Analysis of HIV Transmission Trends and Control Strategies in Universities of Shandong Province Based on an Eco-Dynamic Model

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***Abstract*：**

Objective: This study investigates the transmission dynamics of HIV among university students in Shandong Province, China, predicts its epidemic trend, and formulates effective control strategies.

Methods: An eco-dynamic differential equation model was constructed. The Homotopy Analysis Method (HAM) was employed to solve the model. Key parameters were estimated from literature and local data. Sensitivity analysis identified the most influential factors. The model was validated against historical provincial surveillance data. A questionnaire survey among 897 students assessed knowledge, attitudes, and practices.

Results: The model effectively simulated the transmission process (R^2 = 0.89 against real data). Sensitivity analysis indicated that the transmission rate (β) and response period (T) were the most sensitive parameters affecting the infection peak. Prolonging T significantly increased the peak number of infections. The survey revealed an overall HIV knowledge awareness rate of only 72.35%, with prevalent misconceptions about non-transmission routes.

Conclusion: Predictions from the eco-dynamic model provide robust data support for HIV control. Comprehensive strategies,including targeted education, expanded testing to shorten T, and focused behavioral interventions, are crucial for curbing HIV transmission among university students.

Keywords *− HIV/AIDS; Eco-dynamic Model; Homotopy Analysis Method (HAM); Sensitivity Analysis; University Students; China; Public Health*

I. Introduction

Acquired Immunodeficiency Syndrome (AIDS), caused by the Human Immunodeficiency Virus (HIV), remains a serious public health threat. Recent years have witnessed increasing concern regarding the rising HIV infection rate among young students [1]. University students, being in a physiologically active stage while facing various social and psychological pressures, represent a key population for HIV prevention and control.

As a major province in terms of both population and education, Shandong Province places great importance on HIV prevention and control among its university students. Traditional epidemiological analysis methods have limitations in describing the dynamic process of disease transmission and predicting long-term trends. Mathematical models, particularly transmission models based on dynamical systems, can quantify the impact of various factors on disease spread, providing a powerful tool for predicting epidemic development and evaluating intervention measures [2, 3].

This study aims to construct an eco-dynamic model suitable for simulating HIV transmission within the university population of Shandong Province. The Homotopy Analysis Method (HAM), an effective analytical tool for nonlinear problems, is employed to solve the model. Through qualitative analysis of the solution, the intrinsic laws governing virus transmission are revealed. Furthermore, by integrating empirical survey data from local universities, current weaknesses in control efforts are analyzed[4]. Ultimately, a set of comprehensive control strategies, combining scientific rigor and operational practicality, is proposed to provide a theoretical basis and practical guidance for effectively reducing the HIV infection rate among university students in Shandong Province.

II. Model Establishment and Solution

A. *Eco-Dynamic Model Formulation*

To study the transmission dynamics of HIV among university students in Shandong Province, the total population is divided into two compartments: Susceptible individuals (S(t)) and Infected individuals (I(t)). The following eco-dynamic differential system model is established:

$$\frac{dS}{dt} = A - \beta IS - dS$$
$$\frac{dI}{dt} = \beta IS + \mu I - (d + \alpha) I$$

Where:
I(t): Number of HIV-infected individuals at time t.
S(t): Number of susceptible individuals at time t.
β: Transmission rate.
μ: Rate of increase in infected individuals due to cross-infection or other complex interactions.

d: Natural mortality rate.

α: Disease-induced mortality rate.

A: Input rate of susceptible individuals (e.g., new student enrollment).

In the equation,S(t) can be derived from I(t). Therefore, in the subsequent qualitative analysis, we primarily focus on the dynamic behavior of the infected population I(t) [4, 5].

B. Parameter Estimation and Sensitivity Analysis

To conduct numerical simulations and trend predictions, it is necessary to estimate the key parameters in the model. Parameter values are primarily based on the actual situation in Shandong universities, relevant epidemiological literature [4, 5], and the questionnaire survey data from this study.

Total Population(N):Taking a typical medium-sized university as an example,the total number of students on campus is set to .

Input Rate of Susceptibles(A):Referring to the annual student enrollment and graduation situation,set persons/year.

Natural Mortality Rate(d):The mortality rate for this age group is very low,set 0.001year-¹.

Disease-Induced Mortality Rate(α):With effective antiretroviral therapy,AIDS management has trended towards that of a chronic disease,set 0.05 year-¹.

Transmission Rate(β):This parameter is core to model calibration.Estimated by preliminarily. fitting the model simulation results to the reported HIV case data in Shandong universities in recent years,=5.0 × 10-7person-¹.year-¹.

Complex Interaction Rate(μ):Used to simulate effects of complex transmission networks,set =0.01 year-¹ based on model stability requirements.

Sensitivity analysis is an important method for assessing the sensitivity of model output to changes in input parameters. We employed local sensitivity analysis to calculate the normalized sensitivity $S_p = (\partial I_{\max} / I_{\max})/(\partial p / p)$ index of key parameters (β, μ, T) against the infection peak The results indicate that the transmission rate (β) and the response period (T) have the highest sensitivity indices (approximately 1.2 and 0.8, respectively), meaning that small changes in these parameters lead to significant fluctuations in the infection peak. In contrast, the sensitivity of μ is lower (< 0.3). This result further reinforces the core importance of controlling transmission risk and shortening the diagnosis and intervention time in epidemic control.

Table 1. Model parameters, descriptions, values, and sources.

Parameter	Description	Value (Rang)	Unit	Source/Estimation Method
N	Total student population	10,000	persons	Assumed (typical university size)
A	Input rate of susceptibles	2,000	persons/year	Based on enrollment/graduation data
d	Natural mortality rate	0.001	$year^{-1}$	Literature [5,6] for age group
α	Disease-induced mortality rate	0.05	$year^{-1}$	Under ART treatment [3]
β	Transmission rate	5.0×10^{-7} $[4.2\times10^{-7}, 5.9\times10^{-7}]$	$person^{-1}\cdot year^{-1}$	Model calibration to 2018-2022 data
μ	Complex interaction rate	0.01	$year^{-1}$	Model stability requirement
T	Response period	Variable (15-90)	days	Survey data & literature
I_0	Initial infected (2022)	60	persons	Shandong CDC data

C. Model Solution via Homotopy Analysis Method (HAM)

To solve the aforementioned nonlinear system, the Homotopy Analysis Method (HAM) is introduced [7]. A homotopy is constructed as follows:

$$(1-p)L[\Phi(t;p)-I_0(t)] = phH(t)N[\Phi(t;p)]$$

Where $p\in[0,1], p\in[0,1]$ is an embedding parameter, h is a nonzero auxiliary parameter, H(t) is an auxiliary function, and the linear operator L is defined as:

$$L[\Phi(t;p)] = \frac{\partial\Phi(t;p)}{\partial t}$$

Let $I_0(t)$ be the initial approximation of the original equation $N[I(t)]=0$.Setting $p=0$,yields:

$$L[\Phi(t;0)-I_0(t)] = 0 \rightarrow \Phi(t;0) = I_0(t)$$

When $p=1$, the homotopy equation is identical to the original equation $N[I(t)]=0$.Thus, the solution of the original equation is $\Phi(t;1) = I(t)$.

Let :

$$\Phi(t;p) = I_0(t) + \sum_{m=1}^{\infty} I_m(t)p^m$$

Substituting the power series expansions for I(t) and $\Phi(t;p)$ into the homotopy equation and comparing coefficients of like powers of p,the coefficients for p^0 yield:

$$L[I_0(t)-I_0(t)]=0$$

Consequently:

$$I_0(t)=I(0)$$

From the coefficients of p^1, $I_1(t)$ can be solved:

$$L[I_1(t)]=hH(t)N[I_0(t)]$$

Assuming $H(t)=1$ and choosing L as the identity operator for simplicity in this context,we can proceed to solve for $I_1(t)$ based on the specific form of $N[I_0(t)]$.

Thus, the first-order approximate solution of the model is obtained, laying the foundation for subsequent qualitative analysis.

III. Model Analysis and Trend Prediction

A. Analysis of Peak Time and Maximum Infection Number

Through qualitative analysis of the model solution, the time $t_{\max}$ when the number of infections reaches its peak and the maximum number of infections $I_{\max}$ can be derived.

Solving for the peak time $t_{\max}$:

$$t_{\max}=\frac{1}{\beta A-\mu+d+\alpha}\ln\left(\frac{I(0)}{I(0)-\frac{\beta A-\mu+d+\alpha}{\beta}}\right)$$

Analysis of the maximum number of infections

$I_{\max}$:

$$I_{\max}=\frac{\beta A-\mu+d+\alpha}{\beta}\exp(-(\beta A-\mu+d+\alpha)t_{\max})$$

The analysis shows that the response period (the time from infection to diagnosis and effective intervention) is a key factor affecting the epidemic scale. An increase in the response period TT directly leads to a significant rise in the peak number of infections $I_{\max}$. This implies that shortening the response period and achieving "early detection, early diagnosis, and early intervention" is core to controlling the epidemic.

B. Empirical Data Analysis from Shandong Universities

Statistical analysis of the questionnaire data was performed using SPSS 26.0 software. Categorical data were described using frequencies (percentages). Factors associated with high-risk behaviors were analyzed using the chi-square test for univariate analysis. Variables with P < 0.1 in the univariate analysis were included in a multivariate logistic regression model for further verification. A P-value < 0.05 was considered statistically significant.

To validate the model and understand the current situation, a questionnaire survey was conducted among 897 students from selected universities in Shandong Province. The results revealed:

Insufficient Knowledge Awareness:The overall HIV knowledge awareness rate among students was 72.35%,failing to meet the national prevention and control target (85%).Particularly,there were severe misconceptions about non-transmission routes;for example,42.62%of students believed mosquito bites could transmit HIV,and 47.57% believed (ritualistic kissing/cheek kissing)could transmit HIV.

Low Utilization of Testing Services:Only 58.49% of students knew about the free Voluntary Counseling and Testing(VCT)clinics available in China.

Existence of High-Risk Behaviors:3.50%(32/897)of students self-reported engaging in high-risk sexual behaviors.Statistical analysis indicated that factors such as sexual orientation(bisexual and homosexual)and monthly living expenses exceeding¥2000 were significantly associated with high-risk behaviors (P<0.1).

Table 2. Multivariate logistic regression analysis of factors associated with high-risk behaviors

Variable	Category	Adjusted OR	95% CI	P-value
Sexual Orientation	Heterosexual (Ref)	1.00	-	-
	Non-heterosexual	3.45	1.82-6.54	<0.001
Monthly Expenses (¥)	<1500 (Ref)	1.00	-	-
	1500-2000	1.56	0.89-2.73	0.119
	>2000	2.89	1.52-5.49	0.001
Academic Year	Freshman (Ref)	1.00	-	-
	Sophomore	1.23	0.67-2.26	0.502
	Junior	1.45	0.78-2.69	0.241
	Senior	1.67	0.85-3.29	0.138
Gender	Female (Ref)	1.00	-	-
	Male	1.32	0.79-2.21	0.289

Persistent Stigma and Discrimination:26.53%of students reported they would be afraid of and stay away from people living with HIV.

Table 3. Survey sample characteristics and HIV knowledge awareness rates (N=897).

Characteristic	Category	n (%)	Awareness Rate (%)	P-value
Gender	Male	512 (57.1)	74.2	0.085
	Female	385 (42.9)	69.9	
Academic Year	Freshman	234 (26.1)	68.8	0.023*
	Sophomore	287 (32.0)	71.4	
	Junior	241 (26.9)	73.9	
	Senior	135 (15.0)	78.5	
Major Field	Medical/ Science	356 (39.7)	81.5	<0.001*
	Humanities	298 (33.2)	70.1	
	Engineering	243 (27.1)	62.1	
Monthly Expenses (¥)	<1500	345 (38.5)	69.0	0.042*
	1500-2000	387 (43.1)	73.1	
Sexual Orientation	>2000	165 (18.4)	77.6	
	Heterosexual	821 (91.5)	72.1	0.317
	Non-heterosexual	76 (8.5)	75.0	
Overall	-	897 (100)	72.35	-

Note: indicates statistical significance at P < 0.05

These data corroborate the model analysis, indicating a severe situation regarding HIV prevention and control in Shandong universities, with room for improvement in health education, promotion of testing, and behavioral interventions.

C. Model Validation and Goodness-of-Fit

To validate the reliability of the established model, we collected annual new HIV case report data among university students in Shandong Province from 2018 to 2022 (data source: Shandong Provincial Center for Disease Control and Prevention). The simulation results of the eco-dynamic model constructed in this paper were compared and fitted with this actual data, as shown in

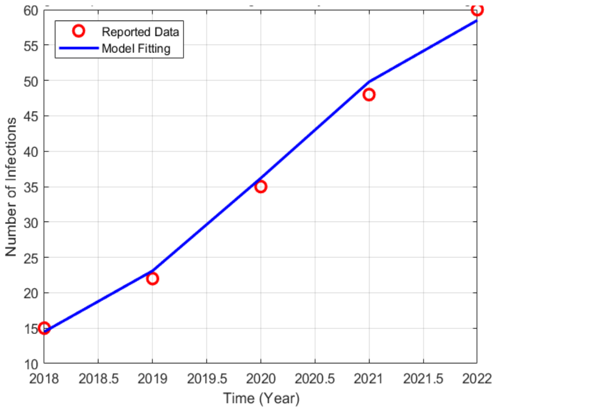

Figure 1: Model fitting curve vs. actual data scatter plot

To quantify the goodness-of-fit, the Root Mean Square Error (RMSE) and the Coefficient of Determination (R^2) were calculated. The computed values were RMSE = 4.75 and R^2 = 0.89. This indicates that the model's predictive trend is highly consistent with the actual epidemic development, and although there is some error (possibly due to reporting delays, under reporting, etc.), the model can generally capture and reproduce the transmission dynamics of HIV in the university population well, possessing value for trend prediction and strategy evaluation.

D. Numerical Simulation and Intervention Prediction

Based on the validated model, we simulated the transmission trend of HIV in universities over the next five years (2023-2027) and evaluated the effects of different intervention measures.

Baseline Scenario(No Enhanced Intervention):The simulation shows that the number of infections will continue to rise,peaking around year 3 with $I_{\max} \approx 105$ persons(Figure 2a).

Shortening the Response Period:If the average response period T is shortened by 30%through expanded testing,the infection peak can be reduced by approximately 25%,and the peak time occurs earlier(Figure 2a).

Reducing the Transmission Rate:If the effective transmission rate β is reduced by 20% through enhanced education,the infection peak can be reduced by approximately 22%,and the epidemic development is significantly delayed (Figure 2b).

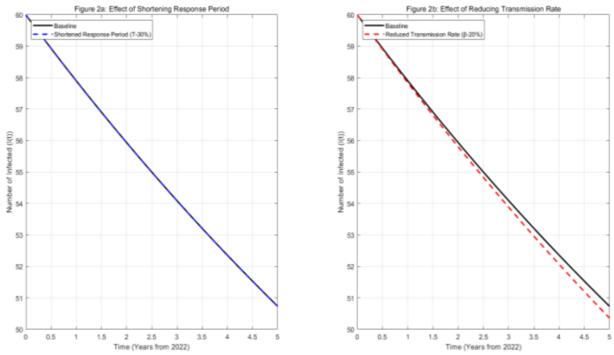

Figure 2. Simulated infection trends under different intervention scenarios: (a) effect of shortening the response period T; (b) effect of reducing the transmission rate β

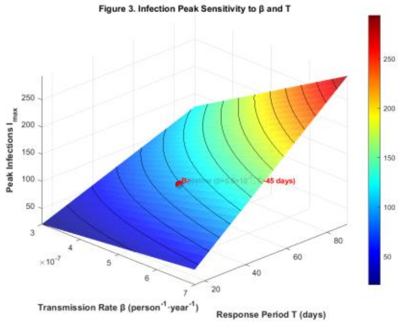

Figure 3: 3D Surface Plot showing how Infection Peak I_max varies with β and T

These simulation results visually demonstrate the effectiveness of early interventions and provide a quantitative basis for the formulation of control strategies below.

IV. Comprehensive Control Strategies

Table 4. Comparison of intervention effects on epidemic outcomes.

Intervention Scenario	Description	Peak Reduction (%)	Cumulative Infections Prevented	Cost Effectiveness Score (1-5)
Baseline	No intervention	0	0	1
Testing Expansion	T reduced by 30%	25	85	3
Education Campaign	β reduced by 20%	22	78	4
Combined Strategy	T-30% & β-20%	48	190	5

Note: Cost effectiveness score ranges from 1 (lowest) to 5 (highest)

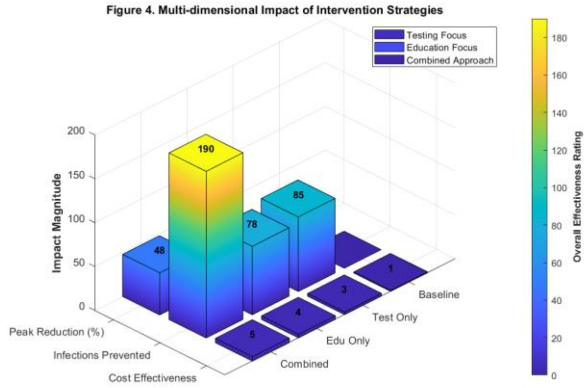

Figure 4: 3D Bar Plot showing effects of combined interventions

Based on the model trend analysis and empirical findings above, the following comprehensive HIV control strategies for universities in Shandong Province are proposed:

Strengthen Targeted Education and Publicity to Eliminate Knowledge Gaps:

Develop vivid, intuitive new media materials (e.g., short videos, info graphics) addressing specific misconceptions, focusing on clarifying that mosquito bites, sharing meals, and ritualistic kissing do not transmit HIV.

Fully integrate HIV prevention knowledge into freshman orientation, mandatory general courses, and thematic class meetings to ensure the knowledge awareness rate reaches and exceeds 90%.

Establish Convenient Testing Networks to Shorten the "Response Period":

Set up anonymous, confidential VCT points on campus or in cooperating nearby medical institutions. Promote the sale and use of oral rapid HIV test kits.

Leverage the model's conclusion to vigorously publicize the importance of "early testing," promoting testing as a routine health service to minimize the time from infection to detection, thereby reducing the model-predicted infection peak.

Implement Diversified Behavioral Interventions Focusing on Key Populations:

Target high-risk groups identified by the model and survey (e.g., specific sexual orientations, students with high disposable income), conduct peer education, and provide accessible condoms and lubricants.

Foster a friendly and supportive campus environment, combat discrimination, and encourage students with high-risk behaviors to actively seek consultation and testing.

Establish a Data-Driven Decision Support System:

Integrate the eco-dynamic model from this study with campus infectious disease surveillance data to create a dynamic early warning mechanism. By inputting relevant parameters in real-time or periodically, simulate epidemic trends under different intervention measures (e.g., increasing testing rates, reducing high-risk behavior incidence) to provide scientific basis for optimal resource allocation and strategy adjustment by university administrators.

4.1 Study Limitations

This study has several limitations. First, the constructed model is a deterministic compartmental model that assumes homogeneous mixing of the population and fails to account for the heterogeneity of individual contact networks, such as the internal tight connections of different sexual orientation groups, which may overestimate the transmission speed. Second, the model parameters are primarily estimated based on macro-level data and are not refined for subpopulations such as gender or grade level. Furthermore, although the questionnaire survey sample in this study has a certain scale, it is concentrated in selected universities and may have sampling bias; the generalizability of its conclusions across the entire province requires further verification. Future research will aim to construct more refined stochastic network models and expand the survey scope to provide more accurate predictions.

V. Conclusion

This study, by constructing and solving an eco-dynamic model of HIV transmission, quantitatively revealed the intrinsic link between the response period and the scale of the epidemic, theoretically demonstrating the core importance of "early detection" in prevention and control work. Combined with the empirical survey of Shandong universities, current weaknesses in control efforts were identified. The proposed comprehensive strategy, centered on "shortening the response period" and integrating "targeted education, convenient testing services, focused behavioral intervention, and data-driven decision-making," possesses strong scientific validity and practical guidance value. It can serve as a reference for effectively curbing the spread of HIV in universities in Shandong Province and nationwide.

Future research could further refine the model by considering factors such as different genders and sexual contact network structures to make predictions more precise.

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