Strategies to Decrease Tuberculosis in US Homeless Populations
A Computer Simulation Model

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Since 1992, tuberculosis (TB) cases have decreased consistently in the United States. In 1998, the US case rate reached a record low of 6.8/100,000 population.1 Despite this tremendous public health achievement, homeless individuals in the United States remain at high risk for TB.2-4

Most studies of TB among homeless persons have focused on chronically homeless individuals or those who use homeless shelters.5-6 These individuals have rates of active TB that may be more than 20 times those of the US general population between the ages of 25 and 44 years.3 In one cross-sectional study7 of individuals using homeless shelters in Birmingham, Ala, 3.1% of residents had undiagnosed active TB. The prevalence of latent TB infection in the homeless population has been reported to be as high as 40%7 to 67%.8 Numerous TB outbreaks have been documented among homeless persons.9-10 Molecular epidemiologic studies have shown that as much as 53% to 71% of active TB cases among homeless people living in urban areas are linked by restriction-fragment-length-polymorphism analysis, suggesting that these cases were caused by recent transmission.11,12 Overall, approximately 6.3% of all US TB cases in 1998 occurred among individuals who had been homeless in the previous 12 months.2

Homeless individuals in shelters also have high rates of substance abuse and

Context The rate of tuberculosis (TB) among US homeless persons may be 20 times that of the general adult population. Studies suggest that the majority of urban homeless TB cases are attributable to ongoing transmission of TB. Optimal TB-control strategies in both chronically and transiently homeless populations are not known.

Objective To examine the effects of TB-control strategies on projected TB cases and deaths in US homeless populations using a computer-based simulation model.

Design, Setting, and Population The US general population and a theoretical population of 2 million homeless individuals in 1995 were divided into 18 clinical states based on the risk for or presence of TB and human immunodeficiency virus (HIV) infection in a semi-Markov model.

Main Outcome Measures Prevalence of transiently and chronically homeless individuals with active TB and deaths from TB as a function of public health measures taken to control and eliminate TB, including improvement of treatment effectiveness, improvement in access to treatment, and vaccination with BCG.

Results A 10% increase in access to treatment among homeless persons with active TB produced larger declines in predicted TB cases and deaths after 10 years (cases and deaths among chronically homeless persons decreased 12.5% and 19.8% and among transiently homeless persons dropped 35.9% and 32.4%, respectively) than improvements in the effectiveness of treatment programs (cases and deaths among chronically homeless persons declined 7.2% and 3.1% and among transiently homeless persons dropped 10.9% and 4.1%, respectively). A 10% increase in access to treatment among homeless persons with latent TB infection led to a 6.7% decline in TB among chronically homeless persons and a 5.7% decline among transiently homeless persons, while a 10% improvement in effectiveness of treatment programs for latent TB infection was associated with declines of 3.0% and 3.3%, respectively. When treatment for latent TB infection was modeled to be the same in vaccinated and nonvaccinated populations, BCG vaccination led to TB case declines of 15.4% and 21.5% in chronically and transiently homeless populations, respectively.

Conclusions Overcoming barriers faced by homeless individuals in accessing TB treatment programs will be crucial to reducing the burden of TB in this high-risk group. Increased treatment access, improvement in the effectiveness of treatment programs, and BCG vaccination of HIV-negative homeless individuals have the best chance to markedly decrease TB morbidity and mortality.

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infection with human immunodeficiency virus (HIV), both of which are factors associated with TB. Despite their excessive risks for TB, however, the prevention and treatment of this disease in homeless individuals are difficult. Homeless individuals are hard to reach to evaluate tuberculin skin tests, even in the setting of an outbreak. They are less likely to complete treatment for active TB or latent TB infection than nonhomeless individuals, even when treatment is given by direct observation. Homeless individuals are less likely to seek health care, which may contribute to their subsequent development of TB and transmission to others. For these and other reasons, the overall mortality rate among homeless persons is approximately 4 times that for the nonhomeless population.

Although TB studies have focused on individuals who use shelters, there is a large population of individuals who are recently or transiently homeless and who may not be in shelters; a substantial part of this population comprises women and children. There are few data on TB risks and rates in recently or transiently homeless individuals. In contrast, chronically homeless individuals are more frequently adult males with a past or current history of substance abuse. The optimal TB control strategies for both populations are unknown.

New recommendations for the elimination of TB in the United States from the Centers for Disease Control and Prevention (CDC) and the Advisory Council for the Elimination of Tuberculosis call for tailored programs to address TB in high-incidence groups. We used computer simulation modeling to evaluate strategies to reduce TB cases and deaths among chronically and transiently homeless populations in the United States. These simulations look at whether recommendations for TB control should differ between the homeless and the general populations.

METHODS

We used a computer simulation model to follow the US population for 10 years and projected the impact of alternative control measures on morbidity and mortality from TB in homeless individuals. The model is based on an adaptation of a semi-Markov process for simulating TB epidemiology previously described. The model runs in a spreadsheet program (Microsoft Excel, Redmond, Wash).

The model starts with the US general population in 1995 and a theoretical cohort of 2 million homeless individuals. Research shows that millions of Americans experience homelessness, yet most do not remain chronically homeless. Therefore, the homeless cohort is further divided at the beginning of the 10-year period into a population of 275,000 chronically homeless individuals at high risk for TB, HIV, and substance abuse and a transiently homeless population of 1,725,000 at lower risk for HIV and TB. Each year, 10% of the chronically homeless population moves back into the transiently homeless population and 10% of the transiently homeless population becomes chronically homeless. Thirty percent of the transiently homeless population moves back into the US general population each year. They are replaced by an equivalent number from the US general population.

Each population is subdivided into 18 nonoverlapping, completely exhaustive clinical states (Markov states) based on TB and HIV status. The states are linked by transition equations developed from decision trees. These equations determine the likelihood that individuals retain a certain disease status, for example, HIV and TB uninfected, or move to another during a particular period. In this model, we used the conservative assumption that individuals successfully treated for TB infection or active TB have the same risk for new TB infections as the general population.

The Markov states and transition equations together make up 1 period. This structure is reproduced to allow for 10 periods of observation of selected outcomes. In all analyses, 1 period equals 1 year. The measured outcomes are the prevalence of transiently and chronically homeless individuals with active TB and deaths from TB as a function of the public health measures taken to control and to eliminate TB.

To assess the impact of different interventions to control TB in homeless populations, a series of strategies are introduced singly and in combination to the US general population, the total homeless population, or only the transiently or the chronically homeless populations. The interventions include relative increases in the percentage of individuals with active TB who access treatment, in TB treatment effectiveness, in the proportion of tuberculin-positive individuals who access treatment for latent TB infection, and in the effectiveness of treatment for latent TB infection, and introducing BCG vaccination.

In the analyses that increase the rate at which individuals access treatment for latent infection or active TB, there is a 10% improvement in the average rate populations start treatment. Treatment effectiveness for active disease is enhanced by a 10% improvement in the cure rate of TB patients, a 10% decrease in the TB mortality rate, a 10% reduction in the risk of relapse with active TB, and a 10% lowering in the proportion of treated patients with ongoing active TB. Treatment effectiveness of latent infection is improved by a 10% decrease in the probability of active TB after treatment of latent TB. BCG is assessed by the annual vaccination of 10% of the non–HIV-infected, tuberculin-negative, BCG-naïve population. In the baseline BCG analyses, only 1% of BCG-vaccinated individuals ever receive treatment for latent TB infection regardless of their indication. Except for BCG, all interventions were repeated using 5% and 20% relative changes to look for threshold effects and to assess the robustness of the results. In the BCG simulations, 5% or 20% of the BCG-eligible population was vaccinated each year.

Published literature was used to estimate the initial percentage of home-
Table 1. Initial Percentage of the Theoretical Homeless Cohorts in Each Markov State Based on HIV and TB Status*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Transiently Homeless Population, %</th>
<th>Chronically Homeless Population, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIV</td>
<td>Seronegative</td>
<td>Seropositive</td>
</tr>
<tr>
<td>No known Mycobacterium tuberculosis infection</td>
<td>85.4</td>
<td>4.0</td>
</tr>
<tr>
<td>High risk for active TB†</td>
<td>1.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Low risk for active TB‡</td>
<td>8.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Drug-sensitive active TB</td>
<td>0.01</td>
<td>. . .§</td>
</tr>
<tr>
<td>Drug-resistant active TB</td>
<td>0.0003</td>
<td>. . .§</td>
</tr>
</tbody>
</table>

*HIV indicates human immunodeficiency virus; TB, tuberculosis; and AIDS, acquired immunodeficiency syndrome.
†Risk attributable to recent M tuberculosis infection or partially treated active TB.
‡Risk attributable to long-standing M tuberculosis infection or partially completed treatment of latent TB infection.
§Ellipses indicate that individuals with HIV infection and active TB have AIDS according to the 1993 Centers for Disease Control and Prevention definition.

Strategies Targeting Persons With Active TB

For homeless individuals with active TB, increasing access to treatment was the most effective single intervention for reducing future TB cases and deaths. A 10% relative increase in the number of chronically homeless individuals with active TB who access treatment each year produced a 12.5% decline in future TB cases in this population after 10 years compared with the number expected without this intervention. Predicted TB deaths declined 19.8% compared with the baseline. In contrast, a 10% relative improvement in the effectiveness of treatment for active TB among chronically homeless individuals produced smaller declines in predicted TB cases and deaths compared with baseline projections (Table 3).

A 5% increase in access to active TB treatment in chronically homeless individuals was associated with a 6.5% decline in future TB cases, while a 20% increase in access to TB treatment reduced future TB cases by 23.7%

RESULTS

The initial population estimates and risks were matched to 1995 US TB data. In the baseline simulations, the model predicted 1341 TB deaths in year 1, 1252 in year 2, and 1116 in year 3. These results are within an absolute 5% of the annual number of TB deaths reported by the CDC for 1995 through 1997. In 1996 and 1997, 6.5% of reported TB cases were among individuals who had been homeless in the previous 12 months; for the corresponding years, the model predicted 6.3% and 6.5% of TB cases among the chronically homeless population.

The robustness of the predicted impact of interventions was further assessed by varying all transition probabilities simultaneously over defined ranges in sensitivity analyses. The model was run 500 times using Latin Hypercube Sampling50-52 (Decisioneering Crystal Ball, Denver, Colo) to create projected distributions for each baseline outcome. The transition probabilities corresponding to a single intervention or a combination of interventions were adjusted and the model was rerun 500 times using the same method to generate a new set of projected TB cases and deaths. The projected TB cases and deaths without and with the intervention for the middle 99% of runs were compared.

Whenever possible, ranges used in the sensitivity analyses were chosen from the literature. Quality of parameter estimates was assessed by examining original published research studies; sample size, study design, reliability, validity, and generalizability were all taken into account. In some cases, the best parameter estimates were found close to the high or low end of the range used for the sensitivity analysis. When there were limited data to construct ranges, probabilities below .50 were routinely varied by 50%. Probabilities greater than .50 were varied by 10%. Ranges were occasionally truncated to maintain biological and epidemiological plausibility.
clined 10% or 38.8%, depending on whether access to TB treatment was increased by 5% or 20%.

For transiently homeless patients with active TB, relative increases in access to treatment also were more effective in reducing future cases and deaths than the same relative improvements in the effectiveness of TB treatment (Table 3). As

### Table 2. Baseline Annual Rates and Ranges for TB Strategies per 10,000 Population

<table>
<thead>
<tr>
<th>Description of Probability</th>
<th>HIV</th>
<th>Seronegative</th>
<th>Seropositive†</th>
<th>AIDS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active TB‡</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>0.5 (0.25-0.75)</td>
<td>9 (5-12.5)</td>
<td>9 (5-12.5)</td>
<td></td>
</tr>
<tr>
<td>Transiently homeless population</td>
<td>1 (0.5-1.5)</td>
<td>9 (6-15)</td>
<td>9 (6-15)</td>
<td></td>
</tr>
<tr>
<td>Chronically homeless population</td>
<td>2 (1-3)</td>
<td>9 (6-17)</td>
<td>9 (6-17)</td>
<td></td>
</tr>
<tr>
<td>Recent tuberculin converters (&lt;2 y)</td>
<td>138 (69-300)</td>
<td>540 (450-810)</td>
<td>3700 (2000-3900)</td>
<td></td>
</tr>
<tr>
<td>Latent <em>Mycobacterium tuberculosis</em> infection (&lt;2 y)</td>
<td>7.3 (3.7-10)</td>
<td>450 (225-540)</td>
<td>1610 (805-2000)</td>
<td></td>
</tr>
<tr>
<td><strong>Annual risk of <em>M tuberculosis</em> infection‡</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>1.8 (0.9-2.7)</td>
<td>3.6 (1.8-5.4)</td>
<td>3.6 (1.8-5.4)</td>
<td></td>
</tr>
<tr>
<td>Transiently homeless population</td>
<td>20 (10-30)</td>
<td>30 (15-45)</td>
<td>30 (15-45)</td>
<td></td>
</tr>
<tr>
<td>Chronically homeless population</td>
<td>200 (100-600)</td>
<td>200 (100-300)</td>
<td>200 (100-300)</td>
<td></td>
</tr>
<tr>
<td><strong>Likelihood of multiple drug resistance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recently acquired TB</td>
<td>180 (0-360)</td>
<td>. . .</td>
<td>970 (180-1600)</td>
<td></td>
</tr>
<tr>
<td>Reactivated TB</td>
<td>80 (0-110)</td>
<td>. . .</td>
<td>80 (40-110)</td>
<td></td>
</tr>
<tr>
<td><strong>TB mortality in treated multiple drug-resistant TB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>200 (120-400)</td>
<td>. . .</td>
<td>1500 (800-2200)</td>
<td></td>
</tr>
<tr>
<td>Transiently homeless population</td>
<td>200 (120-400)</td>
<td>. . .</td>
<td>1500 (800-2200)</td>
<td></td>
</tr>
<tr>
<td>Chronically homeless population</td>
<td>200 (120-400)</td>
<td>. . .</td>
<td>2800 (1800-3800)</td>
<td></td>
</tr>
<tr>
<td><strong>TB mortality in treated drug-sensitive TB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>88 (60-120)</td>
<td>. . .</td>
<td>600 (300-900)</td>
<td></td>
</tr>
<tr>
<td>Transiently homeless population</td>
<td>88 (60-120)</td>
<td>. . .</td>
<td>600 (300-900)</td>
<td></td>
</tr>
<tr>
<td>Chronically homeless population</td>
<td>88 (60-100)</td>
<td>. . .</td>
<td>600 (300-1500)</td>
<td></td>
</tr>
<tr>
<td><strong>Ongoing TB despite treatment for multiple drug-resistant TB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>200 (0-400)</td>
<td>. . .</td>
<td>100 (0-200)</td>
<td></td>
</tr>
<tr>
<td>Transiently homeless population</td>
<td>900 (450-1350)</td>
<td>. . .</td>
<td>100 (0-500)</td>
<td></td>
</tr>
<tr>
<td>Chronically homeless population</td>
<td>1600 (1350-2000)</td>
<td>. . .</td>
<td>100 (0-1000)</td>
<td></td>
</tr>
<tr>
<td><strong>Drug-resistant TB after treatment for drug-sensitive TB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>5 § (2.5-7.5)</td>
<td>. . .</td>
<td>10 (7.5-15)</td>
<td></td>
</tr>
<tr>
<td>Transiently homeless population</td>
<td>62.5 § (7.5-90)</td>
<td>. . .</td>
<td>10 (7.5-20)</td>
<td></td>
</tr>
<tr>
<td>Chronically homeless population</td>
<td>120 § (90-150)</td>
<td>. . .</td>
<td>10 (7.5-15)</td>
<td></td>
</tr>
<tr>
<td><strong>Ongoing TB despite treatment for drug-sensitive TB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>200 (0-300)</td>
<td>. . .</td>
<td>100 (0-200)</td>
<td></td>
</tr>
<tr>
<td>Transiently homeless population</td>
<td>600 (300-1000)</td>
<td>. . .</td>
<td>100 (0-1000)</td>
<td></td>
</tr>
<tr>
<td>Chronically homeless population</td>
<td>1000 § (600-1500)</td>
<td>. . .</td>
<td>100 (0-1000)</td>
<td></td>
</tr>
<tr>
<td><strong>Patient cured with treatment for multiple drug-resistant TB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>8000 (7500-8500)</td>
<td>. . .</td>
<td>5300 (3400-7000)</td>
<td></td>
</tr>
<tr>
<td>Transiently homeless population</td>
<td>650 § (5000-8000)</td>
<td>. . .</td>
<td>5300</td>
<td></td>
</tr>
<tr>
<td>Chronically homeless population</td>
<td>5000 (3300-6700)</td>
<td>. . .</td>
<td>4000</td>
<td></td>
</tr>
<tr>
<td><strong>Patient cured with treatment for drug-sensitive TB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>9000 (8800-9200)</td>
<td>. . .</td>
<td>7080 (6800-9000)</td>
<td></td>
</tr>
<tr>
<td>Transiently homeless population</td>
<td>7000 (6800-9000)</td>
<td>. . .</td>
<td>7080</td>
<td></td>
</tr>
<tr>
<td>Chronically homeless population</td>
<td>6700 § (5000-7400)</td>
<td>. . .</td>
<td>7080</td>
<td></td>
</tr>
<tr>
<td><strong>Mortality among patients who received isoniazid</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>6 (1-9)</td>
<td>42 (6-60)</td>
<td>42 (9-63)</td>
<td></td>
</tr>
<tr>
<td><strong>TB risk reduction with BCG vaccination</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General population</td>
<td>3000 (3400-7000)</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

†Ellipses indicate that individuals with HIV infection and active TB have AIDS according to the 1993 Centers for Disease Control and Prevention definition.29

*Calculated as a complement in the model. The value changes automatically when associated variables are varied across their ranges.

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with the chronically homeless population, 5% improvements were about half as effective as the 10% ones while 20% improvements were approximately twice as effective.

**Strategies Targeting Persons With Latent TB Infection**

Relative changes in strategies targeting persons with latent TB infection were less effective at reducing future TB cases and deaths among homeless persons than changes in strategies targeting those with active TB. Among prevention programs though, changes in access to care remained more effective at reducing future TB morbidity and mortality than improvements in the effectiveness of current prevention programs. A 10% increase in chronically homeless tuberculin-positive individuals accessing treatment for latent TB infection was associated with a 6.7% decline in projected TB cases over 10 years compared with baseline predictions. In contrast, a 10% improvement in the effectiveness of treatment for latent TB infection reduced projected chronically homeless TB cases by 3.0% (Table 3). Increasing access to treatment of latent TB infection also led to larger declines in future TB deaths in the chronically homeless population. A 10% increase in access to treatment of latent TB reduced projected future TB deaths by 3.0% (Table 3). Increasing access to treatment of latent TB infection also led to a 12.2% decrease in future TB cases and a 2.4% decline in TB deaths in this population. Ten percent vaccination of eligible transiently homeless individuals also was more effective in preventing predicted TB cases and deaths than the same relative improvement in the effectiveness of treatment of latent TB infection (Table 3).

A 5% increase in the rate of treatment of latent TB infection in chronically homeless individuals was associated with a 3.4% decline in future TB cases, while a 20% increase in treatment of latent TB infection reduced future TB cases by 12.7%. Predicted TB deaths after 10 years in the chronically homeless population declined 2.1% or 8.1%, depending on whether access to treatment of latent TB infection was increased by 5% or 20%. The predicted effect of increasing access to treatment of latent TB infection did not differ substantially, depending on HIV status among homeless individuals (Table 4).

**BCG Vaccination of Tuberculin-Negative, HIV-Negative Persons**

Vaccination with BCG of 10% of HIV-negative, tuberculin-negative chronically homeless individuals each year was associated with a 10.0% decline in future TB cases and a 2.4% decline in TB deaths in this population. Ten percent vaccination of eligible transiently homeless individuals led to a 12.2% decrease in future TB cases and a 3.1% drop in TB deaths in this group after 10 years. The HIV-negative homeless populations experienced much larger relative declines in TB cases and deaths with a BCG vaccination program than did those with HIV (Table 4).

Unlike the other single interventions studied, doubling the percentage of eligible homeless individuals vaccinated did not double the percentage of predicted TB cases prevented. A 20% annual BCG vaccination program produced a 15.6% decline in future TB cases in the chronically homeless population. The same strategy in the transiently homeless population produced a 19.3% decline in future TB cases.

**Combinations of TB-Control Strategies Across Populations**

Two prevention strategies (increasing access to treat-
ment of latent TB infection and BCG vaccination) demonstrated substantial benefits in reducing TB across populations in this model. When increased access to treatment of latent TB by 10% was expanded from the chronically homeless population to include both homeless populations, predicted TB cases among the chronically homeless population decreased by 8.4%. As noted previously, when this intervention was limited only to the chronically homeless population, future TB cases in this population decreased by 6.7%. Transiently homeless TB cases decreased by 6.5% over 10 years when increased access to treatment of latent TB infection was expanded to include both homeless populations. With a single population intervention, transiently homeless TB cases dropped by 5.7%.

Annual BCG vaccination of 10% of all HIV-negative, tuberculin-negative homeless individuals was associated with 13.7% decrease in predicted TB cases among the chronically homeless population. This result represents an almost 40% relative improvement over the 10.0% decline predicted when vaccination was limited only to chronically homeless individuals. In the transiently homeless population, the decline in TB cases changed from 12.3% to 13.9% when BCG vaccination was expanded from 10% of eligible transiently homeless individuals to 10% of all eligible homeless persons each year.

Vaccination with BCG of 10% of the eligible US general population each year was associated with a 15.6% decline in chronically homeless TB cases and a 4.0% decline in TB deaths. Vaccination with BCG was the only US general population intervention to have any substantial impact on future TB cases and deaths in the chronically homeless population.

When other TB-control interventions were introduced into both homeless populations simultaneously, there was little to no additional benefit over targeting the same intervention in individual homeless populations. For example, increasing access to treatment for all homeless individuals with active TB by 10% led to a 12.9% decline in future TB cases among the chronically homeless population. A similar result was obtained when this intervention was introduced only into the chronically homeless population.

Across Strategies. Allowing BCG-vaccinated individuals to receive treatment for latent TB infection at the same rate as nonvaccinated individuals markedly improved the impact of a vaccination program. The amount of TB cases in the chronically homeless population decreased by 15.4% after 10 years when vaccinated and nonvaccinated persons were eligible to receive treatment for latent TB infection at the same rate. In contrast, TB cases in the chronically homeless population decreased by 10.0% when only 1% of vaccinated persons eligible for treatment of latent TB infection started this treatment. In the transiently homeless population, TB cases decreased by 21.5% when BCG-vaccinated individuals were eligible to receive treatment for latent TB infection at the same rate as nonvaccinated persons and by 12.2% when they were not.

Combining a strategy to increase access to treatment with one that improves the effectiveness of treatment for active or latent TB was more effective at reducing future TB cases and deaths than either individual strategy. Combination strategies were additive though, and not synergistic. The results of combination strategies in the chronically homeless population are shown in the Figure.

Sensitivity Analysis
When the input-transition probabilities were simultaneously varied over defined ranges, increasing access to treatment for active TB remained substantially more effective in reducing future TB deaths in the chronically homeless population than any other single intervention. The results of the sensitivity analyses for each of the single interventions in the homeless populations are shown in Table 3.

COMMENT
The homeless population in the United States remains at high risk for TB. Results from this simulation model revealed a number of important insights for the control and eventual elimination of TB among the US homeless population including:

- Increasing access to care is essential in controlling TB in the US homeless population.
- TB rates are so high among homeless persons that treatment of latent TB infection is crucial for all tuberculin-positive homeless persons, not just those with HIV as was previously seen in the US general population.
- Because of high TB infection rates, a BCG vaccination program for HIV-negative homeless individuals only makes sense if treatment of latent TB...
infection is continually offered to persons who have been vaccinated.

Increasing access to treatment for those with active TB was the single most effective marginal change in reducing predicted TB cases and deaths in homeless persons. Recent studies showing unrecognized active TB among shelter residents and outbreaks caused by homeless individuals with longstanding untreated TB demonstrate that homeless individuals are not receiving treatment for TB in a timely fashion. Lack of care for homeless individuals with active TB is due to a multitude of reasons, and improvements in access to treatment likely require a multifaceted approach. However, successful programs have been designed to increase use of TB services by homeless persons.

Much recent emphasis in TB control has been placed on improving the effectiveness of treatment for latent TB infection. National guidelines for treatment of latent TB infection have just been revised; these guidelines now recommend 9 months of isoniazid instead of 6 months as had been the standard of care. This change was undertaken to maximize the effectiveness of treatment of latent TB. Though improving the effectiveness of treatment of latent TB is beneficial in this model, this strategy alone is not as important as increasing access to care. A 10% relative increase in access to treatment of latent TB produced twice the decline in predicted TB cases and deaths in homeless persons as a 10% relative improvement in the effectiveness of treatment for latent TB infection. Control of TB should not rely solely on strategies to increase program effectiveness. Rather, strategies that increase the accessibility of treatment to homeless individuals must be implemented.

The benefits of BCG vaccination in this model vary substantially depending on assumptions about whether vaccinated individuals receive treatment for latent TB infection at the same rate as nonvaccinated persons. According to current CDC recommendations, BCG-vaccinated individuals should receive treatment for latent TB infection for the same indications as nonvaccinated individuals. The benefits of BCG were limited almost exclusively to homeless individuals without HIV infection. Given the well-documented difficulties in getting homeless individuals to comply with tuberculin skin testing and treatment for latent infection, BCG vaccination should be considered for HIV-negative homeless individuals.

The simulation results also support current recommendations for targeted interventions in certain groups at high risk for TB. With the exception of a general BCG vaccination program for the US general population, increasing access to or improving the effectiveness of TB-control programs in the general population had little or no impact on preventing future TB cases and deaths among homeless persons. Even among the homeless population, increases in access or the effectiveness of TB control among the chronically homeless population had little effect on preventing future TB cases and deaths in the transiently homeless population. The converse was also true. The exceptions were BCG vaccination and increasing access to treatment for latent TB infection.

The main limitations of these analyses are the assumptions necessary in any model when imperfect epidemiological information exists. To minimize assumptions and to address the limitations in data on the homeless population, we took 2 steps. First, we conducted extensive searches of published literature and US government reports to get the most complete possible data. Second, thorough sensitivity analyses of all model inputs using Latin Hypercube Sampling were performed to examine the robustness of the simulation results. The results were consistent across a range of assumptions and levels of program changes.

Public policies for TB control are made with imperfect data, and those making policies are forced to rely on assumptions similar to the ones used in this model. The advantage of a simulation model such as ours is that the underlying assumptions are defined when building the model. These assumptions may remain unrecognized in policy discussions. Assumptions can be varied across a range of values, and the impact of changing assumption values may be assessed. It is difficult for decision makers to intuitively conduct similar assessments. New data also can be readily evaluated in a model.

Policies to control TB also need to consider feasibility. Except for BCG vaccination, all of the strategies considered in the model are already being used in the United States. The model provides an estimate of the expected benefits of relative improvements in these strategies and can help policy makers develop priorities in current programs for TB control in homeless persons. Introducing a BCG vaccination program would require HIV testing and counseling for homeless persons. Human immunodeficiency virus is a major cause of morbidity and mortality in this population. Expanded counseling and testing for HIV in homeless individuals is reasonable regardless of whether BCG vaccination is considered.

Although BCG vaccination has never been used to any substantial extent in the United States, it has been feasible in many countries with far fewer resources. The successful introduction of the hepatitis B and Haemophilus influenzae type b vaccination programs demonstrate that it is possible to achieve high coverage with a new vaccine in the United States. Previous studies also have shown that it is possible to reach vaccine coverage rates well above 10% in the homeless population, or to improve vaccination rates by more than 10% in difficult-to-reach populations.

When provided with medical services that address their needs, homeless individuals will access health care at the same rate as nonhomeless populations. In San Francisco, Calif, providing monetary incentives substantially increased the likelihood that homeless individuals would both keep a first appointment for TB screening and complete treatment for latent TB infec-
tion.65-67 Though homelessness is a well-documented risk factor for nonadherence to TB treatment,66 programs that provide supports for homeless persons, such as housing, transportation, support groups, meal coupons, and other incentives, have demonstrated that it is possible to substantially improve both treatment enrollment and completion rates.67-69 The amount of treatment completed directly influences the effectiveness of the therapy, and increases in treatment completion have been associated with decreases in treatment failure and TB incidence among homeless persons.66,70 The interventions modeled in our simulation study are feasible, as demonstrated by the fact that innovative programs to address TB in the homeless population have been able to achieve changes well above the 10% improvements we modeled.

One limitation of the model is that it does not include cost. The failure to provide effective TB control can be extremely expensive; it was estimated that the 4-year cost of containing a TB epidemic in New York City alone exceeded $1 billion.71 There are limited data to suggest that improvements in TB control among homeless persons may produce substantial cost savings.69 Therefore, improvements in TB control among homeless persons are likely to be more cost-effective than the alternative of allowing TB to spread in this high-risk population. The feasibility and cost of the modeled interventions are unlikely to be substantially more difficult or costly than improvements in TB-control programs that have already been achieved,72 or that have been recommended.72

Based on these simulation results, policy makers who hope to control TB among the homeless population will likely need to look beyond improvements in treatment effectiveness if they ultimately hope to eliminate this disease in the United States. Overcoming barriers faced by homeless individuals to accessing TB programs specifically and health services in general will be crucial to reducing the burden of TB in this high-risk group. However, improving program performance will also decrease future TB cases and deaths among homeless persons. Combining both strategies with BCG vaccination of HIV-negative homeless individuals has the best chance at markedly decreasing TB morbidity and mortality.

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REFERENCES


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