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An economic evaluation of the current measles vaccination program: A case study in Zhejiang Province, east China

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ABSTRACT

Objective: To evaluate the economic impact of the current measles vaccination program in Zhejiang Province, east China.

Methods: A decision tree-Markov model with parameters from published literatures, government documents and surveys was developed and used to simulate over 40 years of a birth cohort in Zhejiang Province during the year 2014. The expected cost and effectiveness of the current measles vaccination program was compared against no vaccination. Costs were assessed from the payer's perspective. Benefits were defined as savings on the direct cost of measles treatment, and the effectiveness was measured according to the number of measles cases and deaths averted. The net present value (NPV), benefit-cost ratio (BCR) and incremental cost-effectiveness ratio (ICER) were also calculated. A threshold for cost-effectiveness of less than 3 times the Gross Domestic Product (GDP) per capita was used. One-way sensitivity analysis was performed to assess parameter uncertainties.

Results: The total vaccination cost was estimated to be $2.52 million. The BCR of the current measles program was found to be 6.06 with a NPV of $73.38 million. It was also calculated that a total of 195,165 measles cases and 191 measles-related deaths would be prevented by vaccination. The ICER was approximately $12.91 per case averted and $13,213.43 per death averted, respectively, which was cost-effective. The models were proven to be robust.

Conclusions: The current measles vaccination program appeared to be cost-effective and to offer substantial benefits. The results of this analysis sought to contribute to the justification of future investments to achieve the goal of measles elimination.

1. Background

Measles is a highly contagious disease caused by the measles virus and is one of the most devastating infectious diseases with serious complications, including diarrhea, otitis media, pneumonia and death, resulting in approximately 89,780 deaths annually worldwide [1–3]. There is no specific antiviral therapy for people with measles [1]. Active vaccination with measles vaccine is considered to be the most common preventative measure against measles. The World Health Organization (WHO) recommends that measles vaccines are included in national immunization programs worldwide [4]. Live attenuated Measles-Mumps-Rubella (MMR) immunization is delivered against measles in more than 90 countries [5]. Significant progress in reducing the number of people dying from measles has been made through measles vaccination. Measles vaccination prevented an estimated 20.4 million deaths, and global measles deaths have decreased by 84% from an estimated 550,100 to 89,780 during 2000–2016. While the annual reported measles incidence decreased by 87%, from 145 to 19 cases per million individuals [6]. The WHO Western Pacific Region has been striving to eliminate measles since 2005 and set a goal to eliminate measles in the region by 2012. China adopted this goal and developed a strategic plan for measles elimination in 2006, contributing to the steady decline of the average measles incidence. Annual incidence decreased from 9.95 per 100,000 individuals in 2008 to 0.46 per 100,000 individuals in 2012 [7–9]. However, indigenous measles virus outbreaks have been continuously reported, and resurgence started in late 2012 and continued into 2013 [9], indicating the remaining immunity gaps that need to be identified and addressed.

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The measles vaccine was first introduced in China in 1965 and included in the Expanded Program on Immunization (EPI) in 1978 [10]. The measles immunization schedule differs among provinces, using either a two-dose or three-dose schedule [11]. In Zhejiang Province, the measles-rubella (MR) vaccine is recommended for children at 8 months of age, followed by the MMR vaccine at 18 months. According to the evaluation of MCV coverage targeting children born from the 1st of January 2005 to the 31st of December 2010 through the Zhejiang provincial immunization information system (ZJIIS), the coverage of full MCV immunization was 93.2% among children at 24 months of age [12]. However, this rate was below the 95% threshold level required for eliminating measles transmission, informing that measles immunization requires further strengthening.

Economic analyses on vaccination provide important insights on the value of prevention and play a critical role in justifying future investments [13]. The health economic analysis of measles vaccination has been reported overseas since 1969 [14]. Either a single-dose or two-dose strategy has been shown to be cost-beneficial in Korea, Japan, the United States and western European countries [15–18]. However, an economic evaluation based on a mathematic model on this topic has not been performed in China, while the efficiency of measles vaccination remains unknown and health policy research about measles vaccine is still missing to date. Additional data is needed to guide decisions on the vaccination strategy required to achieve the goal of national measles elimination.

In the present study, we tried to estimate the economic disease burden of measles and the costs of implementing vaccines based on surveys in Zhejiang Province. In addition, we attempted to evaluate whether the current two-dose measles vaccination program is cost-beneficial and cost-effective compared with no vaccination.

2. Methods

A cost-benefit and cost-effectiveness analysis was conducted in the present study using a decision tree-Markov model from the payer's perspective. The expected cost and effectiveness of the current MR and MMR vaccination programs were compared against no vaccination. The decision tree was used to simulate the compliance and efficacy of the strategies and to perform a comparison between vaccination and no vaccination. A Markov model was constructed based on epidemiological data and vaccine effectiveness, followed by a hypothetical birth cohort of 578,000 children born in 2014 in Zhejiang Province, China. Thirteen mutually-exclusive states were modelled (Fig. 1) to simulate the population without protection against measles. A Markov cycle for each stage was set at 1 year following a cohort through the age of 40 years [18]. It should be noted that the rectangle (from state 2 to 8) states were not regarded as an independent Markov state of the model but the transient process of measles infection occurring in the state of susceptibility to cured or sequela of measles, because their durations were between several days or a months at most instead of a year. Another model, including both immunized and natural death states (Fig. 2), was used to simulate the population with protection. A number of assumptions were made in this study, as follows: (1) Every vaccinated infant completed the entire two-dose schedule; (2) there is no vaccine-induced herd immunity; and (3) all measles case received medical treatment.

2.1. Costs associated with vaccination

The costs of the vaccine introduction financed by the government were estimated. In China, measles immunization is given under the national immunization program and implemented by the Center for Disease Control and Prevention (CDC), which comprises the provincial CDC, municipal CDCs, county CDCs, townships hospitals, and village clinics. At each level, CDCs are in charge of vaccine delivery and surveillance in their administration area, and the superior CDCs are responsible for the inferior centers. Notable, the vaccine inoculations are mainly given in township hospitals to avoid overlap of vaccinations.

The cost for measles routine immunization include the vaccine and syringe costs (as well as expected wastage), and implementation costs (institution costs). A sampling survey was conducted to obtain the implementation costs during the year 2014. The cost accounting theory of health economics was used to calculate EPI service costs at different levels. Firstly, total institution costs were measured and allocated to the immunization program based on the proportion of the immunization staff of the CDC. Secondly, the immunization cost per vaccination dose was distributed based on the number of vaccines that each level CDC annually implemented or supervised. The complete implementation costs for each vaccination involved the sum of the vaccination cost per dose at each level (illustrated in formula (1)).

Formula 1 (per dose costs):

$$C_{\text{implement}} = C_{\text{province}} + C_{\text{municipal}} + C_{\text{county}} + C_{\text{township}} + C_{\text{village}} \quad (1)$$

The full cost of MMR and MR immunization per child is the sum of the cost for the two-dose vaccination, vaccine and syringe. We assumed that the total measles immunization cost included 1/3 MMR immunization cost and 1/2 MR immunization cost to calculate the final measles immunization cost per child (illustrated in formula (2)).

Formula 2:

$$C_{total} = \frac{1}{3}\left(C_{MMR} * (1+\alpha) + C_{\text{syringe}} * (1+\beta) + C_{\text{implement}}\right) + \frac{1}{2}\left(C_{MR} * (1+\alpha) + C_{syring} * (1+\beta) + C_{\text{implement}}\right) \quad (2)$$

α and β refer to the overall wastage rate of vaccine and syringe, respectively.

2.1.1. Sampling process

A multistage sampling study was performed on 5-level systems. Firstly, the Zhejiang CDC was selected at the provincial level. Secondly, 3 municipals (Jinhua, Taizhou and Jiaxing) of the total 11 municipals were selected based on economic and geographical characteristics. Thirdly, 3 counties in each municipal, 3 township hospitals in each county and 3 village clinics in each township were randomly selected, covering a total of 1 provincial CDC, 3 municipal CDCs, 9 county CDCs, 27 township hospitals and 91 village clinics.

2.1.2. Data collection and analysis

The implementation cost was estimated according to the costs of the following five parameters: Administration (labor), regular maintenance, low-value consumables and materials, immunization digital system maintenance and other relative items. The items of resource consumption were filled in by the finance department of each institution, while other items were filled in by the immunization officers. All the questionnaires were checked to ensure accuracy. Data were double inputted into an Epidata 3.02 software database, and discrepancies were checked. After verifying accuracy, the data were analyzed with Excel 2013.

2.1.3. Measles immunization program cost

2.1.3.1. Vaccine implementation cost (institution costs). The total institutional costs of immunization implementation were \$936,481.50, \$384,512.07, \$587,338.81, \$2,556,587.45, \$11,133.62 at provincial CDCs, municipal CDCs, county CDCs, townships

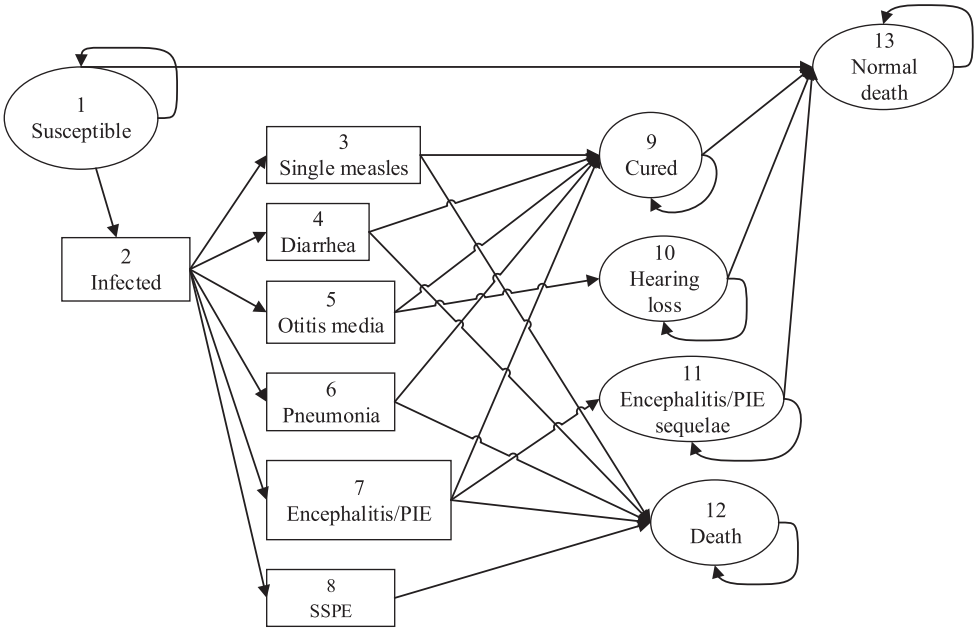

Fig. 1. Markov model of measles infection and progression. Circles represent annual disease states, and arrows represent transitions between states in which individuals follow annual transition to other states. The rectangle (from state 2 to 8) states were not regarded as an independent Markov state of the model but the transient process of measles infection occurring in the state of susceptibility to the state of cured or sequela of measles.

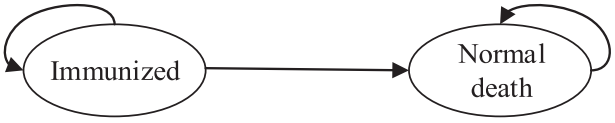

Fig. 2. Markov model of protection.

hospitals, and village clinics, respectively, in the sampled area. When the cost per dose was considered, the total cost of implementation was found to be $3.18, which comprised the total cost of administration, regular maintenance, low-value consumables and materials, immunization digital system maintenance and other items at each level. Detailed information is shown in Table 1.

2.1.3.2. Vaccine/syringe costs and the rate of wastage. The price of the MMR and MR vaccines was $3.39 and $0.94, respectively. The price of a syringe was $0.005. The rate of wastage of vaccine and syringe was 0.05 and 0.02, respectively. These data were acquired from Zhejiang CDC.

2.1.3.3. Total measles routine immunization cost per child. The total cost of the MMR and MR immunization program was $11.02 per child, and it was $4.36 (including two-dose schedule) when allocated to the single measles immunization according to formula (2).

2.2. Estimating the disease burden of measles

The economic disease burden of measles included the direct cost of measles treatment and of measles complications treatment. Direct costs included medical and nonmedical costs, which were obtained from a field survey conducted in the same area where the measles immunization program cost survey was conducted. Due to insufficient evidence in China, the cost of treatment of measles complications was converted from previous studies [18,19].

2.2.1. Sample size

The initial sample size was calculated with the following formula:

Table 1
Institution cost of immunization implementation (USD).

Items	Provincial level	Municipal level	County level	Township level	Village level	Cost per dose
Cost of administration	615,635.18 (65.74%)	287,193.45 (74.69%)	368,935.11 (62.81%)	2,343,192.98 (91.65%)	11,133.62 (100.00%)	2.84
Cost of regular maintenance	239,575.96 (25.58%)	73,893.21 (19.22%)	136,333.05 (23.21%)	152,536.26 (5.97%)	0.00 (0.00%)	0.24
Costs of low-value consumables and materials	81,270.36 (8.68%)	22,773.94 (5.92%)	25,436.78 (4.33%)	30,884.92 (1.21%)	0.00 (0.00%)	0.05
Costs of immunization digital system maintenance	0.00 (0.00%)	456.03 (0.12%)	23,427.69 (3.99%)	5,392.51 (0.21%)	0.00 (0.00%)	0.01
Cost of other items	0.00 (0.00%)	195.44 (0.05%)	33,206.19 (5.65%)	24,580.78 (0.96%)	0.00 (0.00%)	0.04
Total	936,481.50 (100.00%)	384,512.07 (100.00%)	587,338.81 (100.00%)	2,556,587.45 (100.00%)	11,133.62 (100.00%)	3.18
NO. of implemented/supervised vaccines	21,177,159	6,983,432	2,553,281	929,564	106,629	–
Institution cost per vaccine	0.04	0.06	0.23	2.75	0.10	3.18

Note: Costs are converted to U.S. dollars at the average exchange rate of 1:6.14 in 2014.

$$n = \left(\frac{U_{\alpha/2}\sigma}{\delta}\right)^2$$

The confidence coefficient was assumed to be 95%, and sampling error was no more than 10%. Hence, the $U_{\alpha/2}$ was 1.96 and σ was set to 0.5; thus, the sample size was 96. We intended to recruit 40% of the overall registered measles cases in order to ensure the investigation quality, and the sample size was eventually 136.

2.2.2. Data collection and analysis

Data collection was performed parallel to the investigation of the immunization program costs. Patients in the 3 selected cities were identified from the China Information System for Disease Control and Prevention [20] between January 1, 2015 and October 31, 2015. Investigators conducted face-to-face interviews with patients to complete the questionnaire. Before beginning the interview, the exact purpose of this survey was explained to the interviewees, and written informed consent was obtained.

2.2.3. Characteristics of measles cases

The characteristics of study population are shown in Table 2. Among 136 patients, 45 were from Jiaxing, 51 from Jinhua, and 40 from Taizhou. Respondents included an approximately equal number of males and females. The age ranges of 20–40 years (41.91%) and babies <12 months of age (24.26%) accounted for the vast majority of participants. The majority of subjects were inpatients (82.35%), with outpatients accounting for around 17.65%. The farmers and workers (35.29%), children and students (34.56%) account for the vast majority of the respondents. 91 (66.91%) of the patients have an uncertain immunization status, while only 6 patients (4.41%) had clear immunization history of measles vaccine and 39 patients (28.68%) were not vaccinated.

2.2.4. Economic disease burden of measles and complications

As presented in Table 3, our survey demonstrated that the average direct costs per measles case were $747.14. Hospitalization expenditure accounted for 83.5% of the total cost. The direct cost of the age group under 40 years were $695.15, which was applied in the model, and for patients over 40 years old were $910.22.

The cost of measles complications and sequela treatment was converted from previous studies in the US and Belgium based on the ratio of per capita health expenditures in each country, and discounted to the 2014 values at an annual discount rate of 3% (Table 4).

Table 2
Characteristics of 136 measles cases in Zhejiang Province.

Characteristics	No. of cases	%
Gender		
Male	63	46.32
Female	73	53.68
Age		
<12 months	33	24.26
12–23 months	2	1.47
2–4 years	4	2.94
5–19 years	8	5.88
20–40 years	57	41.91
>40 years	32	23.53
City		
Jiaxing	45	33.09
Jinhua	51	37.5
Taizhou	40	29.41
Hospitalization		
Yes	112	82.35
No	24	17.65
Occupation		
Children, Student	47	34.56
Civil Servants, Commercial Service	21	15.44
Farmer, Worker	48	35.29
Jobless, Retired	20	14.71
Major means of payment		
Medical Insurance	75	55.15
Self-pay	61	44.85
Immunization Status		
Yes	6	4.41
No	39	28.68
Unknown	91	66.91

Table 3
Direct costs of measles patient (USD) in Zhejiang.

Item	Average		Total	% of total cost
	≤40 years	>40 years		
Outpatient expenditure	84.91	87.31	84.3	11.28
Hospitalization expenditure	582.07	799.17	623.87	83.50
Self-treatment and nutrition supplements	28.17	23.74	38.97	5.22
Total cost	695.15	910.22	747.14	100.00

Table 4
Conversion of measles complications and sequela disease burden costs.

Complications/Sequela	Original costs	Converted (USD)
Otitis media	$4325 [18]	231.68
Pneumonia	$13864 [18]	742.68
Encephalitis/PIE	$29556 [18]	1583.28
SSPE	$8796 [18]	471.19
Encephalitis/PIE sequela	€3257 [19]	511.89

2.3. Outcome estimation

Outcomes in terms of cost and effectiveness were estimated by assigning transition probabilities and economic disease burden weights from previous studies, government documents and surveys to the Markov model (Table 5). Measles natural incidence rate was obtained according to the average measles incidence rate from 1955 to 1964 reported at Zhejiang CDC. It was assumed that each case of hearing loss needed to wear a hearing aid, with an estimated cost of approximately $814.33. The cost of diarrhea was small and thus ignored in the model. All the costs are converted to U.S. dollars at the average exchange rate of 1:6.14 in 2014 according to the National Bureau of Statistics of China.

2.4. Net present value, benefit-cost and cost-effectiveness analyses

Costs were defined as the vaccination cost and measles infections cost related to failure of immunization. Benefits were defined as the reductions of direct costs. Net present value (NPV) was the sum of the discounted benefits from the vaccination program minus the sum of the discounted immunization program costs. NPV can be defined as:

$$\mathrm{NPV} = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

where B_t and C_t were the benefits and immunization program costs, respectively, in year t. T was 40 years of the total Markov cycle, and r was the discount rate.

In addition, BCR was equal to the costs averted with the vaccination program divided by the vaccination costs, and can be calculated as follows:

$$\mathrm{BCR} = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} \Big/ \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

All costs and benefits in the future were discounted at a rate of 3% annually for the base case analysis.

Table 5
Parameter values including ranges used in the sensitivity analyses.

Parameters	Base-case value	Range	References
Vaccine efficacy (%)	95.00	80.00–98.00	[21]
Vaccine coverage (%)	93.00	85.00–99.00	[12]
Newborns in 2014	578,000		[22]
Per capita gross domestic product (USD)	11883.88		[22]
Per capita measles immunization costs (USD)	4.36	2.00–8.14	Investigation
Natural mortality (%)			[23]
≤1	0.38		
1–4	0.03		
5–14	0.02		
15–40	0.04		
Natural incidence (%)	1.21	0.39–6.69	[18,21,24]
Complications rates			
Pneumonia (%)			[18,25]
<12 months	3.71		
12–23 months	3.92		
2–4 years	2.77		
5–19 years	1.04		
20–40 years	2.90		
Diarrhea (%)	8.00		[26]
Otitis media (%)			[18,25]
<12 months	14.11		
12–23 months	14.46		
2–4 years	8.60		
5–19 years	2.34		
20–40 years	1.46		
Encephalitis/PIE (%)			[18,25]
<12 months	0.05		
12–23 months	0.09		
2–4 years	0.07		
5–19 years	0.03		
20–40 years	0.09		
SSPE (%)	0.001		[19]
Sequela rates (%)			
Otitis media sequela	0.01		[27]
Encephalitis/PIE sequela	25.00		[19,28]
Death rates (%)			
Acute measles	0.10	0.08–0.2	[29]
SSPE	100.00		[19]
Economic burden (USD)			
Measles	695.15	±25%	Investigation
Otitis media	231.68		Converted[18]
Pneumonia	742.68		
Encephalitis/PIE	1583.28		
SSPE	471.19		
Hearing loss	814.33		Assumption
Encephalitis/PIE sequela	511.89		Converted[19]
Discounting (%)	3.00	0.00–8.00	[30]

Note: Costs are converted to U.S. dollars at the average exchange rate of 1:6.14 in 2014.

The measurement of cost-effectiveness involved the cost per measles case prevented and the cost per early death averted. The ICER can be calculated as:

$$\mathrm{ICER} = \frac{C_B - C_A}{E_B - E_A}$$

A threshold for cost-effectiveness of less than 3 times the Gross Domestic Product (GDP) per capita ($35651.64 for Zhejiang Province) was used [31].

2.5. Sensitivity analyses

Sensitivity analysis assess the robustness of economic estimates, and is helpful for investigators to estimate the impact of potential changes to the vaccination program. In the current study, one-way sensitivity analysis was conducted to appraise the stability of BCR.

3. Results

3.1. Base case

In the present study, it was estimated that among a cohort of 578,000 children, 220,899 measles infections would happen over 40 years in the absence of the vaccination program, resulting in 216 early deaths. These infections would result in a direct cost of $85.90 million. By contrast, the current vaccination program cost approximately $2.52 million, with $10.01 million illness costs due to immunization failure. The BCR would be 6.06 with a NPV of $73.38 million. Compared with no vaccination, a total of 195,165 measles cases and 191 early deaths would be prevented under vaccination program. The ICER was calculated to be $12.91 per case averted and $13213.43 per death averted, respectively. These ICER values fell below 3 times the GDP per capita in Zhejiang Province. Therefore, these results demonstrate the likely cost-effectiveness of the current vaccination program (see Table 6).

3.2. Sensitivity analysis

With varying parameters and assumptions, the main findings remained stable in the sensitivity analysis (Fig. 3). The results showed that the vaccine coverages, efficacy rates and incidence rates were among the most important parameters that can change the BCR. However, even at a low rate of each of these parameter, the BCR values were still over 1, which suggested that the results were robust to changes in the value of any single major variables.

4. Discussion

Cost-benefit and cost-effectiveness analyses were conducted in the present study on the current routine measles vaccination program for a birth cohort in Zhejiang Province. Our study showed that the two-dose strategy appears to be cost-effective and to offer substantial benefits. For every dollar spent on immunization, the program saves $6.06. The results of this analysis are consistent with previous studies conducted in China, although different assumptions and methodology used makes comparison difficult. Measles vaccination has been proven to be a significant cost-saving intervention in China, with BCRs from 2.96 to 61.75 [32–34]. The results of these previous studies varied greatly by provinces, mainly because none of these studies used mathematic models, or considered the variation in costs and effects measured.

Economic analyses of measles vaccination have been conducted in several countries and reported that such vaccination is highly cost-beneficial. A Japanese study using a static model involving

Table 6
Key vaccination program outcomes over a 40-year period.

	No vaccination	Current program
Program cost (million USD)	–	2.52
Illness cost (million USD)	85.90	10.01
Adverted illness cost (million USD)	–	75.90
NPV (million USD)	–	73.38
BCR	–	6.06
Number of measles infection	220,899	25,735
Number of measles deaths	216	25
Total number of case averted	–	195,165
Total number of death averted	–	191
Incremental cost-effectiveness ratio (ICER) per		
Case averted (USD)	–	12.91
Death averted (USD)	–	13,213.43
GDP Thresholds (for references)		
Cost-effective (3 times the GDP/per capita)	–	Yes

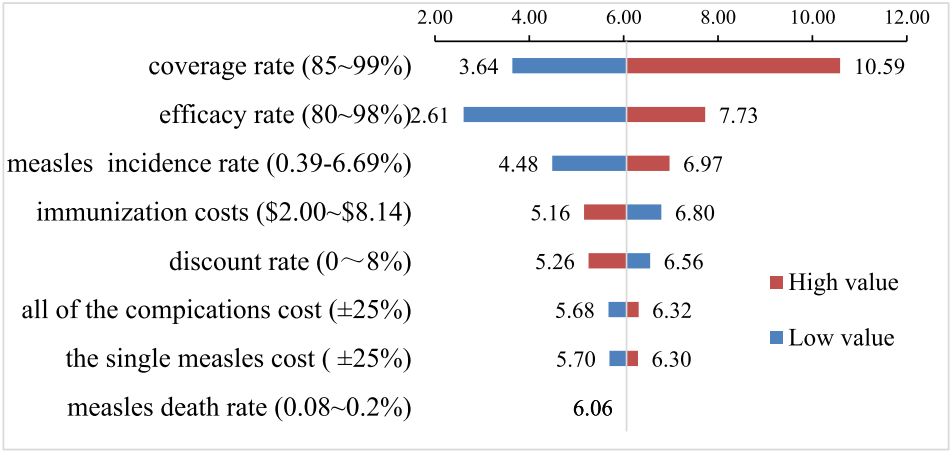

Fig. 3. Tornado diagram presenting one way sensitivity analyses.

one-dose vaccination found that the BCR was 2.48 and ranged from 2.21 to 4.97, according to sensitivity analyses [16]. In a Korean study, the BCR of the two-dose MMR keep-up program with MR catch-up is 1.27 [15]. A published study about a two-dose MMR vaccination program in the United States showed that the direct and societal BCR values were 14.2 and 26.0, respectively [18]. The discrepancy in the BCR for these studies suggests that parameter variations among studies could account for the disparity in the ratios. It is notable that treatment costs of measles complications and sequelae were considered in the present study, which may increase the total disease economic burden and lead to the BCR increase. In addition, the lower vaccination costs may also contribute to the BCR increase. The cost of completing measles immunization is $4.36 per child in Zhejiang Province, while this cost is $42.1 per child in Japan [16], and completing the MR and MMR program costs $70 in the United States [18].

We estimated that the cost per case and per death averted is $12.91 and $13,213.43, respectively. These costs were less than 3 times the GDP per capita for Zhejiang in the year 2014, suggesting that the current strategy would be cost-effective, which were supported by results from earlier studies. A study performed in Latin American and Caribbean countries showed that the vaccination strategy prevented a single case of measles at the cost of $71.75 and prevented a measles death at the cost of $15,000 [35]. Another published study reported that, in low and middle income countries that have not yet eliminated measles, the ICER was $20 to $25 per measles death averted [36]. A Ugandan study further revealed that the ICER was $20 to $58 per death averted [37].

The conclusions made in the present study were considered to be robust based on the results of the sensitivity analyses. The vaccine efficacy and vaccine coverage rate were the most important parameters that could affect the BCR. However, even in the worst-case scenario, the BCR was still over 1, suggesting that the vaccination strategy was always favorable relative to no vaccination. The sensitivity analyses also indicated that a higher vaccine coverage rate brings more significant benefits, which was also shown by a number of previous studies [17,36].

The findings of the present study are subject to several limitations. First, only recurrent costs were considered when estimating the immunization program cost, while capital costs, such as the cost of fixed assets and cold chain, were excluded. This may lead to underestimation of the total cost of vaccination. A study showed that cost of cold chain took 11.9% of the total immunization costs in Malawi, and it was the main component of the system cost [38]. However, the budget of cold chain is vague due to the special structure and obligation of the financial system in China. It is too difficult to distinguish the central and local government payments, and the actual costs may differ between areas, leading to the data being unavailable. Second, the economic disease burden as a result of measles complications and sequela was converted from research in other countries conducted in 1999 and 2001. However, health care costs have risen substantially since those analyses, which may underestimate the actual costs and affect the economic favorability of vaccination. Moreover, clinical evidence for the efficacy of vaccination in the model was adopted from studies carried out in other countries, although there are differences in vaccine strains, ethnicities and healthcare systems among different countries [39]. In addition, herd immunity was not considered in the present study. In reality, measles incidence would decrease gradually and the costs caused by measles epidemics could be significantly reduced when a birth cohort is vaccinated and herd immunity is increased [16]. Dynamic modeling might be considered as more realistic in capturing the impact of herd immunity [40]. However, it is difficult to collect data for dynamic analysis. Thus, we conducted static analysis using the best data that could be obtained. Finally, surveillance data was used for estimating the incidence of measles. However, surveillance data generally under-report cases, which may appear to underestimate the number of the measles cases in the no-vaccination program, resulting in an underestimation of BCR.

5. Conclusion

The current measles vaccination program is estimated to be cost-effective and to have a high BCR, which would offer substantial benefits. The economic analysis conducted in the present study would most likely play a critical role in justifying future investments to attain the goal of measles elimination.

6. Financial support

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Conflict of interest

The authors declare that they have no competing interests and there has been no significant financial support for this work that could have influenced its outcome.

Ethical approval

Ethical approval was obtained from the ethical review committee of the Zhejiang Provincial Center for Disease Control and Prevention. All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee, and with the 1964 Helsinki declaration and its later amendments, or comparable ethical standards.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.vaccine.2019.04.057.

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