A simple simulation model of tuberculosis epidemiology for use without large-scale computers

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A large-scale computer service is not always available in many countries with tuberculosis problems needing epidemiological analysis. To facilitate work in such countries, a simple epidemiological model was made to calculate annual trends in the prevalence and incidence of tuberculosis and its infection, in tuberculosis mortality, and in BCG coverage, using average parameter values not specific for age groups or birth year cohorts. To test its approximation capabilities and limits, the model was applied to epidemiological data from Japan, where sufficient information was available from repeated nation-wide sample surveys and national statistics. The approximation was found to be satisfactory within certain limits. The model is best used with a desk-top computer, but the calculations can be performed with a small calculator or even by hand.

Up-to-date epidemiological information is very desirable when planning a tuberculosis control programme to meet existing demands. However, planning often has to be based on old survey data, since it is not easy to repeat surveys even in countries that can afford it technically and financially. If the epidemiological time trend can be estimated using old data, the present status can also be estimated within certain limits. There must be cases when it is worth using such estimates and risking some errors rather than relying on old data, since the epidemiological situation is unlikely to be static for a long period in many countries.

There are various models for simulating the time trend of tuberculosis epidemiology, such as that of Waaler (1–4). For applying these models a large-scale computer service is needed, and such a service is often inaccessible in countries with a tuberculosis problem.

A simple model was made to enable calculations to be made without a large-scale computer. It was tried out on survey data from Japan, where information was sufficient both for the estimation of necessary parameter values and for a comparison of simulated with observed trends. The results were satisfactory within certain limits.

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For the sake of simplicity, the model was made to apply average parameter values of the population instead of being age, sex, and cohort specific. Also, the waning effect after infection and vaccination was ignored and no importance was attached to exogenous reinfection in the development of the disease.

DESCRIPTION OF THE MODEL

The present model is intended for a closed community, the population changing through births and deaths alone.

The total population is divided into three groups, namely *non-infected*, *BCG-vaccinated* and *TB-infected*. BCG-vaccinated includes a sub-group, *BCG-protected*. TB-infected includes a sub-group, *TB*, with a sub-sub-group, *TB-treated*. The population is continuously supplied with inflow from birth while losing a portion by outflow from its various components into death. The flow of the population between these categories is shown in Fig. 1.

The assumptions were made, for the sake of simplification, that protection remains constant after effective BCG vaccination given before tuberculosis infection, that healing occurs only in the TB-treated group (this assumes that the cure rate is roughly proportional to the size of the TB-treated group), and that the general death rate in each group is equal to that in the total population.

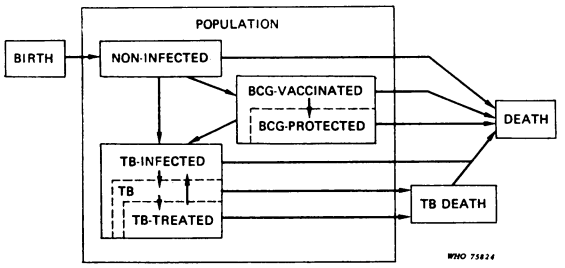

Fig. 1. Population flow between different categories of the epidemiology model.

The model consists of a set of 15 equations based on the flow chart of Fig. 1, as shown in Table 1. Equations 1–4 give, respectively, the one-year trend from year 0 to year 1 of the population size (POP), the number of TB-infected (INF), the number of BCG-vaccinated (BCG), and the number of tuberculosis cases (TB) by the balance between the annual number of births (B), annual number of deaths (D), primary infections (inf), primary vaccinations given in the non-infected group (bcg), tuberculosis deaths (TBD), tuberculosis cures (HEAL), and annual incidence (inc).

Equations 5–11 determine the value of each variable causing the above-mentioned trends. Equations 12–15 give, respectively, the annual trends of the regularity of tuberculosis treatment (REG), the treatment coverage in existing tuberculosis cases (COV), the birth rate, and the death rate.

It is assumed that the number of primary infections is proportional to that of non-treated tuberculosis cases and to the relative frequency of non-infected, non-BCG-protected persons in the population as expressed by equation 5; that the tuberculosis death rate is constant (T) in non-treated cases and also constant (T′) in the treated (equation 7); and that the tuberculosis incidence rate in the tuberculosis infected but not diseased population is constant (i) (equation 9). The total number of deaths in tuberculosis cases is approximated by the sum of tuberculosis deaths and the general death rate in equation 4. This is based on a study by Kihara (5) who revealed, by analysing data from nation-wide follow-up sample surveys in Japan, that the increase in the death rate among patients with tuberculosis compared with that of the general population was about equal to deaths from tuberculosis.

In Table 1, subscripts 0 and 1 indicate the values of year 0 and year 1, respectively. When the values of the variables at year 0 and the value of each constant are given, those at year 1 can be obtained by simple arithmetic. Thus the trend with those variables can be estimated for any given year, starting with a set of initial conditions, under an assumption that the conditions determining the value of those constants remain unchanged.

Table 1. Equations for the simulation model of tuberculosis epidemiology

$$POP_1 = POP_0 \cdot (1 - D_0 + B_0) \quad (1)$$

$$INF_1 = INF_0 \cdot (1 - D_0) + inf_0 \quad (2)$$

$$BCG_1 = BCG_0 \cdot (1 - D_0) + bcg_0 \quad (3)$$

$$TB_1 = TB_0 \cdot (1 - D_0) - TBD_0 - HEAL_0 + inc_0 \quad (4)$$

$$inf_0 = k \cdot (TB_0 - TR_0) \cdot (POP_0 - INF_0 - BCGP_0)/POP_0 \quad (5)$$

$$BCGP_0 = BCG_0 \cdot p \quad (6)$$

$$TBD_0 = (TB_0 - TR_0) \cdot T + TR_0 \cdot T' \quad (7)$$

$$HEAL_0 = TR_0 \cdot REG_0 \cdot C/2 \quad (8)$$

$$inc_0 = i \cdot (INF_0 - TB_0) \quad (9)$$

$$TR_0 = TB_0 \cdot COV_0 \quad (10)$$

$$bcg_0 = (POP_0 - BCG_0) \cdot (1 - D_0 + B_0) \cdot (1 - A) + BCG_0 \cdot B_0 \quad (11)$$

$$REG_1 = 1 - (1 - REG_0) \cdot f \quad (12)$$

$$COV_1 = COV_0 + (1 - COV_0) \cdot g \quad (13)$$

$$B_1 = B_0 \cdot b \quad (14)$$

$$D_1 = D_0 \cdot d \quad (15)$$

POP:	population size	B:	annual birth rate
INF:	number of TB-infected	D:	annual death rate
BCG:	number of BCG-vaccinated	k:	ratio of risk of infection to prevalence of non-treated TB cases
TB:	number of TB cases	T:	TB death rate in non-treated cases
BCGP:	number of BCG-protected	T′:	TB death rate in treated cases
inf:	number of primary infections	p:	protection effect of BCG vaccination
bcg:	number of primary vaccinations	C:	cure rate in regularly treated cases
TBD:	number of TB deaths	i:	TB incidence in infected non-TB population
HEAL:	number of cures	A:	annual decrease in prevalence of non-vaccinated
inc:	number of new TB cases	g:	annual decrease in prevalence of non-treated in TB cases
TR:	number of treated TB cases	f:	annual reduction coefficient of treatment irregularity
REG:	relative frequency of regular cases in the treated population	b:	annual rate of decrease in birth rate
COV:	treatment coverage	d:	annual rate of decrease in death rate

ESTIMATION OF INITIAL CONDITIONS AND PARAMETER VALUES

" Tuberculosis " was defined as bacteriologically confirmable pulmonary tuberculosis in the study, since tuberculosis prevalence as determined by X-ray is limited in its use as an epidemiological index; this is due to the inconsistency of the criterion for " active tuberculosis " and to the variability of prognosis and infectivity of " active tuberculosis ", caused by the changing distribution pattern of patients by type and extent of X-ray shadows.

The initial values in 1953 were estimated for the variables by the results of the national tuberculosis prevalence surveys and follow-up surveys made during 1953–1973 (6), since some of the values had to be estimated by applying the time trends revealed by the surveys. The estimates are given in Table 2.

The trend in the number of annual prmiary vaccinations is expressed by equation 11 so as to estimate the trend in the prevalence of BCG-vaccinated observed by the surveys under the influence of annual birth and death rates. The protection effect of BCG vaccination was set at 80% following the results of the BMRC trial (7).

Table 2. Initial conditions in 1953

Population	87.033 million
Annual birth rate	1.8370 %
Annual death rate	0.8273 %
Prevalence of non-infected	21.1 %
Prevalence of TB-infected	44.8 %
Prevalence of BCG-vaccinated	31.4 %
Prevalence of tuberculosis	0.7447 %
Treatment coverage in TB cases	20.76 %
Risk of infection	2.9 %
Incidence of tuberculosis	0.05 %
TB mortality in non-treated cases	10.15 %
TB mortality in treated cases	6.30 %
BCG primary vaccinations	1.9175 million
Annual reduction rates:	
treatment irregularity	11 %
non-treated/TB cases	2.8 %
birth rate	0.0930 %
death rate	1.2787 %

The trend in the population of the country was estimated by applying the birth and death rates for 1953 (1.837% and 0.827%, respectively) to the initial population of 87.033 million given by the 1953 national statistics, and decreasing by annual rates of 0.093% and 1.2787%, respectively.

Further, the initial value of treatment regularity was set at 60%, with irregularity decreasing annually by a rate of 11%, with 99% of regularly-treated cases being cured every year. The number of cases cured annually is calculated with equation 8, assuming that about half of the cases under treatment begins treatment each year, that one year of treatment is required to cure the majority of cases, and that in the majority of cases the effect of more than one year of treatment is negligible. In the calculation, the overall effect of the treatment was simulated so that the annual cure rate in treated cases increased from 29.7% in 1953 to 47.57% in 1973 with a gradually falling rate of increase.

COMPARISON OF THE SIMULATED AND OBSERVED TRENDS

Table 3 gives the simulated 20-year trends for the period 1953–1973 for population size, tuberculosis prevalence, tuberculosis mortality rate, prevalence of tuberculosis infection, BCG vaccination coverage in the population, and treatment coverage in tuberculosis cases, and compares them with data obtained from the national statistics and the national prevalence surveys. The simulated population size tends to be a little larger in later years, but the approximation is considered good enough for calculations with this simple model.

The simulated tuberculosis mortality rate is compared with that for all types of tuberculosis given by the national statistics, ignoring a slight difference caused by extrapulmonary tuberculosis deaths included in the latter. As is also shown in Fig. 2, the yearly trend is estimated quite well by the simulation, the difference remaining between 1.1 and 6.1 per 100 000 since 1957.

The simulated prevalence of tuberculosis infection is compared with the prevalence of non-vaccinated tuberculin-positive reactors estimated by the national surveys. The simulation values are slightly higher than the survey data but the difference is below 2.5%. This is due to 20% of the vaccinated population being treated as non-protected in the simulation. The simulation of BCG vaccination coverage is slightly higher than the survey data, the

Table 3. Comparison of the simulation results with observed estimates

Year	Population (millions)		TB prevalence (per 1 000)		TB mortality (per 100 000)		Prevalence of TB infection (%)		BCG coverage (%)		Treatment coverage (%)	
	observed	simulated	observed	simulated	observed	simulated	observed	simulated	observed	simulated	observed	simulated
1953	87.033	87.033	7.447	7.447	66.5	69.6	44.8	44.80	34.1	34.20		20.76
1954	88.293	87.911		6.662	62.4	61.7		44.78		35.75		22.98
1955[a]	89.275	88.807		5.942	52.3	54.5		44.63		37.28		25.14
1956	90.259	89.719		5.289	48.6	48.1		44.37		38.76		27.25
1957	91.088	90.648		4.702	46.9	42.4		44.03		40.21		29.29
1958	92.010	91.595	5.616	4.181	39.4	37.4	42.0	43.62	38.2	41.63	31.3	31.27
1959	92.971	92.559		3.723	35.5	33.0		43.15		43.01		33.20
1960[a]	93.418	93.541		3.324	34.2	29.2		42.64		44.36		35.08
1961	94.285	94.541		2.979	29.6	26.0		42.10		45.68		36.90
1962	95.178	95.560		2.684	29.3	23.2		41.54		46.96		38.67
1963	96.156	96.596	1.914	2.432	24.2	20.9	38.5	40.95	47.1	48.22	40.4	40.39
1964	97.186	97.652		2.217	23.6	18.9		40.36		49.45		42.07
1965[a]	98.274	98.726		2.035	22.8	17.2		39.76		50.64		43.69
1966	99.056	99.820		1.879	20.3	15.8		39.16		51.81		45.27
1967	99.637	100.933		1.747	17.8	14.5		38.55		52.96		46.81
1968	100.794	102.066	0.924	1.633	16.8	13.5	35.6	37.94	52.9	54.07	48.3	48.30
1969	102.022	103.218		1.534	16.1	12.6		37.34		55.16		49.75
1970[a]	102.736	104.392		1.449	15.5	11.8		36.74		56.22		51.16
1971	104.345	105.585		1.373	13.0	11.1		36.15		57.26		52.54
1972	105.742	106.800		1.307	11.9	10.5		35.56		58.27		53.87
1973	108.079	108.035	1.203	1.247	11.1	10.0		34.98	58.5	59.26	44.4	55.16

[a] Census year.

difference being about 1% except in 1958 when it was 3.4%.

Treatment coverage is very well approximated by the simulation up to 1968, but it is higher than the survey value by almost 11% in 1973, when coverage by the survey drops suddenly. This may be due to random fluctuation owing to too small a sample size: coverage was estimated in the survey in only 59 patients with infectious tuberculosis.

Simulated tuberculosis prevalence shows some difference from the survey data as shown in Fig. 3, the difference being between 0.004% and 0.144%. The "observed values" of tuberculosis prevalence are actually estimates calculated from the weighted average of the bacteriology-positive rate in various categories of X-ray finding. Owing to the low prevalence, the standard error had to be relatively large, ranging between 6% and 20% of the estimate in the surveys. Furthermore, the estimate of tuberculosis prevalence in 1958 was based on 334 positive cases detected, among which 22 out of 308 examined strains were non-tuberculosis acid-fast bacilli. Concerning the 1963 and 1968 prevalence rates, laryngeal swabs were mainly used instead of sputum specimens for bacteriological examinations in these two survey years; this is suspected to have resulted in a lower positive rate. Taking into consideration the above-mentioned discrepancies the simulation may be considered satisfactory.

Tuberculosis incidence was estimated at 0.05%,

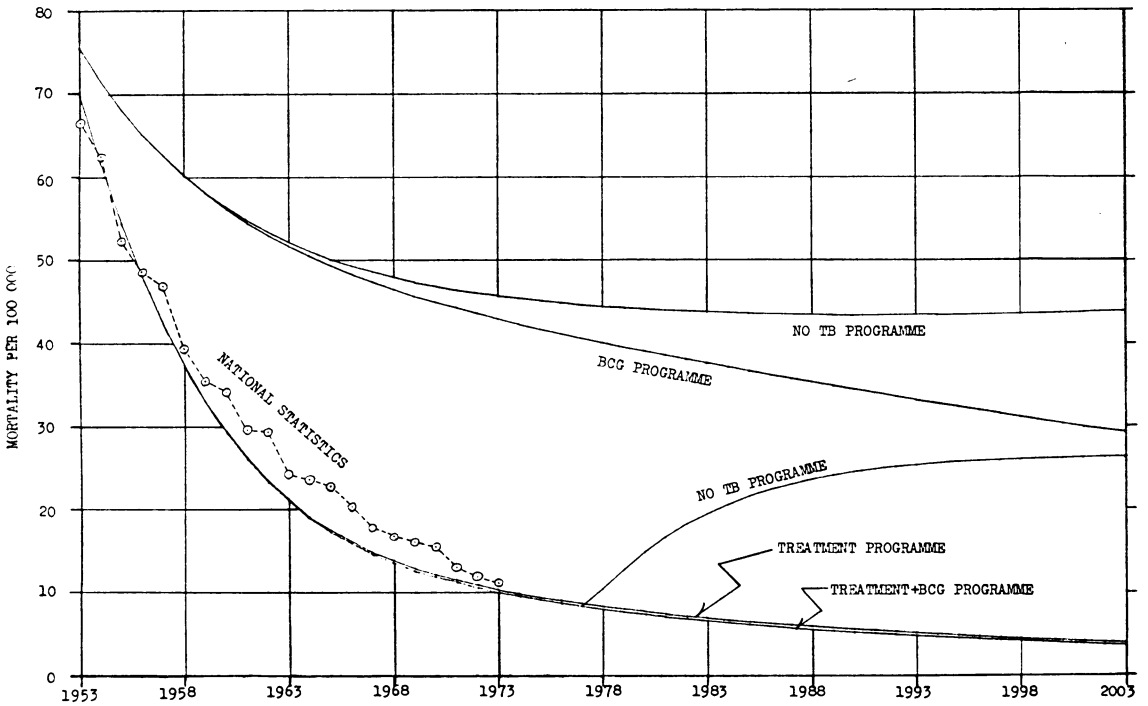

Fig. 2. Trend of tuberculosis mortality by simulation with various schemes.

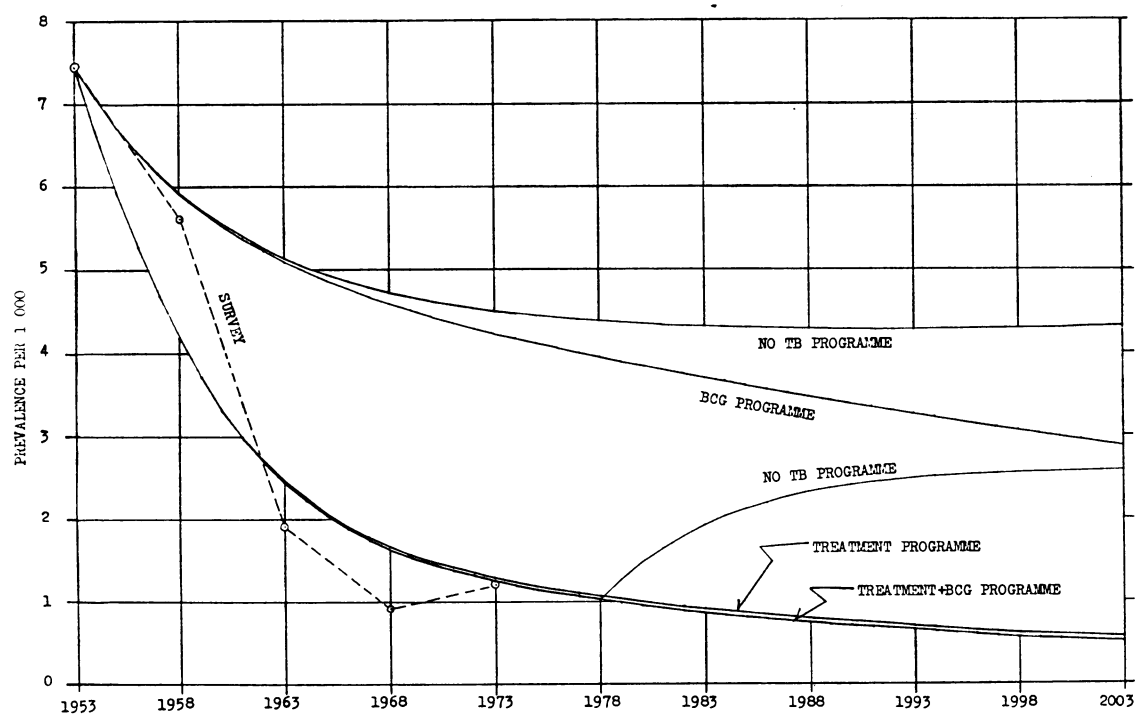

Fig. 3. Trend of tuberculosis prevalence by simulation with various schemes.

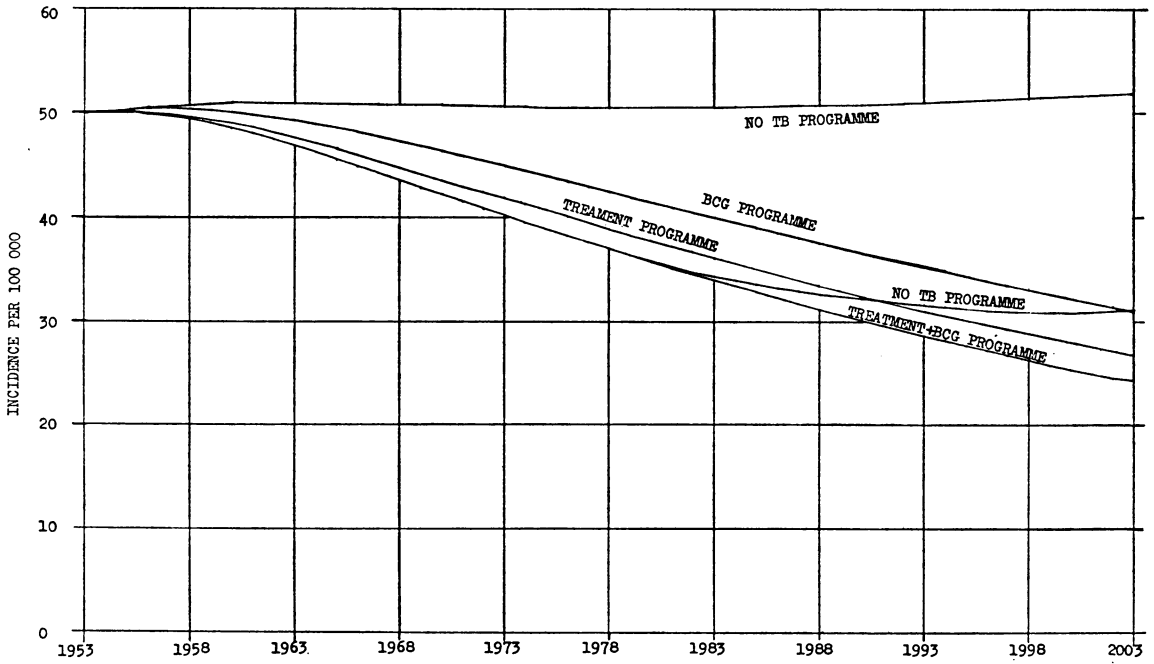

Fig. 4. Trend of tuberculosis incidence by simulation with various schemes.

0.03%, and 0.02% per year, respectively, for 1953/54, 1958/59 and 1963/64 by the one-year follow-up surveys. As these were estimated from a few cases occurring in a sample population of about 20 000, it may be concluded only that there was a declining trend in tuberculosis incidence during the period from an initial value of about 0.05% in a range of the same order. In the simulation, incidence declines gradually from 0.05% in 1953 to 0.04% in 1973, as shown by the lowest curve in Fig. 4.

Thus, the model was found suitable for the simulation of epidemiological trends in tuberculosis, at least in respect of data from Japan.

After the model was found usable, it was further evaluated on the effect of the national tuberculosis control programme by inserting a few more items into the calculation programme to reveal the cumulative sum of annual workloads of BCG vaccination and treatment.

ESTIMATION OF EPIDEMIOLOGICAL EFFECT OF TUBERCULOSIS PROGRAMME

The epidemiological trend resulting from no tuberculosis programme was calculated by entering zero values for BCG vaccination and treatment in

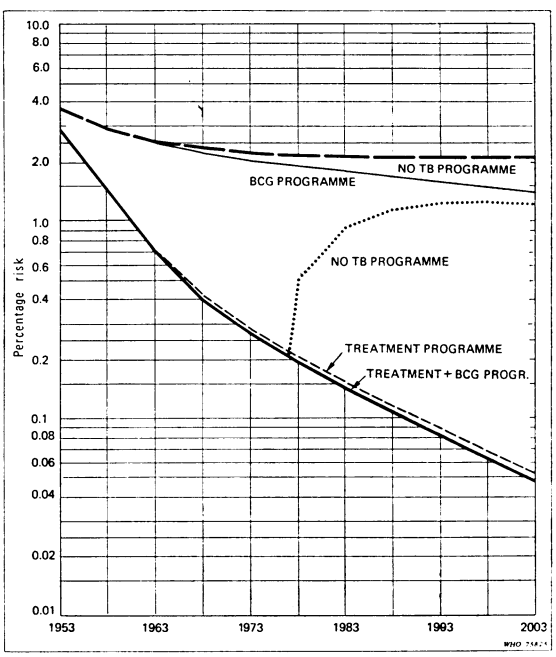

Fig. 5. Trend of annual risk of tuberculosis infection by simulation with various schemes.

the simulation model, with all other initial conditions and parameter values unchanged, as shown by the curve *No TB programme* in Fig. 2–5; the trend of the national tuberculosis programme is given by the curve *Treatment + BCG programme*. Reduction in the tuberculosis problem is indicated by the area between those two curves in the figures. In this case the " time-perspective " as discussed by Waaler & Piot (4) was not taken into account for the sake of simplicity. The trends resulting from no tuberculosis programme include the remaining effects of the tuberculosis programme carried out before 1953.

The cumulative sums of tuberculosis case-years, tuberculosis deaths, and new tuberculosis cases are given in Table 4 for periods of 25 and 50 years from 1953. The problem reduction rate is expressed as the percentage decrease compared with no tuberculosis programme. The epidemiological effect of the national tuberculosis programme in Japan was thus estimated with problem reduction rates of 46.5%, 13.0%, and 55.6%, respectively, for case-years, new cases, and tuberculosis deaths for the 25-year period from 1953.

Also given in Fig. 2–5 are the trends for treatment alone from 1953, for BCG alone from 1953, and for stopping the national programme of BCG and treatment in 1978. As shown by these figures, the treatment programme has a remarkable effect on tuberculosis mortality and prevalence, and also on the risk of infection, owing to its rapid effect. As regards incidence, the effect of BCG vaccination is largely due to the long-term replacement of the infected population with the vaccinated population. The effect of the combined programme is smaller than the sum of the two owing to some overlapping of effects.

An estimated 2.397 million treatment-years and 52.114 million primary BCG vaccinations are needed

Table 4. Tuberculosis problem reduction rate by various schemes

	1953-1978		1953-2003	
	cumulative sum (million)	problem reduction (%)	cumulative sum (million)	problem reduction (%)
Tuberculosis cases				
no TB programme	12.858	—	27.290	—
national TB programme (treatment + BCG)	6.882	46.47	9.665	64.58
treatment alone	6.959	45.87	9.941	63.57
BCG alone	12.499	2.79	23.761	12.93
no programme after 1978	6.882	46.47	14.493	46.89
Tuberculosis deaths				
no TB programme	1.312	—	2.768	—
national TB programme (treatment + BCG)	0.582	55.59	0.759	72.56
treatment alone	0.588	55.18	0.777	71.91
BCG alone	1.278	2.58	2.421	12.52
no programme after 1978	0.582	55.59	1.340	51.57
Tuberculosis incidence				
no TB programme	1.259	—	2.962	—
national TB programme (treatment + BCG)	1.095	12.96	2.081	29.74
treatment alone	1.122	10.86	2.183	26.29
BCG alone	1.172	6.84	2.373	19.89
no programme after 1978	1.095	12.96	2.178	26.45

Table 5. The efficiency of treatment and BCG vaccination programmes in tuberculosis problem reduction

	Reductions:				No. of vaccinations equivalent to one treatment-year	
	per 100 treatment-years		per 100 vaccinations			
	1953–1978	1953–2003	1953–1978	1953–2003	1953–1978	1953–2003
TB-years	242.75	408.30	0.68	3.02	352	135
TB deaths	29.79	46.85	0.06	0.29	457	157
TB incidence	5.63	18.33	0.16	0.50	34	36

to achieve the above-mentioned effects during the 25 years from 1953, excluding revaccination and treatment of non-bacillary patients. The efficiency of the BCG programme and that of the treatment programme in the country may be estimated by dividing the problem reduction by the total workload required for each programme. As shown in Table 5, the efficiency of a single programme is calculated for 1953–1978 as 242.8 case-years, 29.8 tuberculosis deaths, and 5.6 new tuberculosis cases prevented per 100 treatment-years, and 0.7 case-years, 0.1 tuberculosis deaths, and 0.2 new cases prevented per 100 primary BCG vaccinations. This means that, in the prevention of case-years, tuberculosis deaths, and new cases 352, 457, and 34 primary vaccinations, respectively, were equivalent to one treatment-year. It is evident that the efficiency of BCG vaccination in public health is, despite its slow effect, very remarkable, particularly when the cost per vaccination is considered, which in Japan is about 0.05% of the cost of one year of treatment.

PROJECTION OF FUTURE TRENDS IN TUBERCULOSIS EPIDEMIOLOGY

Simulation was made for a further 25-year period from 1978 as already mentioned, assuming unchanged conditions, to determine parameter values and trends of treatment coverage and BCG vaccinations (Fig. 2–5).

In the simulation tuberculosis prevalence and mortality continue to decline but more slowly, decreasing to 1/7 and 1/10, respectively, in the first 25 years from 1953, whereas both fell to only 1/2 in the following 25 years. Tuberculosis incidence, however, does not show such a marked slowing down, decreasing to about 7/10 of its initial value throughout the 50 years. Accordingly, the problem reduction rate over the full 50 years is 2.3 times that in the first 25 years in the case of tuberculosis incidence, 1.4 times as regards case-years, and 1.3 times as regards tuberculosis deaths. As shown in Fig. 5, the risk of infection declines at a decreasing rate and is thus not linear on the semilogarithmic scale. The risk is reduced to 1/15 of its 1953 value in the first 25 years, but only to 1/4 of its 1978 value in the second 25 years.

A further simulation was tried to see what would happen if all tuberculosis programme activities cease in 1978. Prevalence, mortality, incidence, and risk of infection would increase rapidly, leaving only the after-effect of the BCG programme. The situation would regress 10 years in 5 years and 15 years in 10 years, approaching the trend of the BCG programme alone in 25 years.

The tuberculosis prevalence and mortality rates have been declining rapidly since 1953 in Japan, and have begun to show a deceleration in recent years. This might give the impression that the reduction in the problem brought about by the national tuberculosis programme is approaching its limit and that the declining trend would continue even were the tuberculosis programme to be ended. However, the above-mentioned simulation results suggest that the tuberculosis problem would deteriorate should the programme be abandoned.

A spontaneous reduction in the tuberculosis problem can occur without tuberculosis programmes, since the trend is determined by the balance between incidence, death, and healing which can be affected by various factors other than tuberculosis control measures, even by a sudden change in the trend of population growth. The results of this simulation indicate that conditions are not yet favourable enough to allow the trend to continue without programmes and that the present trend in Japan is

being maintained by the pressure of the national tuberculosis programme.

DISCUSSION

The model described was found suitable, insofar as it has been tested on the data from the nation-wide sample surveys of tuberculosis prevalence in Japan, for estimating the time trend of tuberculosis epidemiology and also future trends based on a number of assumptions.

Each step of the calculation is simple. The epidemiological indexes can be calculated for successive points in time with a given time interval, depending on the unit of time used.

The stepwise calculation can be made with a simple calculator or even by hand. A calculation table can easily be made with several lines for calculations and a column for each year or unit of time. If a desk-top computer is available with a minimum capacity of about 50 words of memory and about 500 programme steps the simulation can be made very easily with a programme formulated by breaking down and rearranging the equations in Table 1 in accordance with the machine's characteristics.

The only problem with the model is the collection of information for supplying the model with the initial conditions and parameter values listed in the lower part of Table 1. Of these the annual trends of BCG and treatment coverages, birth and death rates, and treatment regularity can be expressed differently according to the country's available information. Tuberculosis death rates in treated and non-treated cases can be estimated if the annual tuberculosis death rate, the tuberculosis prevalence, and the treatment coverage are available for a number of years. A follow-up study of treated cases would give useful information on this, and for the estimation of the cure rate as well. Some of the parameter values may need to be based on assumptions, but these could be adjusted by trial simulation.

As already mentioned, age- or cohort-specific parameter values are not used in the present model. However, it has been observed in various countries that the overall pattern of tuberculosis is changing, together with its age- and cohort-specific patterns. This may result in changes in some of the parameter values used in the present model, such as incidence in the infected population, and particularly in the tuberculosis death rate. Therefore, when the model is applied to a fairly long-term trend it should be carefully checked by comparing, for instance, simulated tuberculosis mortality with the reported value, to see whether the parameter values are deviating too much and are resulting in unrealistic estimates.

RÉSUMÉ

MODÈLE SIMPLE POUR LA SIMULATION DE L'ÉPIDÉMIOLOGIE DE LA TUBERCULOSE UTILISABLE SANS GROS ORDINATEUR

Un modèle simple pour la simulation de l'évolution épidémiologique de la tuberculose, utilisable sans gros ordinateur, a été construit. Pour des raisons de simplicité, il est conçu pour s'appliquer à des valeurs paramétriques moyennes de la population, et non à tel et tel groupe d'âge, sexe ou cohorte. Il n'a d'autre part pas été tenu compte de l'atténuation possible avec le temps des effets de la vaccination par le BCG et de l'infection tuberculeuse.

Le modèle a été testé sur des données démographiques et épidémiologiques provenant du Japon, où des enquêtes nationales par sondage sur la prévalence de la tuberculose ont été faites tous les cinq ans de 1953 à 1973, et où l'on dispose de renseignements suffisants sur la population et sur la mortalité tuberculeuse. Les tendances simulées ont été comparées à celles qui avaient été déterminées d'après les statistiques et les enquêtes nationales en ce qui concerne: l'effectif de la population; la mortalité, la prévalence et l'incidence tuberculeuses; la prévalence de l'infection; le risque d'infection; et la couverture de la vaccination par le BCG et du traitement antituberculeux. La concordance s'est révélée satisfaisante dans certaines limites. Le modèle a d'autre part été utilisé pour évaluer l'efficacité du programme national de lutte contre la tuberculose et pour établir une projection des tendances épidémiologiques futures.

Le modèle est utilisable avec un ordinateur de bureau ayant une mémoire minimale d'environ 50 mots et permettant quelque 500 phases de calcul. Les calculs peuvent également être opérés au moyen d'un petit calculateur, voire à la main.

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