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1 **A live attenuated vaccine confers better protection than BCG against**

2 ***Mycobacterium tuberculosis* Beijing in mice**

3

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24

25

26 **ABSTRACT**

27 Tuberculosis still claims more lives than any other pathogen, and a vaccine better than BCG
28 is urgently needed. One of the challenges for novel TB vaccines is to protect against all
29 *Mycobacterium tuberculosis* lineages, including the most virulent ones, such as the Beijing
30 lineage. Here we developed a live attenuated *M. tuberculosis* mutant derived from GC1237,
31 a Beijing strain responsible for tuberculosis outbreaks in the Canary Islands. The mutant
32 strain is inactivated both in the Rv1503c gene, responsible for surface glycolipid synthesis,
33 and in the two-component global regulator PhoPR. This double mutant is as safe as BCG in
34 immunodeficient SCID mice. In immune-competent mice and guinea pigs, the mutant is as
35 protective as BCG against *M. tuberculosis* strains of common lineage 4 (Euro-American). By
36 contrast, in mice the vaccine is protective against a *M. tuberculosis* strain of lineage 2 (East-
37 Asian, Beijing), while BCG is not. These results highlight differences in protection efficacy of
38 live attenuated *M. tuberculosis*-derived vaccine candidates depending on their genetic
39 background, and provide insights for the development of novel live vaccines against TB,
40 especially in East-Asian countries where *M. tuberculosis* strains of the Beijing family are
41 highly dominant.

42

43

44 **1. Introduction**

45 With an estimated 1.6 million deaths in 2017 according to the World Health Organization,
46 tuberculosis (TB) is among the top 10 causes of death worldwide, and the leading cause of
47 death from a single pathogen [1]. The only TB vaccine currently in use, Bacillus Calmette
48 Guérin (BCG), is known to protect efficiently against disseminated forms of TB in infants [2],
49 and even protects against other childhood infectious diseases, possibly through trained
50 immunity-related mechanisms [3]. Due to their broad antigen content, long-lasting and
51 natural adjuvant properties, live attenuated vaccines, such as BCG, are generally considered
52 most promising for conferring durable immunity, compared to subunit vaccines [4].
53 Protection conferred by BCG was reported to last up to 10-15 years, and even longer in
54 some instances [5-7]. Yet, the efficacy of BCG to prevent *Mycobacterium tuberculosis*
55 infection or TB reactivation in adults is too variable, ranging from nil to 80%, and novel
56 vaccines or vaccination strategies against TB are highly needed [2, 8, 9]. BCG revaccination at
57 adolescence was long considered a possible strategy to boost protection conferred by BCG
58 administered at birth. Several large-scale studies showed that BCG revaccination confers
59 only modest, if any, improved protection [10, 11], most likely due to immune sensitization
60 following pre-exposure to environmental mycobacteria [8, 12, 13]. These results were
61 challenged by a recent study conducted in South Africa that reported BCG revaccination
62 protected against sustained *M. tuberculosis* infection, as reflected by sustained
63 QuantiFERON-TB Gold In-tube assay conversion, with an efficacy of 45% [14]. The apparent
64 discrepancy between these results and those from previous studies are thought to be due,
65 at least in part, to the low level of exposure to environmental mycobacteria in the Cape
66 Town area. This will nevertheless need to be evaluated, and these results will need to be
67 confirmed in other settings and on longer time periods. In the meantime, and given the

68 variability of efficacy of BCG, there is a strong rationale for development of alternative live
69 attenuated vaccines that would perform better than BCG.

70 To be considered for advancing in the preclinical pipeline, live vaccine candidates other than
71 BCG need to be at least as safe as BCG and more effective than BCG, considered as a
72 benchmark, in small animal models of TB, such as mice and guinea pigs [15].

73 A few live vaccine candidates based on recombinant BCG and attenuated *M. tuberculosis* are
74 currently in preclinical or clinical development [8, 16, 17]. These include VPM1002, a
75 recombinant BCG strain expressing listeriolysin and lacking the urease component UreC [18-
76 21]; and MTBVAC, a *M. tuberculosis* mutant inactivated in FadD26, involved in the synthesis
77 of the virulence lipids PDIM, and the master transcriptional regulator PhoP [22-25].

78 Noteworthy, such live vaccine candidates are also considered to be used as boosters, on the
79 top of BCG, and MTBVAC already showed promise in this direction, significantly reducing TB
80 disease [26].

81 One of the major challenges in TB vaccine development is to develop a vaccine that confers
82 protection against all *M. tuberculosis* strains, including the most virulent ones, such as those
83 of lineage 2 (East-Asian or Beijing) [27-29]. Indeed BCG is thought to poorly protect against
84 strains of the Beijing lineage, which might explain, at least in part, the global spread of this
85 lineage [30, 31]. This hypothesis is supported by experiments in TB animal models in some
86 reports [32, 33], but not in others [34, 35], which calls for more studies in this context.

87 We recently isolated *M. tuberculosis* mutants generated in the GC1237 strain, which belongs
88 to lineage 2, with an impaired capacity to prevent phagosome acidification in macrophages
89 and to survive in these cells [36]. One of these mutants, inactivated in the Rv1503c gene,
90 was affected in glycolipid synthesis and was found to be attenuated both in macrophages

91 and *in vivo* in mice [36]. Here we exploited this mutant to generate a double mutant in both
92 Rv1503c and the *phoPR* operon, involved in mycobacterial virulence [37]. The resulting
93 double mutant was found to be as safe as BCG in immune-deficient SCID mice and as
94 protective as BCG against common strains of lineage 4 (e.g. the laboratory strain H37Rv) in
95 mice and guinea pigs. Strikingly, this mutant was protective against a Beijing isolate, while
96 BCG was not. These results highlight the importance of taking the genetic background of *M.*
97 *tuberculosis* into consideration when generating novel live attenuated *M. tuberculosis*-based
98 vaccines, and provide clues for the development of TB vaccines with broader efficacy against
99 multiple strains and lineages of the TB bacillus.

100

101

102 **2. Materials and methods**

103 **2.1 Media and bacterial strains**

104 All *M. tuberculosis* strains and BCG (Danish strain 1331) were grown in Middlebrook 7H9
105 culture medium (Difco, Sparks MD) supplemented with 10% albumin-dextrose-catalase
106 (ADC, Difco), glycerol, 0.05% Tween 80, kanamycin (25 µg/mL) and/or hygromycin (50
107 µg/mL) in the case of the mutants. *M. tuberculosis* GC1237 and the Rv1503c transposon
108 insertion mutant (Rv1503c::Tn) were previously described [36].

109 **2.2 Construction of the *phoPR* deletion mutant**

110 Construction of the GC1237 Rv1503c::TnΔ*phoPR* double mutant was performed using the
111 thermosensitive bacteriophage phWM27 constructed previously [38]. This construct
112 harbours a DNA fragment overlapping the *phoPR* genes from H37Rv and carrying a
113 deletion/insertion replacing the 3' end of *phoP* and the 5' end of *phoR* by a hygromycin-
114 resistance marker. This fragment was cloned into the recombinant bacteriophage phAE87
115 [39]. The phWM27 bacteriophage was transferred into the recipient strain GC1237 Rv1503
116 ::Tn as described previously [39] and hygromycin resistance colonies were selected on 7H11
117 OADC Hyg (50µg/ml) agar plates incubated at 37°C. Six individual clones were analysed by
118 PCR amplification using primers *phoE* (5'-CTTGTCGATCAGTCCGCCT-3') and *phoF* (5'-
119 GACACGAAAGCAGCAACCC-3'), located upstream and downstream respectively on the *M.*
120 *tuberculosis* genome from the DNA fragment carried by the phWM27 bacteriophage, and
121 the *hyg* gene specific primers H1 (5'-GGGATCGCCAATCTCTACG-5') and H2 (5'-
122 GCCTTCACCTTCTGAC-3'). One clone exhibiting the expected PCR amplification profile for
123 allelic replacement was retained for further studies and named GC1237 Rv1503c::TnΔ*phoPR*.

124 **2.2 Ethics and animal experiments**

125 Intranasal safety experiments in SCID mice and protection assays in C3H/HeNRj mice were
126 conducted in strict accordance with French laws and regulations in compliance with the
127 European community council directive 68/609/EEC guidelines and its implementation in
128 France. All protocols were reviewed and approved by the Comité d’Ethique Midi-Pyrénées
129 (reference MP/03/07/04/09) and the Comité d’Ethique FRBT (APAFIS #11404).

130 Intravenous safety experiments in CB17 SCID mice and protection assays in CB6F1 mice and
131 in guinea pigs were approved by the UK Home Office (HO) regulations for animal
132 experimentation which requires a HO-approved licence and approval from local ethical
133 committees of Public Health England, Porton Down (Licence number PPL30/3236) and
134 London School of Hygiene and Tropical Medicine (LSHTM) Animal Welfare and Ethical
135 Review Board (Authorization # 70/6934).

136 Immunogenicity and efficacy experiments in C57BL/6J mice infected with Beijing and non-
137 Beijing TB strains, were carried out accordingly following the guidelines of the Korean Food
138 and Drug Administration (KFDA). The experimental protocols used in this study were
139 reviewed and approved by the Ethics Committee and Institutional Animal Care and Use
140 Committee (Permit Number: 2015-0041) of the Laboratory Animal Research Center at Yonsei
141 University College of Medicine (Seoul, Korea).

142 **2.3 Safety assays**

143 For intranasal testing of residual virulence, 3 groups of severe combined immunodeficient
144 (SCID) mice were infected via the intranasal route with *M. tuberculosis* wild-type (GC1237,
145 Beijing strain), or the Rv1503c::Tn (500 CFU/animal) or 1,000 CFUs BCG Pasteur. For
146 intravenous assays, two groups of 8, female CB17 SCID mice were subjected to challenge
147 with a single dose of bacteria (nominally 10^6 CFU/mouse) of either BCG Danish 1331 or the
148 candidate vaccines GC1237 Rv1503c::Tn or GC1237 Rv1503c::Tn Δ *phoPR*, in a total volume of

149 200 μ L diluted in pyrogen-free sterile saline. Actual number of bacteria administered to each
150 group was assessed by CFU counting of the diluted inocula on the day of challenge (see
151 Figure legend). Percentage of body weight change was calculated over time. Data are
152 presented as survival curves compared to the gold standard BCG Danish 1331 using the
153 Kaplan-Meier method. Statistical differences were assessed using GraphPad Prism 7.01
154 software using the Log-Rank (Mantel-Cox) test with Bonferroni correction with statistical
155 significance considered to be a *P* value equal or smaller than 0.05.

156 **2.4 Protection assay in mice**

157 For protection assays in CB6F1/Crl mice, groups of 6, female mice aged 6-8 weeks were
158 used. The following three experimental groups were evaluated: saline, BCG Danish 1331,
159 and GC1237 Rv1503c::Tn Δ *phoPR*. Mice were vaccinated subcutaneously with 5×10^6
160 CFU/mouse in 100 μ L pyrogen-free sterile saline. Six weeks after vaccination mice were
161 subjected to an aerosol challenge with *Mycobacterium tuberculosis* H37Rv aiming for an
162 infective dose level of 100 CFU/mouse. Lungs and spleens from mice infected with H37Rv
163 were harvested 6 weeks after challenge. For logistic reasons lungs were homogenized and
164 plated on the same day as harvest on complete 7H11 agar plates, while spleens were kept
165 refrigerated overnight and homogenates were prepared prior to plating corresponding
166 dilutions for CFU counting. The CFU data obtained were analysed using One-way ANOVA
167 statistical test followed by Tukey's test for multiple comparison tests to compare mean
168 values of the various experimental groups. GraphPad Prism 7.01 software was used for the
169 statistical analysis. A *P* value equal or less than 0.05 was considered significant.

170 For protection assays in C3H/HeNRj mice, 3 groups of 6 8–10 weeks old females were
171 vaccinated subcutaneously (100 μ L) with 10^6 CFU of the vaccine strains in PBS (Saline, BCG
172 Danish or GC1237Rv1503::Tn Δ *phoPR*). Eight weeks post vaccination, mice were intranasally

173 challenged with 500 CFU of H37Rv in 25 μ L of PBS. Bacterial burden was assessed 4 weeks
174 post challenge by plating homogenized lungs on solid medium.

175 For comparative protection assays against *M. tuberculosis* M2 and HN878, 6-7-week old
176 female C57BL/6 mice were used. The following three experimental groups were evaluated
177 against *M. tuberculosis* M2 and HN878: saline, BCG Pasteur 1173P2, and GC1237
178 Rv1503c::Tn Δ phoPR. Mice were vaccinated subcutaneously with 1×10^6 CFU/mouse in 300 μ l
179 pyrogen-free sterile saline. Nine weeks after vaccination mice were subjected to an aerosol
180 challenge with *M. tuberculosis* strain M2 or HN878 aiming for an infective dose level of 200-
181 250 CFU/mouse. The protective efficacy of BCG Pasteur 1173P2, and GC1237
182 Rv1503c::Tn Δ phoPR against *M. tuberculosis* strain M2 and HN878 was determined at 6
183 weeks from challenge through analysis of the histopathology and bacterial growth in the
184 lung and spleen. For the lung histopathology analysis, the right-superior lobes were
185 preserved overnight in 10% formalin and embedded in paraffin. The lung was sectioned at
186 4–5 μ m and stained with H&E. For the bacterial growth analysis, the lung and spleen were
187 homogenized, and serially diluted samples were plated onto Middlebrook 7H11 agar plates
188 (Becton Dickinson, Franklin Lakes, NJ, USA) supplemented with 10% OADC (Difco
189 Laboratories), 2 μ g/ml 2-thiophenecarboxylic acid hydrazide (Sigma-Aldrich, St. Louis, MO,
190 USA) and amphotericin B (Sigma-Aldrich). After incubation at 37°C for 3-4 weeks, the
191 bacterial colonies were counted. The comparison of lung inflamed area and CFU data
192 obtained were analysed using One-way ANOVA statistical test followed by Tukey's test for
193 multiple comparison tests to compare mean values of the various experimental groups.
194 GraphPad Prism 7.01 software was used for the statistical analysis. A *P* value equal or less
195 than 0.05 was considered significant.

196

197 **2.5 Protection assay in guinea pigs**

198 Animals were individually identified using subcutaneously implanted microchips (Plexx, the
199 Netherlands) to enable blinding of the analyses wherever possible. Group sizes were
200 determined by statistical power calculations (Minitab, version 16) performed using previous
201 data (SD, approximately 0.5) to reliably detect a difference of 1.0 log₁₀ in the mean number
202 of colony-forming units (CFU) per millilitre. Groups of eight female Dunkin-Hartley guinea-
203 pigs (250 g) were s.c. vaccinated with saline, BCG Danish 1331 (5x10⁴ CFU in 250 µl), or the
204 GC1237 Rv1503c::TnΔ*phoPR* vaccine candidate (5x10⁶ CFU in 100 µl). Six weeks after,
205 animals were aerosol-challenged with a low dose (10–50 CFU/animal) of *M. tuberculosis*
206 H37Rv, generated from a suspension at 3x10⁶ CFU/mL using a modified Henderson
207 apparatus and AeroMP control unit. Four weeks post-challenge, animals were euthanized by
208 intraperitoneal injection of sodium pentobarbital (Dolethal, Vetoquinol UK Ltd) and lungs
209 and spleen were removed aseptically. The spleen minus a small apical section and the
210 combined left apical, cardiac, right cardiac and right diaphragmatic lung lobes were
211 homogenized in 5 and 10 mL sterile water, respectively. Serial dilutions were plated (0.1 mL
212 per plate, in duplicate) on Middlebrook 7H11 selective agar (bioMerieux UK Ltd). After 3–4
213 weeks incubation at 37 °C, colonies were counted to measure CFU/mL of homogenate. Total
214 CFU was calculated by multiplying CFU/mL by the homogenate volume. Where no colonies
215 were observed, a minimum detection limit was set by assigning a count of 0.5 colonies,
216 equating to 5 CFU/mL. Samples for histopathology were processed and analysed as
217 described [40]. Pair-wise analysis of the log transformed CFU values was performed using
218 the Mann-Whitney non-parametric test to compare between the groups. The histopathology
219 scores for the lung were the product of a subjective scoring system [40]. Therefore,

220 statistical analysis was not performed on these data, but a two-sample *t*-test was used to
221 compare the number of lesions in the spleen.

222 **2.6 Immunogenicity assays in mice**

223 In order to evaluate immunogenicity of GC1237 Rv1503c::Tn Δ *phoPR* mutant, C57BL/6 mice
224 were vaccinated with BCG or GC1237 Rv1503c::Tn Δ *phoPR* mutant subcutaneously (1×10^6
225 CFU/mouse). Nine weeks after vaccination, non-vaccinated, BCG- or GC1237
226 Rv1503c::Tn Δ *phoPR* mutant-vaccinated groups were sacrificed for analysis. The lungs and
227 spleens were removed and used for the preparation of single-cell suspensions. Lung cell and
228 splenocyte were treated with 2 μ g/ml PPD for 12 h, and the level of IFN- γ secreted from the
229 lung and spleen cells were measured with ELISA. For the analysis of functional CD4⁺ and
230 CD8⁺ T cells secreting IFN- γ , TNF- α , and IL-2, individual lung and spleen cells were prepared
231 and cultured with stimulation of with 2 μ g/ml PPD for 12 h in the presence of GolgiPlug and
232 GolgiStop (BD, Bioscience). First, the cells were washed with PBS, and the Fc receptor was
233 blocked with anti-CD16/32 blocking antibody at 4°C for 15 min. Surface molecules were
234 stained with fluorochrome-conjugated antibodies against Thy1.2, CD4, CD8 and CD44 and
235 using the LIVE/DEAD™ Fixable Dead Cell Kit for 30 min at 4°C. The cells were then washed
236 with PBS, fixed and permeabilized with Cytofix/Cytoperm (BD Biosciences) for 30 min at
237 4°C. The permeabilized cells were washed twice with Perm/Wash (BD Biosciences) and
238 stained anti-IFN- γ , anti-TNF- α and anti-IL-2 Abs for 30 min at 4°C. Cells were washed
239 twice with Perm/Wash and fixed with IC fixation buffer (eBioscience) for flow cytometry
240 analysis.

241

242

243

244 3. Results and Discussion

245 We previously isolated several *M. tuberculosis* mutants defective for phagosomal
246 maturation arrest and intracellular survival in macrophages [36]. These mutants were
247 generated in a *M. tuberculosis* strain, GC1237, that belongs to the East-Asian/Beijing family
248 (lineage 4), and which was responsible for TB outbreaks in the Canary Islands [41]. Two of
249 these mutants, in Rv1503c and Rv1506c, were further characterized as defective in the
250 biosynthesis of various surface glycolipids and were found attenuated in mice [36]. Based on
251 these results, we sought to explore whether such mutants may represent promising live
252 attenuated vaccine candidates for TB.

253 We further explored the residual virulence of the Rv1503c-inactivated mutant in immune-
254 deficient SCID mice in two models: a mildly severe model of intranasal infection, and a more
255 stringent model of intravenous infection. When given intranasally, the mutant was as safe as
256 BCG over a 140-day period (Fig. 1A). However, the more stringent intravenous model
257 revealed that this mutant retained significant virulence, with the infected animals starting to
258 show signs of disease, as reflected by weight loss, and to die 40 days post-infection (Fig.
259 1B,C). For this reason, we sought to further attenuate the Rv1503c-inactivated mutant
260 through genetic deletion of the two-component system PhoPR, which regulates a large
261 number of virulence genes in *M. tuberculosis* [37, 42]. The double mutant was found as safe
262 as BCG in the stringent intravenous model (Fig. 1D,E).

263 Next, the protective efficacy of the Rv1503c/*phoPR* double mutant against *M. tuberculosis*
264 laboratory strain H37Rv (lineage 2) was assessed in two mouse lines and in guinea pigs. In
265 CB6F1 mice, a cross between BALB/c and C57BL/6 mice, the mutant was as protective as
266 BCG (Fig 2A,B). We also used C3H/HeNRj mice, which were recently showed to exhibit better
267 protection against *M. tuberculosis* than BALB/c or C57BL/6 animals when vaccinated with

268 the live *M. tuberculosis*-derived vaccine MTBVAC [43]. In these mice, protection was
269 observed with both BCG and the double Rv1503c/*phoPR* mutant (with *P* values of 0.09 and
270 0.07, respectively), however the double mutant protected equally to BCG against H37Rv (Fig
271 2C). Similar results were obtained in guinea pigs, a widely used animal model to evaluate
272 protective efficacy of live and subunit TB vaccine candidates. In this model, the
273 Rv1503c/*phoPR* double mutant protected equally to BCG against *M. tuberculosis* H37Rv (Fig.
274 3). Altogether, these results indicate that the Rv1503c/*phoPR* double mutant is as protective
275 as BCG against *M. tuberculosis* H37Rv in small rodent animal models.

276 The H37Rv strain belongs to the Euro-American lineage (lineage 4) of *M. tuberculosis*.

277 Because our vaccine candidate was generated in a Beijing background, we next sought to
278 assess whether it could confer better protection than BCG against *M. tuberculosis* strains of
279 this lineage. Indeed, BCG is reported to poorly protect against *M. tuberculosis* Beijing in
280 several animal models [32, 33], and it has been suggested that the same might happen in
281 humans, which may explain, at least in part, the global spread of this lineage worldwide [30,
282 31].

283 C57BL/6J mice were immunized with either saline, BCG or the Rv1503c/*phoPR* double
284 mutant. Pre-infection immunogenicity analysis revealed that the double mutant induced an
285 increased production of IFN γ , compared to BCG, in the lungs and spleen (Fig. 4A). The
286 mutant also induced more TNF α -producing effector CD4⁺ T cells in the lungs, and more
287 multi-functional effector CD4⁺ T cells in the spleen, compared to BCG (Fig. 4B). More TNF α -
288 producing CD8⁺ T cells were also observed in the spleen of mice vaccinated with the double
289 mutant, compared to BCG (Fig. 4B).

290 Nine weeks after vaccination, vaccinated mice were challenged with *M. tuberculosis* M2, a
291 strain of the Euro-American lineage 4, or HN878, a Beijing strain of the East-Asian lineage 4.

292 Six weeks later, lungs and spleen were recovered for CFU and histo-pathological analyses. As
293 previously reported [44], BCG did not confer significant protection against the Beijing strain
294 of *M. tuberculosis* (Fig. 5A). Remarkably, the GC1237 Rv1503c/*phoPR* double mutant
295 conferred significant long-term (15 weeks post-vaccination) protection to both the M2 and
296 the HN878 strains (Fig. 5A). As previously reported [45], lung cells from mice infected with
297 the HN878 Beijing strain produced less IFN γ than lung cells from mice infected with the non-
298 Beijing strain, when restimulated *ex vivo* with PPD (Fig. 5B). Nevertheless, increased
299 protection against HN878 conferred by the Rv1503c/*phoPR* double mutant was
300 accompanied by an increased production of IFN γ by lung cells from the mutant-vaccinated
301 mice, compared to unvaccinated mice ($P=0.0015$) or to BCG-vaccinated mice ($P=0.09$; Fig.
302 5B). In line with bacterial growth control results, Rv1503c/*phoPR* double mutant vaccination
303 resulted in slightly better restoration of inflamed lesion than BCG vaccination in HN878
304 infected mice, but BCG vaccination displayed more mitigated lung lesion than
305 Rv1503c/*phoPR* double mutant vaccination in M2 infected mice compared to non-
306 vaccinated animals (Fig. 5C,D).

307

308 **4. Conclusion**

309 To our knowledge our report is the first to date of a live attenuated *M. tuberculosis*-derived
310 vaccine candidate generated in a Beijing/lineage 2 background.

311 Although this vaccine confers equal protection to BCG against *M. tuberculosis* H37Rv and M2
312 strains, which both belong to lineage 4, in mice and guinea pigs, it confers protection against
313 HN878, a Beijing strain, while BCG does not, at least in mice. This may be explained, in part,
314 by differential antigen expression in *M. tuberculosis* Beijing and non-Beijing strains, such as
315 that reported in the DosR regulon [46, 47], which will require further investigation. These

316 results suggest that combining live attenuated TB vaccines generated in multiple genetic
317 backgrounds might be a promising approach to develop a multivalent vaccine with broader
318 efficacy against all *M. tuberculosis* strains, including the Beijing family that is particularly
319 dominant in Eastern Europe and South-East Asia.

320

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332

333 **Authors' contribution**

334 Conceptualization & Methodology, F.L., K.H., K.W.K, S.C., F.C., W.M., C.G., G.J.B., A.W., S.J.S.,
335 Y.P., and O.N.; Resources, P.B. and B.G.; Writing, F.L., Y.P. and O.N.; Proofreading and
336 editing, S.C., A.W., and S.J.S.; Supervision, Y.P. and O.N.

337

338 **Conflict of interests**

339 The authors declare no conflicting interests.

340 **References**

- 341 1. WHO. Global tuberculosis report 2018, World Health Organization, Geneva. **2018**.
342 2. Furin J, Cox H, Pai M. Tuberculosis. *Lancet* **2019**; 393:1642-56.
343 3. de Bree LCJ, Koeken V, Joosten LAB, et al. Non-specific effects of vaccines: Current
344 evidence and potential implications. *Semin Immunol* **2018**; 39:35-43.
345 4. Scriba TJ, Kaufmann SH, Henri Lambert P, Sanicas M, Martin C, Neyrolles O. Vaccination
346 Against Tuberculosis With Whole-Cell Mycobacterial Vaccines. *The Journal of infectious*
347 *diseases* **2016**; 214:659-64.
348 5. Abubakar I, Pimpin L, Ariti C, et al. Systematic review and meta-analysis of the current
349 evidence on the duration of protection by bacillus Calmette-Guerin vaccination against
350 tuberculosis. *Health Technol Assess* **2013**; 17:1-372, v-vi.
351 6. Aronson NE, Santosham M, Comstock GW, et al. Long-term efficacy of BCG vaccine in
352 American Indians and Alaska Natives: A 60-year follow-up study. *JAMA* **2004**; 291:2086-91.
353 7. Nguipdop-Djomo P, Heldal E, Rodrigues LC, Abubakar I, Mangtani P. Duration of BCG
354 protection against tuberculosis and change in effectiveness with time since vaccination in
355 Norway: a retrospective population-based cohort study. *The Lancet Infectious diseases*
356 **2016**; 16:219-26.
357 8. Andersen P, Scriba TJ. Moving tuberculosis vaccines from theory to practice. *Nature*
358 *reviews Immunology* **2019**; 19:550-62.
359 9. Fine PE. Variation in protection by BCG: implications of and for heterologous immunity.
360 *Lancet* **1995**; 346:1339-45.
361 10. Randomised controlled trial of single BCG, repeated BCG, or combined BCG and killed
362 *Mycobacterium leprae* vaccine for prevention of leprosy and tuberculosis in Malawi.
363 Karonga Prevention Trial Group. *Lancet* **1996**; 348:17-24.
364 11. Rodrigues LC, Pereira SM, Cunha SS, et al. Effect of BCG revaccination on incidence of
365 tuberculosis in school-aged children in Brazil: the BCG-REVAC cluster-randomised trial.
366 *Lancet* **2005**; 366:1290-5.
367 12. Barreto ML, Pereira SM, Pilger D, et al. Evidence of an effect of BCG revaccination on
368 incidence of tuberculosis in school-aged children in Brazil: second report of the BCG-REVAC
369 cluster-randomised trial. *Vaccine* **2011**; 29:4875-7.
370 13. Barreto ML, Pilger D, Pereira SM, et al. Causes of variation in BCG vaccine efficacy:
371 examining evidence from the BCG REVAC cluster randomized trial to explore the masking
372 and the blocking hypotheses. *Vaccine* **2014**; 32:3759-64.
373 14. Nemes E, Geldenhuys H, Rozot V, et al. Prevention of *M. tuberculosis* Infection with
374 H4:IC31 Vaccine or BCG Revaccination. *The New England journal of medicine* **2018**; 379:138-
375 49.
376 15. Walker KB, Brennan MJ, Ho MM, et al. The second Geneva Consensus:
377 Recommendations for novel live TB vaccines. *Vaccine* **2010**; 28:2259-70.
378 16. Kaufmann SHE, Dockrell HM, Drager N, et al. TBVAC2020: Advancing Tuberculosis
379 Vaccines from Discovery to Clinical Development. *Frontiers in immunology* **2017**; 8:1203.
380 17. Voss G, Casimiro D, Neyrolles O, et al. Progress and challenges in TB vaccine
381 development. *F1000Res* **2018**; 7:199.
382 18. Grode L, Ganoza CA, Brohm C, Weiner J, 3rd, Eisele B, Kaufmann SH. Safety and
383 immunogenicity of the recombinant BCG vaccine VPM1002 in a phase 1 open-label
384 randomized clinical trial. *Vaccine* **2013**; 31:1340-8.

- 385 19. Grode L, Seiler P, Baumann S, et al. Increased vaccine efficacy against tuberculosis of
386 recombinant *Mycobacterium bovis* bacille Calmette-Guerin mutants that secrete
387 listeriolysin. *The Journal of clinical investigation* **2005**; 115:2472-9.
- 388 20. Loxton AG, Knaul JK, Grode L, et al. Safety and Immunogenicity of the Recombinant
389 *Mycobacterium bovis* BCG Vaccine VPM1002 in HIV-Unexposed Newborn Infants in South
390 Africa. *Clinical and vaccine immunology : CVI* **2017**; 24.
- 391 21. Nieuwenhuizen NE, Kulkarni PS, Shaligram U, et al. The Recombinant Bacille Calmette-
392 Guerin Vaccine VPM1002: Ready for Clinical Efficacy Testing. *Frontiers in immunology* **2017**;
393 8:1147.
- 394 22. Arbues A, Aguilo JI, Gonzalo-Asensio J, et al. Construction, characterization and
395 preclinical evaluation of MTBVAC, the first live-attenuated *M. tuberculosis*-based vaccine to
396 enter clinical trials. *Vaccine* **2013**; 31:4867-73.
- 397 23. Martin C, Williams A, Hernandez-Pando R, et al. The live *Mycobacterium tuberculosis*
398 *phoP* mutant strain is more attenuated than BCG and confers protective immunity against
399 tuberculosis in mice and guinea pigs. *Vaccine* **2006**; 24:3408-19.
- 400 24. Spertini F, Audran R, Chakour R, et al. Safety of human immunisation with a live-
401 attenuated *Mycobacterium tuberculosis* vaccine: a randomised, double-blind, controlled
402 phase I trial. *The lancet Respiratory medicine* **2015**; 3:953-62.
- 403 25. Tameris M, Mearns H, Penn-Nicholson A, et al. Live-attenuated *Mycobacterium*
404 *tuberculosis* vaccine MTBVAC versus BCG in adults and neonates: a randomised controlled,
405 double-blind dose-escalation trial. *The lancet Respiratory medicine* **2019**.
- 406 26. Clark S, Lanni F, Marinova D, Rayner E, Martin C, Williams A. Revaccination of Guinea Pigs
407 With the Live Attenuated *Mycobacterium tuberculosis* Vaccine MTBVAC Improves BCG's
408 Protection Against Tuberculosis. *The Journal of infectious diseases* **2017**; 216:525-33.
- 409 27. Gagneux S. Ecology and evolution of *Mycobacterium tuberculosis*. *Nature reviews*
410 *Microbiology* **2018**; 16:202-13.
- 411 28. Niemann S, Merker M, Kohl T, Supply P. Impact of Genetic Diversity on the Biology of
412 *Mycobacterium tuberculosis* Complex Strains. *Microbiol Spectr* **2016**; 4.
- 413 29. Orgeur M, Brosch R. Evolution of virulence in the *Mycobacterium tuberculosis* complex.
414 *Current opinion in microbiology* **2018**; 41:68-75.
- 415 30. Merker M, Blin C, Mona S, et al. Evolutionary history and global spread of the
416 *Mycobacterium tuberculosis* Beijing lineage. *Nature genetics* **2015**; 47:242-9.
- 417 31. Parwati I, van Crevel R, van Soolingen D. Possible underlying mechanisms for successful
418 emergence of the *Mycobacterium tuberculosis* Beijing genotype strains. *The Lancet*
419 *Infectious diseases* **2010**; 10:103-11.
- 420 32. Lopez B, Aguilar D, Orozco H, et al. A marked difference in pathogenesis and immune
421 response induced by different *Mycobacterium tuberculosis* genotypes. *Clinical and*
422 *experimental immunology* **2003**; 133:30-7.
- 423 33. Tsenova L, Harbacheuski R, Sung N, Ellison E, Fallows D, Kaplan G. BCG vaccination
424 confers poor protection against *M. tuberculosis* HN878-induced central nervous system
425 disease. *Vaccine* **2007**; 25:5126-32.
- 426 34. Henao-Tamayo M, Shanley CA, Verma D, et al. The Efficacy of the BCG Vaccine against
427 Newly Emerging Clinical Strains of *Mycobacterium tuberculosis*. *PloS one* **2015**;
428 10:e0136500.
- 429 35. Jeon BY, Derrick SC, Lim J, et al. *Mycobacterium bovis* BCG immunization induces
430 protective immunity against nine different *Mycobacterium tuberculosis* strains in mice.
431 *Infection and immunity* **2008**; 76:5173-80.

432 36. Brodin P, Poquet Y, Levillain F, et al. High content phenotypic cell-based visual screen
433 identifies *Mycobacterium tuberculosis* acyltrehalose-containing glycolipids involved in
434 phagosome remodeling. *PLoS pathogens* **2010**; 6:e1001100.

435 37. Perez E, Samper S, Bordas Y, Guilhot C, Gicquel B, Martin C. An essential role for *phoP* in
436 *Mycobacterium tuberculosis* virulence. *Molecular microbiology* **2001**; 41:179-87.

437 38. Gonzalo-Asensio J, Malaga W, Pawlik A, et al. Evolutionary history of tuberculosis shaped
438 by conserved mutations in the *PhoPR* virulence regulator. *Proceedings of the National*
439 *Academy of Sciences of the United States of America* **2014**; 111:11491-6.

440 39. Bardarov S, Bardarov S, Jr., Pavelka MS, Jr., et al. Specialized transduction: an efficient
441 method for generating marked and unmarked targeted gene disruptions in *Mycobacterium*
442 *tuberculosis*, *M. bovis* BCG and *M. smegmatis*. *Microbiology* **2002**; 148:3007-17.

443 40. Bottai D, Frigui W, Clark S, et al. Increased protective efficacy of recombinant BCG strains
444 expressing virulence-neutral proteins of the ESX-1 secretion system. *Vaccine* **2015**; 33:2710-
445 8.

446 41. Alonso H, Aguilo JI, Samper S, et al. Deciphering the role of IS6110 in a highly
447 transmissible *Mycobacterium tuberculosis* Beijing strain, GC1237. *Tuberculosis* **2011**;
448 91:117-26.

449 42. Gonzalo-Asensio J, Mostowy S, Harders-Westerveen J, et al. *PhoP*: a missing piece in the
450 intricate puzzle of *Mycobacterium tuberculosis* virulence. *PloS one* **2008**; 3:e3496.

451 43. Aguilo N, Gonzalo-Asensio J, Alvarez-Arguedas S, et al. Reactogenicity to major
452 tuberculosis antigens absent in BCG is linked to improved protection against *Mycobacterium*
453 *tuberculosis*. *Nature communications* **2017**; 8:16085.

454 44. Groschel MI, Sayes F, Shin SJ, et al. Recombinant BCG Expressing ESX-1 of
455 *Mycobacterium marinum* Combines Low Virulence with Cytosolic Immune Signaling and
456 Improved TB Protection. *Cell reports* **2017**; 18:2752-65.

457 45. Manca C, Tsenova L, Bergtold A, et al. Virulence of a *Mycobacterium tuberculosis* clinical
458 isolate in mice is determined by failure to induce Th1 type immunity and is associated with
459 induction of IFN- α / β . *Proceedings of the National Academy of Sciences of the United*
460 *States of America* **2001**; 98:5752-7.

461 46. Domenech P, Zou J, Averbach A, et al. Unique Regulation of the *DosR* Regulon in the
462 Beijing Lineage of *Mycobacterium tuberculosis*. *Journal of bacteriology* **2017**; 199.

463 47. Fallow A, Domenech P, Reed MB. Strains of the East Asian (W/Beijing) lineage of
464 *Mycobacterium tuberculosis* are *DosS/DosT-DosR* two-component regulatory system natural
465 mutants. *Journal of bacteriology* **2010**; 192:2228-38.

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468

469 **Legends to figures**

470 **Figure 1. Safety of the vaccine candidates. (A)** SCID mice (n=5 per group) were infected
471 intranasally with 1,000 CFUs of BCG (Pasteur), 500 CFUs of the single mutant Rv1503c::Tn
472 [36], or 500 CFUs of the GC1237 parental strain. Mice were killed when reaching the
473 humane endpoint, defined as the loss of >20% of bodyweight in accordance with ethics
474 committee guidelines. The median survival time was of 62 days for mice infected with
475 GC1237. **(B,C)** SCID mice (n=8 per group) were infected intravenously with saline, 10⁶ CFUs
476 of BCG Danish (1331) or 10⁶CFUs of the single mutant Rv1503c::Tn. Mice were killed (B)
477 when reaching the humane endpoint, defined as the loss of >20% of bodyweight (C), in
478 accordance with ethics committee guidelines. The median survival time was of 42 days for
479 mice infected with GC1237 Rv1503c::Tn. **(D,E)** SCID mice (n=8 per group) were infected
480 intravenously with 3x10⁵ CFUs of BCG Danish (1331) or 7x10⁵ CFU of the double mutant
481 Rv1503c::Tn Δ phoPR. Mice were killed (D) when reaching the humane endpoint, defined as
482 the loss of >20% of bodyweight (E), in accordance with ethics committee guidelines. The
483 median survival time was of 79 days for mice infected with BCG, and of 79.5 days for mice
484 infected with GC1237 Rv1503c::Tn Δ phoPR. **, P<0.01; ***, P<0.001; ****, P<0.0001.

485

486 **Figure 2. Efficacy studies in mice against *M. tuberculosis* H37Rv infection. (A,B)** CB6F1 mice
487 (n=6 per group) were vaccinated subcutaneously with 1.3x10⁶ CFU BCG Danish (1331) or
488 7x10⁶ CFU the GC1237 Rv1503c::Tn Δ phoPR strain. Control mice received saline. Six weeks
489 after vaccination, mice were subjected to an aerosol challenge with *M. tuberculosis* H37Rv
490 aiming for an infective dose level of 100 CFU/mouse. Lungs (A) and spleens (B) from infected
491 mice infected were harvested 6 weeks after challenge and homogenates were prepared
492 prior to plating onto 7H11 medium for CFU scoring. **(C)** C3H/HeNRj mice (n=6 per group)

493 were vaccinated subcutaneously with 10^6 CFU BCG Danish (1331) in PBS (100uL) or 10^6 CFU
494 the GC1237 Rv1503c::Tn Δ phoPR strain. Control mice received saline. Eight weeks after
495 vaccination, mice were subjected to intranasal challenge with *M. tuberculosis* H37Rv aiming
496 for an infective dose level of 200 CFU/mouse. Lungs from infected mice were harvested 4
497 weeks after challenge and homogenates were prepared prior to plating onto 7H11 medium
498 for CFU scoring. Data show mean and S.E.M.

499

500 **Figure 3. Efficacy studies in guinea pigs against *M. tuberculosis* H37Rv infection. (A, B)**

501 Dunkin Hartley guinea pigs (n=8 per group) were vaccinated subcutaneously with 5×10^4 CFU
502 BCG Danish (1331) or 5×10^6 CFU GC1237 Rv1503c::Tn Δ phoPR strain. Control guinea pigs
503 received saline. 16 weeks after vaccination, guinea pigs were subjected to a nose-only
504 aerosol challenge with *M. tuberculosis* H37Rv aiming for an infective dose level of 10-20
505 CFU/animal. Lungs (A and B left) and spleens (A and B right) from infected guinea pigs
506 infected were harvested 4 weeks after challenge. Homogenates were prepared from lung
507 and spleen prior to plating onto Middlebrook 7H11 agar medium for CFU scoring (A, left and
508 right, respectively). Lung and spleen sections from the same animals were also taken for
509 histological examination (B, left and right respectively)). Data show mean and S.E.M. ns, not
510 significant; *, $P < 0.05$; **, $P < 0.01$.

511

512 **Figure 4. Immunogenicity studies in mice.** C57BL/6 mice (n=6 per group) were vaccinated

513 subcutaneously with 10^6 CFU BCG Pasteur (1173P2) or 10^6 CFU of the GC1237

514 Rv1503c::Tn Δ phoPR mutant. Control mice received saline. Nine weeks after vaccination,

515 lungs and spleen were harvested for immunogenicity study. **(A)** Lung and spleen cells were

516 stimulated with PPD (2 µg/mL) at 37°C for 12 h. IFN γ production was quantified by ELISA in
517 the cell culture supernatant. **(B)** Lung (upper panels) and spleen (lower panels) cells were
518 stimulated with PPD (2 µg/mL) at 37°C for 12 hours in the presence of GolgiStop and
519 GolgiPlug and stained for FACS analysis. The frequency of IFN γ -, TNF α - and IL-2-producing
520 CD4⁺CD44⁺ (left panels) or CD8⁺CD44⁺ (right panels) T cells was determined by intracellular
521 cytokine staining. Data show mean and S.E.M. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

522

523 **Figure 5. Efficacy and immunogenicity studies in mice infected with *M. tuberculosis* M2**

524 **and HN878.** Mice were vaccinated as in Fig. 4. Nine weeks after vaccination, mice were
525 subjected to an aerosol challenge with *M. tuberculosis* M2 or HN878 aiming for an infective
526 dose level of 200 CFU/mouse. Six weeks after challenge, mice were sacrificed and lungs were
527 collected for analysis. **(A)** Lungs were homogenized and plated onto 7H11 medium for CFU
528 scoring. **(B)** IFN γ production by isolated lung cells was performed as in Fig. 4A. **(C)** The lung
529 lesions were visualized by H&E staining of the superior lobe of the right lung. The percentage
530 and area (mm²) of inflamed area was calculated and shown in dot graphs **(D)**. Data show
531 mean and S.E.M. **, $P < 0.01$; ***, $P < 0.001$.

532