Tuberculosis in a South African prison – a transmission modelling analysis

Simon Johnstone-Robertson, Stephen D Lawn, Alex Welte, Linda-Gail Bekker, Robin Wood

Background. Prisons are recognised internationally as institutions with very high tuberculosis (TB) burdens where transmission is predominantly determined by contact between infectious and susceptible prisoners. A recent South African court case described the conditions under which prisoners awaiting trial were kept. With the use of these data, a mathematical model was developed to explore the interactions between incarceration conditions and TB control measures.

Methods. Cell dimensions, cell occupancy, lock-up time, TB incidence and treatment delays were derived from court evidence and judicial reports. Using the Wells-Riley equation and probability analyses of contact between prisoners, we estimated the current TB transmission probability within prison cells, and estimated transmission probabilities of improved levels of case finding in combination with implementation of national and international minimum standards for incarceration.

Results. Levels of overcrowding (230%) in communal cells and poor TB case finding result in annual TB transmission risks of 90% per annum. Implementing current national or international cell occupancy recommendations would reduce TB transmission probabilities by 30% and 50%, respectively. Improved passive case finding, modest ventilation increase or decreased lock-up time would minimally impact on transmission if introduced individually. However, active case finding together with implementation of minimum national and international standards of incarceration could reduce transmission by 50% and 94%, respectively.

Conclusions. Current conditions of detention for awaiting-trial prisoners are highly conducive for spread of drug-sensitive and drug-resistant TB. Combinations of simple well-established scientific control measures should be implemented urgently.

South Africa has the fourth highest global incarceration rate, with more than 165 000 prisoners in 237 operational prisons.7 There is a rapid turnover of awaiting-trial prisoners with 79% being incarcerated in sub-Saharan Africa by a high prevalence of HIV infection among inmates, as TB is the most common opportunistic infection among people living with HIV in Africa.8 A high TB prevalence and poor control policies within prisons also create potential breeding grounds for multidrug-resistant TB (MDR-TB).9 TB transmission within prisons can also significantly impact on the wider community.5

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Methods

Study design

TB transmission probabilities were estimated using the Wells-Riley equation, a well-known transmission model that has been applied to a wide range of transmission scenarios, including describing airborne transmission probabilities within a single enclosed room or space with defined ventilation characteristics. We used this equation in combination with the distribution of inmates per cell and their probability of having TB that had been infectious for different periods of time, in order to explore prisoner-to-prisoner TB transmission probabilities. The modelled transmission probabilities were adjusted for daily lock-up periods and variable cell ventilation characteristics.

We then explored the effects of decreased crowding, shorter lock-up times, improved ventilation and improved case finding on TB transmission probabilities. Finally we explored combinations of changes to the TB control programme and prison conditions necessary to achieve significant reductions in TB transmission. Table 1 shows the values and ranges of key parameters used to populate the model.

Prison population

Pollsmoor maximum-security prison is the third-largest facility housing sentenced prisoners in South Africa, with approximately 3 200 awaiting-trial and unsentenced prisoners at any time. They are predominantly incarcerated in communal cells of 40 - 60 prisoners and confined for 23 hours each day. Overcrowding is persistently high with reported average occupancy rates of 235% in 2003 and 239% in 2008. Cell ventilation is poor with a single slatted window on an exterior wall with openings of 6 088 cm² and a small ventilator grille with area of 126 cm² on the solid metal door, which is closed at night.

The TB control programme

South African prisons’ TB control programme is similar to the national TB programme, which focuses on passive case finding of sputum smear-positive cases and directly observed short-course therapy. However, because of chronic nursing shortages the strategy was poorly implemented, with no active case finding, and inmates with symptomatic TB could wait up to 4 months before referral to the prison hospital. Medical staff did not systematically screen newly arriving prisoners for symptoms or signs of TB. Notification registers between 1998 and 2009 were inconsistently completed, resulting in significant under-reporting of TB cases; 177 prisoners commenced TB therapy in 2001 – a notification rate of 5.5 TB cases per 100-person prison years. However, a prison medical officer gave evidence that during the year, 264 prisoners had laboratory confirmation of acid-fast bacilli on direct sputum smear, indicating marked under-reporting of a TB incidence rate of 8.25 cases per 100-person prison years, that MDR-TB was prevalent among inmates, and that a staff member had died from this form of the disease.

Mathematical transmission model

The number of TB infections (C) occurring in a prison cell with susceptible prisoners (S) was assumed to be a function of the number of infectious cases (I), their infectivity (q = quanta of infectious particles produced per hour), time of exposure (t = time of exposure in minutes), respiration rate (p = litres per hour), and germ-free ventilation (Q = litres per hour) as given by Wells-Riley equation C = S(1-e⁻λtq/Q). The prevalence (P) of infectious adults at any time is given by the annual smear-positive incidence rate (M = per cent) and the period of infectivity (Δ = days) as P = M/[365/Δ]. The risk of contact with an infectious adult is given by the Poisson distribution (λ/I)!e⁻λ, where λ = P*(A-1) is the expected number of infectious cases in a cell with ‘A = I + S’ adults.

Modelled input parameters

Germ-free ventilation (Q) was calculated as air changes per hour (ACH) for a standard cell of 9.1 m long × 6.4 m wide × 3.35 m high with a volume of 195 m³. Current cell ventilation would provide less than 1 ACH with all windows and the door ventilator grille open with

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Values</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>TB incidence rate</td>
<td>5.5 cases/100-person prison years*</td>
<td>Lee v Minister of Correctional Services</td>
</tr>
<tr>
<td>Δ</td>
<td>Period of infectiousness</td>
<td>1 - 180 days</td>
<td>Lee v Minister of Correctional Services, Storla et al.</td>
</tr>
<tr>
<td>q</td>
<td>Infectious quanta</td>
<td>1 per hour</td>
<td>Riley et al., Cantazarro, Noakes &amp; Sleigh, Nardell et al., Furuya et al., Wood et al.</td>
</tr>
<tr>
<td>Q</td>
<td>Ventilation</td>
<td>1, 3, 8, 12 ACH⁷</td>
<td>Lee v Minister of Correctional Services, Dara et al., WHO</td>
</tr>
<tr>
<td>p</td>
<td>Respiratory volume</td>
<td>360 litres/hour</td>
<td>Pinna et al.</td>
</tr>
<tr>
<td>s</td>
<td>Prisoners/cell</td>
<td>58.24 m²/3.34 m²²</td>
<td>Lee v Minister of Correctional Services</td>
</tr>
<tr>
<td>C</td>
<td>Cell dimensions</td>
<td>9.1 m × 6.4 m × 3.35 m</td>
<td>Lee v Minister of Correctional Services, Dara et al., WHO</td>
</tr>
<tr>
<td>F</td>
<td>Floor area per prisoner</td>
<td>1.42 m², 3.34 m², 5.4 m²</td>
<td>Lee v Minister of Correctional Services, Dara et al., WHO</td>
</tr>
</tbody>
</table>

NB *TB incidence rate based on 177 cases in prison population of 3 200.¹³

¹ACH = air changes per hour for cell of 195 m³ volume.

²Cell floor area is 9.1 m × 6.4 m = 58.24 m². Prisoners per cell = the floor area divided by the space allocated per prisoner, a minimum of 3.34 m² according to South African regulations. If the cell was 200% full then there would be twice as many prisoners present.
totally free flow of air through the cell and a 10 km/h wind directed
towards the window.26 International recommendations for prison
ventilation22 based on the floor area of this cell would recommend
1.8–3.58 ACH, and the World Health Organization (WHO)
recommends 12 ACH for health settings and congregate settings
where TB is prevalent.23 Four values of ACH were therefore modelled:
the status quo of 1 ACH (poor ventilation); 3 ACH (minimum
international recommended ventilation); 8 ACH (intermediate
ventilation); and 12 ACH (optimal ventilation).

A wide range of estimated values for the rate of production of
infectious TB quanta (q) have been reported. Laryngeal TB is highly
infectious with q estimated at 60 infectious quanta per hour.24 In a
workplace outbreak due to an untreated smear-positive pulmonary
case, q was estimated at 12.7 infectious quanta per hour.25 Over a
2-year period in a TB ward, q was directly measured at 1.25 infectious
quanta per hour.26 A study applying molecular strain characterisation
to track airborne TB transmission from HIV/TB-infected inpatients
to guinea pigs demonstrated markedly variable infectiousness.27
Values of q for infectious cases varied between 3 and 12 and 2.5 and
226 quanta per hour for individuals with drug-sensitive and MDR-TB
respectively. In order to be conservative, q was modelled at a mean
value of 1 infectious quantum per hour.

The mean respiratory rate of adults (p) was estimated to be 360
litres per hour corresponding to a normal adult respiratory minute
volume of 6 litres per minute.28

A key parameter of the model, the period of infectiousness (Δ),
has a strong inverse association with the TB control programme
effectiveness of case finding. Δ is a composite of delays, including
time to access medical care, diagnostic delay and time to commence
chemotherapy. The diagnostic delay period during which an adult
may be infective is variable, but is frequently reported to be 60–90
days.29 However, delays in accessing treatment within this prison
were reported to be very prolonged; therefore analyses were performed
with values of Δ from 1 day up to 180 days.

Passive case finding depends on individuals with symptoms of TB
self-presenting for investigation. It was modelled that with increased
TB awareness health messaging, minimal delay in accessing TB
services, expeditious diagnosis and rapid initiation of chemotherapy,
the period of infectiousness (Δ) could be reduced to 60 days. Active
case finding (regular seeking out symptomatic prisoners) and rapid
diagnostic testing29 was modelled with values of Δ of less than 60
days.

Results

We explored the impact of cell occupancy on TB transmission
probabilities. Transmission probabilities at existing levels of
overcrowding, the recommended minimum South African and
international recommended occupancy are shown across a spectrum
of time periods of infectiousness of source cases (Δ) from 1 to
180 days in Fig. 1. Transmission probabilities under prevailing
conditions of incarceration were estimated at 90% per annum
for all values of Δ (>60 days) currently implementable by the
prison TB control programme. The benefits of decreasing cell
crowding were proportionate at all values of Δ. Implementing current
South African recommended cell minimum levels of occupancy
would reduce transmission by 30% and implementing international
recommendations would reduce transmission by 50%, even with
current levels of TB case finding.

The effect of decreasing lock-up time (period restricted to cells
each day) is shown for the existing conditions of 23 hours per day and
for reductions to 12 and 8 hours per day respectively in Fig. 2. The
benefits of decreasing lock-up time are modest at current values of Δ

\[
\Delta = \text{Period of infectiousness (Days)}
\]

(approximately 180 days). However, the benefits of decreased lock-
up times are amplified by improving case finding with consequent
reductions in Δ. When Δ is reduced to 60 days, reduction of lock-up
time to 12 and 8 hours would reduce TB transmission by 10% and
20%, respectively.

The effect of cell ventilation on TB transmission probability is
shown in Fig. 3. Three levels of ventilation were modelled in addition
to the current reported estimate of 1 ACH: 3 ACH; 8 ACH; and
12 ACH. Improved ventilation markedly decreases TB transmission
probabilities at all values for Δ. However, improvements in ventilation
are amplified when accompanied by reductions in the value of Δ
which could be achieved by improved case finding.

Finally, we explored effects of improved case finding in three
different scenarios (Fig. 4): scenario 1 – status quo; scenario 2 –
current South African regulations for imprisonment with modest
increase of ventilation to 3 ACH fully implemented; and scenario 3 –
international standards for imprisonment together with ventilation

\[
\text{Annual Risk of Infection} = \frac{100 \times \text{Rate of Production of Infectious Quanta}}{\text{Respiratory Rate}}
\]
for diagnosis and implementing therapy, 21 markedly increase the international environmental standards22, 23 could reduce transmission by as much as status quo months in accessing medical care,13 together with time required the probability of contact with infectious sources. Delays of 3 - 4 risks. Overcrowding of cells directly and proportionately increases control programme combine to contribute to high TB transmission are extremely conducive for ongoing transmission of TB. Crowding, This study shows that conditions prevailing in a South African prison implementation of scenario 2, and 90% with implementation of respectively. Active case finding to achieve a Δ of 30 days would achieve a Δ of 60 days would have minimal effect on TB transmission in scenario 1 and 20% and 50% reductions in scenarios 2 and 3, actively. Case finding to achieve a Δ of 30 days would decrease transmission by 10% with current scenario 1, 50% with implementation of scenario 2, and 90% with implementation of scenario 3.

Discussion
This study shows that conditions prevailing in a South African prison are extremely conducive for ongoing transmission of TB. Crowding, substandard living conditions and a poorly functioning prison TB control programme combine to contribute to high TB transmission risks. Overcrowding of cells directly and proportionately increases the probability of contact with infectious sources. Delays of 3 - 4 months in accessing medical care,17 together with time required for diagnosis and implementing therapy,17 markedly increase the prevalence of infectious cases, and act as the primary source for ongoing transmission.

We show that the very high prevalence of infectious cases within the prison population potentially negates the benefits of improved ventilation and shortened exposure time within cells. The interdependence of all the transmission risk factor parameters is further highlighted by the observation that improved passive case finding sufficient to reduce the period of infectiousness from 6 to 2 months would have a minimal effect under current conditions of crowding and poor ventilation. However, the multiplicative benefits of concurrent improvements in case finding, crowding and environmental conditions are demonstrated. Active case finding and implementing current national minimum standards of cell occupancy3 can reduce transmission by 50%. Introducing international environmental standards22, 23 could reduce transmission from the status quo by as much as 94%. Our study strength was available accurate information specific to this prison: number of TB cases, cell dimensions, number of prisoners per cell and likely delays in accessing TB treatment. A limitation of the model is that precise enumeration of the number

![Graph showing TB transmission probabilities for 3 scenarios](image1)

![Graph showing annual risk of infection](image2)

![Graph showing annual risk of infection](image3)
simple scientifically based disease control measures that need to be tailored to circumstances and resources. Many strategies are available to address the problem. The Judicial Inspectorate has repeatedly proposed the measures required to decrease the awaiting-trial prison population. Cell ventilator grills should not be closed at night; cross-ventilation of communal cells could be encouraged by using barred rather than solid doors and incorporating corridor ventilator extraction systems. Since 1847, carbon dioxide levels have been used as a measure of adequate ventilation and carbon dioxide monitoring could readily establish if effective improvements in cell ventilation are being achieved. Prison TB control programmes should incorporate recent technological advances in rapid TB diagnosis and drug resistance. TB notification data for South African prisons should not be considered secret or restricted information, but accurate data should be made available to the Judicial Inspectorate of Prisons to include in the annual report on the state of our prisons. TB transmission risks within our prison system are unacceptably high, posing a direct hazard to prisoners and contributing to the general population TB burden. Overlooking TB prevention and control in prisons carries serious health consequences for both prisoners and the general community.\(^{1-2,18}\)

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References


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