The immunogenicity of recombinant Mycobacterium smegmatis bearing BCG genes

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Specific pathogen-free C57BL/6 mice infected with recombinant Mycobacterium smegmatis (rM. smegmatis) bearing BCG genes showed increased splenic survival compared to those receiving the vector control (plasmid DNA only). The mouse-passaged rM. smegmatis (J3R) survived in peritoneal macrophages better than the vector control, regardless of whether the macrophages were infected in vivo or in vitro. When rM. smegmatis J3R was cultured in synthetic Proskauer-Beck-Tween medium, protein bands characteristic of BCG culture filtrates and not present in the vector control preparation were observed. Mice immunized with two doses of heat-killed J3R suspended in Freund's adjuvant were able to limit the growth of virulent Mycobacterium tuberculosis within the lung and spleen compared to that observed in control mice receiving adjuvanted vector control or Freund's adjuvant alone.

Keywords: Mycobacterium smegmatis, BCG genes, macrophages

INTRODUCTION

Bacille Calmette–Guérin (BCG) has been used for more than 70 years for the prevention of pulmonary tuberculosis, especially in children living in Third World countries. Despite the widespread use of the BCG vaccine, as much as one third of the world’s population is infected with tubercle bacilli, with 8 million new cases and nearly 3 million deaths being reported each year (Sudre et al., 1992). As a result, tuberculosis is still the most important life-threatening bacterial disease in the world today and has recently been declared to be a global health emergency by the World Health Organization (WHO, 1993). Neonatal immunization with live BCG vaccine constitutes the major component of tuberculosis control programmes in many parts of the world, despite questions raised by several recent field trials regarding its overall protective value (Fine, 1989). As a result of uncertainties regarding the protective ability of currently available BCG vaccines, a number of proposals have been made to increase the immunogenicity of existing BCG vaccines by cloning more protective genes and transferring them into suitable carriers (Bloom, 1989; Curtiss et al., 1989). The recent development of the integrating shuttle cosmid (Snapper et al., 1988) makes it possible to transfer genetic material from one mycobacterial species to another and could lead to the development of new, improved vaccines for use against this important human disease (Collins, 1991).

The present study examines the ability of recombinant Mycobacterium smegmatis (rM. smegmatis) selected in vivo and bearing BCG genes to produce protein antigens capable of enhancing resistance to the growth of virulent tubercle bacilli within the lungs of aerogenically challenged mice.

METHODS

Animals. Specific pathogen-free C57BL/6 mice (6–8 weeks old) were obtained from the Trudeau Animal Breeding Facility, Saranac Lake, New York. They were maintained under barrier conditions and fed sterilized commercial mouse chow and acidified water ad libitum (Collins, 1972).

Organisms. Mycobacterium bovis BCG Pasteur (TMC 1011) and Mycobacterium tuberculosis H37Rv (TMC 102) were obtained from the Trudeau Mycobacterial Culture Collection, Saranac Lake, New York. They were grown in Proskauer-Beck-Tween (PBT) liquid medium enriched with 10% oleic acid/albumin/dextrose/catalase additive, harvested after incubation at 37 °C for 10 d (mid-exponential growth phase) and dispensed into

Abbreviation: rM. smegmatis, recombinant Mycobacterium smegmatis.

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1 ml ampointes which were kept frozen at —70 °C until required (Kim & Kubica, 1972). M. smegmatis strain mc²155 was derived from M. smegmatis ATCC 607 (Snapper et al., 1990) and was cultured in PBT medium at 37 °C for 3 d before being stored at —70 °C. The viability of the recombinants was checked by thawing randomly selected ampointes, sonicating the organisms briefly to disperse any clumps and plating tenfold saline dilutions on Middlebrook 7H11 agar (Difco) enriched with 10 μg kanamycin ml⁻¹ (Snapper et al., 1988). Plates were incubated at 37 °C in sealed plastic bags and the colonies counted using a plate microscope.

Construction of M. smegmatis/BCG recombinant pools. A genomic library from M. bovis BCG Pasteur, which had been grown as a surface pellicle on Proskauer and Beck medium for 14 d at 37 °C, was prepared by mechanical disruption and phenol/chloroform extraction (Grosskinsky et al., 1989). The DNA was digested into 30-50 kb fragments with Sae3A before being ligated to the integrating shuttle cosmide vector pYUB178 (Jacobs et al., 1991). The pYUB178::BCG DNA or pYUB178 DNA was electroporated into M. smegmatis mc²155 which had been grown in PBT medium for 3 d at 37 °C (Snapper et al., 1988). Separate pools of approximately 250 transformants were selected from kanamycin agar (theoretically sufficient to represent the entire BCG genome) and picked into 50 ml Middlebrook 7H9 broth enriched with 10 μg kanamycin ml⁻¹ and incubated at 37 °C for 3 d. The vector control (pYUB178) was prepared as a pool of 15 transformants. The recombinant pools were dispensed in 5 ml aliquots and stored at —70 °C until needed.

Infection and enumeration of recombinant bacteria in vivo. A frozen ampointe was thawed, sonicated briefly to break up any clumps and suitable saline dilutions were injected intravenously into C57BL/6 mice. Each mouse received approximately 10⁶ c.f.u. of each recombinant suspended in 0.2 ml saline. At intervals up to 14 d, groups of five randomly selected mice were killed by cervical dislocation, and selected organs were removed aseptically and homogenized separately in cold sterile saline before being plated on Middlebrook 7H11 agar enriched with 10 μg kanamycin ml⁻¹ and incubated at 37 °C for 3 d. The vector control (pYUB178) was prepared as a pool of 15 transformants. The recombinant pools were dispensed in 5 ml aliquots and stored at —70 °C until needed.

Challenge protocol. Groups of vaccinated and control mice were infected aerogenically with approximately 10³ c.f.u. of each recombinant suspended in 0.2 ml saline. At intervals up to 14 d, groups of five randomly selected mice were killed by cervical dislocation, and selected organs were removed aseptically and homogenized separately in cold sterile saline before being plated on Middlebrook 7H11 agar enriched with 10 μg kanamycin ml⁻¹. Colonies were counted after 3 d incubation at 37 °C, representative rough, opaque colonies were checked for purity and a 3 d broth culture was stored at —70 °C until required.

Infection of mouse macrophages in vivo. Peritoneal exudate macrophages were infected with mouse-passaged rM. smegmatis J3R or vector control suspensions. The exudate was induced by the intraperitoneal injection of 2 ml 10% (w/v) casein in saline and the peritoneal cavity was washed out 3 d later using 5 ml RPMI 1640 medium enriched with 10% (v/v) heat-inactivated foetal calf serum (Gibco) plus 5 μl heparin ml⁻¹ (Stokes & Collins, 1988). The peritoneal exudate cell suspension was washed twice with RPMI plus 1% FCS and the number of viable cells was determined by trypsin blue exclusion. The cells were suspended at a concentration of 2 x 10⁶ cells per ml of RPMI 1640 medium containing 10% FCS, 1 mM sodium pyruvate, 2 mM l-glutamine and 10 mM HEPES (complete medium), dispensed into 24-well plates (Costar) and incubated at 37 °C in 5% CO₂-enriched humidified air for 24 h. Non-adherent cells were removed by gentle washing and at least 95% of the adherent cells were determined to be macrophages based on non-specific esterase staining (Hubbard & Collins, 1991).

Macrophage monolayers were infected with 10⁶ c.f.u. mycobacteria suspended in 1 ml complete medium and incubated in CO₂-enriched air for 4 h at 37 °C. The monolayers were washed gently with RPMI plus 10% FCS before adding 1 ml complete medium containing 5 μg gentamicin ml⁻¹ (the MIC for M. smegmatis) and reincubating at 37 °C for up to 48 h. At approximately 6 h intervals, coverslips were removed from three of the wells, washed twice with warm PBS (0.145 M NaCl, 0.15 M sodium phosphate, pH 7.4), fixed and then stained by the Ziehl–Neelsen method to determine the percentage of infected macrophages and their multiplicity of infection. Other coverslips were treated with naphthol blue black (Sigma) at a concentration of 0.5 mg (ml⁻¹ 1 M citric acid)⁻¹ and 1% Triton X-100 (Stokes et al., 1986). This solution lysed the adherent cells releasing any intracellular mycobacteria and the phagocyte nuclei. The bacteria were counted by immediately diluting 0.1 ml of the lysate in 0.9 ml 0.2 M phosphate buffer (pH 7.4), which was briefly sonicated to disperse any clumped bacteria, and plating on agar enriched with 10 μg kanamycin ml⁻¹. Colonies were counted after 3 d incubation at 37 °C. The number of macrophages per well was determined by counting the stained nuclei using a haemocytometer. Viable mycobacteria were expressed per 10⁷ macrophages present on the monolayer at the time of harvest (Stokes et al., 1986).

Infection of mouse macrophages in vivo. Normal mice were injected intraperitoneally with casein 3 d prior to inoculation with 10³ c.f.u. M. smegmatis suspended in 0.5 ml 0.05% Tween/saline. The mice were sacrificed 10 min later and their peritoneal cavities washed out with 5 ml RPMI 1640 medium containing 10% FCS plus heparin. The cell suspension was washed, its viability was checked by trypan blue exclusion and diluted to 2 x 10⁶ cells (ml complete medium)⁻¹. The infected cells were cultured in 24-well plates in 5% CO₂-enriched air for 2 h when the monolayers were washed gently to remove non-attached cells before being replaced with complete medium containing 5 μg gentamicin ml⁻¹. The average number of viable mycobacteria was calculated per 10⁶ macrophages from three wells per time point.

M. smegmatis culture filtrate antigens. The mycobacteria were grown in Proskauer-Beck-Tween medium without added albumin (Collins et al., 1988) and harvested during the mid-exponential growth phase (3 d for M. smegmatis and 8–10 d for M. bovis BCG). Cells were removed by centrifugation at 10,000 g for 30 min at 4 °C and the supernatant fluid was sterilized by filtration through a 0.22 mm pore-size membrane (Millipore). Proteins were precipitated by 80% ammonium sulfate saturation at 4 °C overnight. The precipitate was dissolved in 0.5 M PBS (pH 7.4) and dialysed in the cold until free of ammonium ions. The protein content was determined using the bichinchonic acid assay (Pierce) against a bovine serum albumin standard (Hubbard et al., 1992). Culture filtrate proteins were separated by SDS-PAGE run under reducing conditions in an 11% (w/v) acrylamide gel and stained with Coomassie blue (Collins et al., 1988).

Statistical analysis. The viability data were analysed by Student's t-test or an analysis of variance for differences between two or several independent means using a Statview 512+ program (Brainpower, Calabases) run on a Macintosh SE computer.
RESULTS

Mouse passage of *M. smegmatis* (pYUB178::BCG) recombinants

C57BL/6 mice were infected intravenously with the *M. smegmatis* recombinant pool. Viable counts were carried out on spleen (Fig. 1) and lung homogenates (data not shown) at intervals up to 14 d. The number of viable recombinants present in the spleen declined steadily with time and did not resemble the growth of BCG in normal mice (Collins, 1984). Colonies were selected from the day 14 splenic homogenates plated on kanamycin agar, checked for purity and grown in 7H9 broth for 3 d, then stored at -70 °C until required.

Growth of r*M. smegmatis* J3R in mouse macrophages

Peritoneal exudates were induced in C57BL/6 mice and the macrophage monolayers were infected 24 h later with approximately 10⁶ c.f.u. mouse-passaged r*M. smegmatis* J3R or the vector control. The number of viable organisms was then determined at intervals up to 48 h. Both suspensions were rapidly taken up by the macrophages and few non-cell-associated organisms were detected in the stained monolayers (Fig. 2). The viability of the recombinant challenge declined steadily with time although usually at a slower rate than the vector control (Fig. 3). Little difference was seen in the percent infected macrophages in these monolayers or in the number of acid-fast bacilli (multiplicity of infection) per macrophage, even after 48 h incubation (Table 1). There was no evidence of intracellular growth by the recombinant in these macrophage monolayers, regardless of whether infection occurred *in vitro* (Fig. 3) or *in vivo* (Fig. 4).

Protein antigens present in r*M. smegmatis* J3R culture filtrates

When culture filtrates from r*M. smegmatis* J3R grown in PBT medium were examined for protein bands by SDS-PAGE, an intensely staining 65 kDa band was observed (Fig. 5, lane 3). Culture filtrates prepared from BCG were also characterized by a strong 65 kDa protein band (lane 2) which was virtually absent from the vector control preparation (lane 4). A number of higher molecular mass (80–120 kDa) bands were also present in the r*M. smegmatis* and BCG culture filtrates, which were not present in the corresponding vector control preparation. This suggests that the recombinant was able to express transferred BCG gene(s) and so a study of the protective ability of this organism was undertaken in appropriately vaccinated mice.

Protection of mice vaccinated with r*M. smegmatis* J3R

C57BL/6 mice were infected intravenously with approximately 10⁶ c.f.u. r*M. smegmatis* J3R suspended in 0.2 ml saline. Three weeks later they were challenged aero-genically with 10³ c.f.u. *M. tuberculosis* H37Rv, but the resulting growth curve indicated no increase in anti-

<p>| Table 1. Survival of r<em>M. smegmatis</em> J3R in mouse peritoneal macrophages |
|-------------------|------------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Time (h)</th>
<th>Strain*</th>
<th>Macrophage infection</th>
<th>Viable count (c.f.u. ± SD)</th>
<th>Survival (%)</th>
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<td></td>
<td>Percentage infected</td>
<td>Multiplicity</td>
<td></td>
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<tr>
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<td>1–5</td>
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<td></td>
<td>VC</td>
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<td>5</td>
<td>1.6 ± 0.87 × 10⁴</td>
</tr>
<tr>
<td>6</td>
<td>J3R</td>
<td>ND</td>
<td>ND</td>
<td>2.8 ± 0.76 × 10⁴</td>
</tr>
<tr>
<td></td>
<td>VC</td>
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<td>ND</td>
<td>1.2 ± 0.20 × 10⁴</td>
</tr>
<tr>
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<tr>
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<td>ND</td>
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<tr>
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<tr>
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<td>2–5</td>
<td>1.5 ± 0.25 × 10⁴</td>
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ND, Not determined.

* J3R, r*M. smegmatis* J3R; VC, vector control.
tuberculous resistance, even when vaccination was given as 3 weekly doses of live organisms prior to challenge (V. Falcone, unpublished data).

In a second vaccination protocol, the C57BL/6 mice were injected subcutaneously with two doses of 20 μg (approximately 10⁹ acid fast bacilli) heat-killed rM. smegmatis J3R suspended in 0.2 ml Freund's incomplete adjuvant given after a 3 week interval (Collins & Mackaness, 1970b). A group of control mice were vaccinated with a standard inoculum of live BCG Pasteur. The challenge inoculum in these mice was distinguished from the residual BCG by plating the lung homogenates on Middlebrook 7H11 agar containing 2 μg thiophene-carboxylic acid hydrazide ml⁻¹ (Collins & Mackaness, 1970a). Other controls received Freund's incomplete adjuvant alone or 20 μg killed vector control suspended in Freund's incomplete adjuvant. The vaccinated mice (together with age-matched unvaccinated controls) were challenged aerogenically with 10⁸ c.f.u. M. tuberculosis 3 weeks later and the growth of these organisms in the lungs and spleen was compared with the controls (Fig. 6). Mice receiving two doses of adjuvanted rM. smegmatis showed a significant reduction in the number of viable M. tuberculosis present in the lungs (P < 0.01) and the spleen (P = 0.05) compared to the controls 28 d later. The reduction was only slightly less than that observed in the BCG vaccinated controls (Fig. 6).

**DISCUSSION**

Recent advances in gene cloning technology make it possible to transfer BCG genes to a variety of vectors, which will overproduce the specific protective antigen(s) to provide a long-lasting resistance to a subsequent tuberculous infection (Bloom, 1989). However, to be
Immunogenicity of recombinant *M. smegmatis*

**Fig. 3.** Survival of *M. smegmatis J3R* (△, ▲) and the vector control (□, ▼) in peritoneal macrophages infected *in vitro*. The vertical bars represent the SEM for three determinations.

fully effective, the vector must be capable of establishing a persistent, self-limiting infection within the reticuloendothelial organs of the vaccinated host (Collins, 1991). Thus, the carrier must be able to survive *in vivo* for a long period of time without inducing detectable levels of immunopathology; the more persistent the infection, the better the protection (Curtiss et al., 1989). The r*M. smegmatis* was eliminated from the mouse tissues at a slightly, though consistently slower rate than the vector control (Fig. 1). Different commercially available BCG vaccines vary extensively in their persistence (and immunogenicity) when tested in mice or guinea pigs under standardized laboratory conditions (Lagrange et al., 1976; Wiegeshaus et al., 1971). Any new recombinant vaccine must induce a longer-lived, memory immune T-cell response than any of the existent strains of BCG (Collins, 1991). At present, we know very little about the antigens (or genes) responsible for inducing this type of persistent immune memory response (Orme, 1988).

The ability of mice to inactivate *M. smegmatis* has been ascribed to the presence of the *Bcg* gene and seems to be independent of an acquired T-cell-mediated immune response (Denis et al., 1990). These investigators reported substantial survival by *M. smegmatis* in peritoneal and splenic macrophages isolated from B10.A mice lacking the *Bcg* gene. In the present study, C57BL/6 (*Bcg*) mice rapidly inactivated both the r*M. smegmatis* and its vector.

**Fig. 4.** Survival of r*M. smegmatis J3R* (△, ▲) and the vector control (□, ▼) in peritoneal macrophages infected *in vivo*. The vertical bars represent the SEM for three determinations.

**Fig. 5.** SDS-PAGE gel showing culture filtrate proteins obtained from BCG (lane 2), r*M. smegmatis J3R* (lane 3) or the vector control (lane 4) when stained with Coomassie blue. Protein standards are shown in lane 1.
control and survival of the recombinant in the corresponding macrophage cultures was equally short-lived (Figs. 3 and 4). Despite the mycobactericidal activity shown by the macrophage monolayer, this assay may still constitute a suitable screening procedure for the detection of in vivo growth (ing) genes (Pascopella et al., 1994) transferred from other mycobacterial species. The in vivo infection protocol has the additional technical advantage that phagocytosis occurred more efficiently at lower multiplicities of infection, resulting in fewer extracellular mycobacteria within the macrophage culture. The presence of gentamicin in the culture medium to prevent overgrowth by non-cell-associated organisms may explain the decreased survival of M. smegmatis noted in the present study compared to that reported in the earlier study (Denis et al., 1990).

In the present study, the BCG genomic library was expressed in M. smegmatis, which has long been known to be completely avirulent for both mice and people (Collins, 1983). Even when introduced into the tissues in massive numbers, the recombinant was inactivated before it could induce a detectable cell-mediated immune response to the transferred BCG antigens. The only way to achieve protection with this recombinant was to suspend the killed tubercle bacilli. Effect of adjuvant on the allergenicity and immunogenicity of heat-killed Mycobacterium smegmatis culture filtrate. Infect Immun 56, 1260–1266.


Grosskinsky, C. M., Jacobs, W. R., Clark-Curtiss, J. & Bloom, B. R. (1989). Genetic relationships among Mycobacterium leprae, M. tuberculosis and candidate leprosy vaccine strains determined by viable numbers of H37Rv in the lungs of the J3R versus vector control vaccinated mice was modest, it was statistically significant (P < 0.01) and comparable to that achieved using live BCG vaccine (Fig. 6). This difference correlated with increased survival by the J3R-vaccinated mice, none of which died during the 12 week challenge period, while all of the vector controls succumbed to the aerogenic challenge. The need for this type of adjuvant renders the present vaccine of little practical value for use in humans, but the mere fact that it worked at all makes this recombinant worth investigating further.

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REFERENCES


