \tag{2}$$

$$\frac{dI_i}{dt} = h(S_i, G_i, I_j; \beta_{ij}, \alpha_{ij}) - \delta_i I_i - \gamma_i I_i \tag{3}$$

$$\frac{dD_i}{dt} = \gamma_i I_i - \delta_i D_i. \tag{4}$$

In these equations, r_i is net recruitment of new susceptibles, Φ is the rate at which individuals recover from STI, μ is natural mortality rate, δ_i is mortality rate associated with HIV, and γ_i is progression rate to AIDS. The λ_{ij}, α_{ij} and β_{ij} are, respectively, transmission rates of STI (excluding HIV), STI infected to HIV, and HIV from susceptibles from subpopulation j of the opposite gender. The functions f, f', g and h are all of mass action form (for full details see [3]).

We parametrised the model using data from a number of sources, including census data, sample registration system data, research publications and reports, fitting sub-models to specific data and using de-convolution methods. We provided model-based estimates on PLHIV projections based on the pre-adjusted and post-adjusted HIV cases during NACP II. Although both sets of projections were presented in our published work, for practical purposes of planning we used the post-adjusted PLHIV numbers.

We numerically simulated the model to predict the outcome of three different types of interventions: (i) Interventions to continue at NACP II levels (that is, no change in strategy), (ii) rapid scale-up of anti-retroviral therapy (ART), (iii) increased targets, ranging from 50 % (up from less than 30 % under NACP II) to 100 % coverage of intervention and prevention treatments for high-risk groups.

Model Validation and Predictions

The model was used to make projections, at the national level, of the outcome by 2011 of the various programme interventions mentioned above from the starting point of the estimated 2.47 million PLHIV (in the case of post-adjusted numbers) for 2006. However, before doing this, it was important to validate our model. This we did by running our model in a retrospective study for the period 2000–2006 to compare with NACP II estimates on disease prevalence and using Monte Carlo methods for validation and sensitivity analysis. Multi-stage models and hidden Markov models were used to estimate transition rates between different stages of the disease. Detailed studies were then done regarding the outcome of interventions (i) and (ii) and we refer the interested reader to the original paper [3]. Here we focus on intervention (iii).

In Fig. 1 we plot our predictions under the intervention which targets high risk groups (female sex workers, casual sex, male homosexual sex and injecting drug users). We see that, if 100 % effective, this intervention would lead to a reduction to 1.7 million PLHIV, while the more realistic 50 % effectiveness would lead to 2.08 million PLHIV by end of 2011 (see Fig. 1). A further prediction was 1.95 million if effectiveness was 75 % of target. As can be seen the NACO PLHIV estimates for 2009 and 2011 are slightly higher than the model predictions for 50 % targeted interventions. The NACO estimates were also higher than the model predicted numbers obtained with NACP II level of intervention (see [3]).

As it is not possible to easily measure what target is actually achieved, it makes sense to interrogate the model for predictions based on likely targets reached. In this respect the model predicts that for 50–75 % effectiveness, there will be approximately 2 million PLHIV by 2011, a result that is in remarkably close agreement with the government estimated figures. Since our collaborators in [3] were also members of the NACP III team, they were able to convey to the NACO how our model predictions should be interpreted as acting as a guiding principle to judge the level of the effectiveness of targeted interventions.

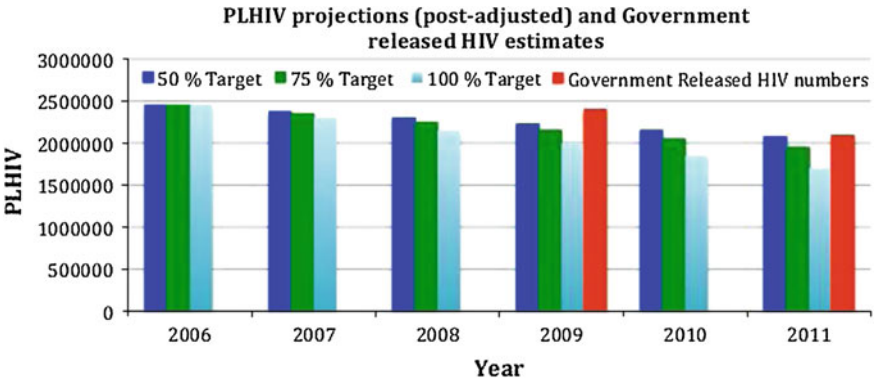

Fig. 1 Model predictions of the number of PLHIV [3] for different levels of interventions compared with subsequently released government estimates. The model predictions very closely match the estimates of the number of PLHIV in 2009 (released in 2010) and in 2011 (released in 2012) [2]

Impact

While working on the original article, Rao was invited to lead a mathematical modelling study for projecting HIV numbers at district level in the state of Tamil Nadu to work with NACP III planning members (Drs. K. Sudhakar, K. Thomas, B. Charles) to assist future district level program planning of HIV in India. During that project, Rao visited Maini twice at Oxford (2009 and 2010) for critical discussion of the project and a preliminary report on this study is available online [4].

Some time after the original publication and report sent to the planning committee, the estimated figures were released and, as can be seen, our model predictions were a very good match. This success resulted in an invitation from the NACO for Rao to become part of the NACP IV (2012–2017) sub-group on HIV surveillance and help guide planning and development. Furthermore Rao, along with Drs. K. Sudhakar and K. Thomas (who were co-authors of [3] and are part of NACP IV) have extended the study to make predictions on the outcome of ART treatment [5]. This model is aiding the government in framing policy for ART treatment by predicting the annual number of PLHIV who would require second line ART treatment, and in development and planning by predicting survival patterns of PLHIV. Maini served as a consultant on that work providing input into model development and validation.

It would be fair to say that the success of the original model in predicting numbers of PLHIV subsequently validated by government estimates, has convinced the Indian government to make mathematical modelling an integral part of their policy making process.

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to collaborate with them to develop model-based AIDS policies (In 2002, Rao and Sudhakar were part of a larger team gathered by The World Bank to model costs and consequences of HIV/AIDS treatment policies in India). During the research for [3], PKM was partially supported by a Royal Society-Wolfson Research Merit Award and ASRSR was a permanent faculty member at the Indian Statistical Institute, Kolkata when he was contributing to the NACP III and NACP IV program planning. He spent about a year at the University of Oxford during 2005–2006 to collaborate with PKM. This collaboration was initiated by funding from the London Mathematical Society.

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