Hindawi Publishing Corporation
Tuberculosis Research and Treatment
Volume 2011, Article ID 574591, 9 pages
doi:10.1155/2011/574591

Review Article

Mycobacterium bovis Bacille Calmette-Guérin as a Vaccine Vector for Global Infectious Disease Control

Kazuhiro Matsuo[1] and Yasuhiro Yasutomi[2,3]

[1] *R & D Department, Japan BCG Laboratory, 3-1-5 Matsuyama, Kiyose, Tokyo 204-0022, Japan*
[2] *Tsukuba Primate Research Center, National Institute of Biomedical Innovation, 1-1 Hachimandai, Tsukuba, Ibaraki 305-0843, Japan*
[3] *Department of Immunoregulation, Mie University Graduate School of Medicine, Tsu City, Mie Prefecture 514-8507, Japan*

Correspondence should be addressed to Kazuhiro Matsuo, matsuo@bcg.gr.jp

Received 13 January 2011; Accepted 7 March 2011

Academic Editor: Brian Eley

Mycobacterium bovis bacille Calmette-Guérin (BCG) is the only available vaccine for tuberculosis (TB). Although this vaccine is effective in controlling infantile TB, BCG-induced protective effects against pulmonary diseases in adults have not been clearly demonstrated. Recombinant BCG (rBCG) technology has been extensively applied to obtain more potent immunogenicity of this vaccine, and several candidate TB vaccines have currently reached human clinical trials. On the other hand, recent progress in the improvement of the BCG vector, such as the codon optimization strategy and combination with viral vector boost, allows us to utilize this bacterium in HIV vaccine development. In this paper, we review recent progress in rBCG-based vaccine studies that may have implications in the development of novel vaccines for controlling global infectious diseases in the near future.

1. Introduction

Mycobacterium bovis bacille Calmette-Guérin (BCG) is the only licensed vaccine that has substantially helped controlling tuberculosis (TB) for more than 80 years. This vaccine affords ~80% protection against TB meningitis and miliary TB in infants and young children [1]. However, the BCG-induced protective effects against pulmonary diseases over all ages are variable; the escalation of the worldwide TB epidemic is evidence that the vaccine does not work well to prevent pulmonary TB [2]. Recently, studies on the advanced molecular biology and genomics of mycobacteria have revealed that the BCG genome has various mutations and deletions compared with the original virulent strain of *Mycobacterium tuberculosis* and *M. bovis* [3]. Interestingly, there are substantial differences in the genomic DNA even among BCG substrains [4, 5] that can cause biological differences in the population of BCG vaccines.

Since a host-vector system in mycobacteria was developed in 1987 [6], recombinant BCG (rBCG) technology has been extensively applied in the development of vaccines against a variety of infectious diseases, including bacterial, viral, and parasitic infections in addition to TB [7, 8]. BCG is attractive as a vaccine vector because of its extensive safety record in humans, heat stability, low production cost, induction of long-lasting type 1 helper T cell (Th1) immunity, $CD8^+$ T-cell triggering, adjuvant activity, usability in newborns and its mucosal immune induction by oral administration. Taking the current situation of serious epidemics of emerging and reemerging diseases mainly in developing African and Asian countries into account, a new global vaccine should be affordable in such areas. Therefore, the low price and heat stability of BCG-based vaccines would be desirable. In this paper, we review various efforts to develop novel BCG vector-based vaccines mainly for controlling TB and HIV/AIDS.

2. Immunological Properties of BCG Vector

The immune responses induced by BCG are outlined in Figure 1. The most characteristic response to BCG is the induction of innate (nonspecific) immunity by cell wall components through toll-like receptors (TLRs) 2 and 4 on dendritic cells and macrophages [9]. After phagocytosis,

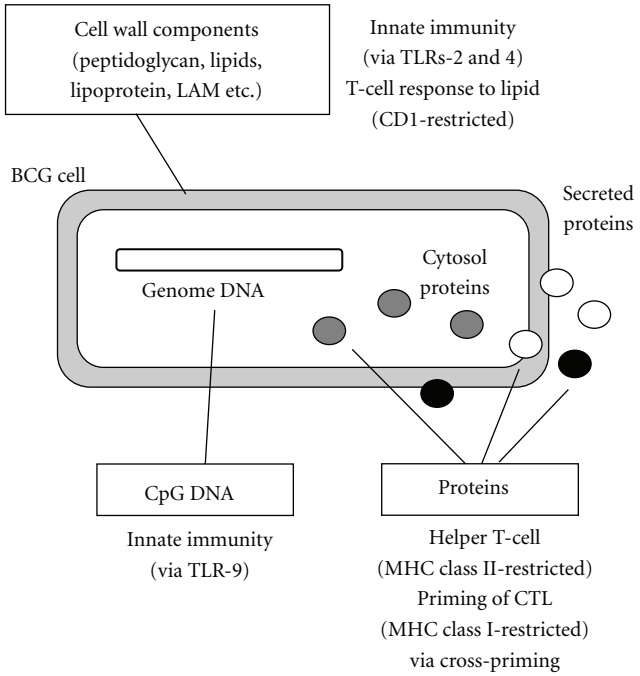

Figure 1: Outline of immune responses by BCG. Both innate immunity via TLRs and antigen-specific immunity via MHC- or CD1-restricted antigen presentation to T cells are induced by various BCG cell components.

BCG is degraded by lysosomal enzymes, and the processed antigen can be presented to the host immune system via various pathways. DNA fragments containing the CpG motif may activate innate immunity via the TLR9 route [10]. Lipids such as mycolic acid presented by CD1 stimulate CD1-restricted $CD8^+$ T cells [11]. Protein antigens, such as antigen 85 complex produced by BCG, induce Th1 response through presentation by major histocompatibility complex (MHC) class II. This pathway is the major route of BCG-induced responses and is indispensable for protective immunity against *M. tuberculosis* infection via protective cytokine interferon (IFN)-γ production. On the other hand, the processing and presentation of protein antigens via the MHC class I pathway are also elicited in the BCG-infected antigen presenting cell (APC). As reported by Goonetilleke et al. [12], immunizing BCG-sensitized animals with recombinant vaccinia virus MVA expressing antigen 85A greatly enhances the MHC class I-restricted CTL response against antigen 85A, indicating that BCG priming could be a novel type of prime-boost vaccine. This immunological feature of BCG vector allows its application in vaccines against chronic viral infectious diseases such as HIV/AIDS. In addition, the strong Th1 induction by BCG would be favorable to aid the maturation and maintenance of CTL [13]. Thus, the BCG vector is expected to induce effective cell-mediated immunity against a targeted antigen.

3. TB Vaccine

3.1. Background of the Global TB Epidemic. TB kills 1.7 million people worldwide each year; someone dies from TB every 19 seconds [14]. Although the TB treatment protocol was established a long time ago, the recent increase of multidrug-resistant *M. tuberculosis* infection has generated a serious situation. New vaccines are urgently needed to eliminate TB as a public health threat and should be a major global public health priority. TB is a disease that is spread from person to person through the air. Furthermore, the terrible synergy between TB and HIV makes this disease even more dangerous, especially in sub-Saharan African countries. For instance, according to the World Health Organization's (WHO) Global TB report 2010 [14], South Africa had nearly 400,000 new TB cases in 2009 with an incidence rate of an estimated 806 cases per 100,000; TB is one of the leading causes of death in both adults and children of this country. The case fatality rate has increased from 3% in 1993 to 24.3% in 2007. A major reason for the increased fatality rate is South Africa's concurrent HIV epidemic. The prevalence of HIV infection in South Africa in 2009 was approximately 7%, which has been decreasing as a result of various efforts toward prevention. TB is a common opportunistic infection among people living with HIV, and 60% of new TB cases occurred in persons who were also infected with HIV in 2009 [14]. We can observe similar critical situations in the countries surrounding South Africa. Regarding the vaccination, such situation has raised concerns about the safety of using BCG vaccine in HIV-infected infants because between 10 and 30% of pregnant women are HIV infected in many sub-Saharan African countries.

3.2. Current Efforts toward New TB Vaccine Development. The global plan to stop TB 2011–2015 report [15] offers 7 objectives as follows: (i) to maintain a robust TB vaccine pipeline by supporting research and discovery, (ii) to conduct research to identify correlates of protection and preclinical studies to assess new TB vaccine candidates, (iii) to ensure the availability of vaccine production capacity by expanding manufacturing facilities for TB vaccines, (iv) to build capacity for large-scale clinical trials (phases II and III) of TB vaccine candidates at field sites in TB-endemic countries, (v) to conduct phase I, II, and III clinical trials of TB vaccine candidates, (vi) to develop delivery, regulatory, and access strategies for new TB vaccines, (vii) to build support for TB vaccine development and uptake through advocacy, communications, and resource mobilization. All these objectives are important to realize new TB vaccine development.

The main goal of vaccine development in the Global Plan to Stop TB 2006–2015 is for 2 vaccines to be in proof-of-concept trials by 2010 and that 1 new and safe vaccine is available by 2015. As of 2009, 12 TB vaccine candidates had entered clinical trials. Of these, 9 are still being tested (Table 1) : 5 are in phase I clinical trials, 2 are in phase II trials, and 2 are in phase IIb proof-of-concept trials [15]. One vaccine has produced estimates of safety and effectiveness in a targeted HIV-infected population. At least 6 TB vaccine candidates are in preclinical development, and at least 21 additional next-generation candidates are in the vaccine discovery phase [15]. As mentioned earlier, the current BCG vaccine has limited and variable effectiveness against TB.

Table 1: Summary of candidate TB vaccines in clinical trials 2009. Nine candidate preventive TB vaccines are currently in clinical phases.

Status	Products	Product description	Sponsor
Phase IIb	MVA85A/AERAS-485	Vaccinia virus MVA	OETC/AERAS
Phase IIb	AERAS-402/Crucell Ad35	rBCG/adenovirus 35	Crucell/AERAS
Phase II	Hybrid-I + IC31	Ag85B/ESAT6 + adjuvant	SSI/TBVI
Phase II	M72	Fusion protein + adjuvant	GSK/AERAS
Phase I	AdAg85A	adenovirus 5/Ag85A	McMaster Univ.
Phase I	VPM 1002	rBCG/listeriolysin::ΔureC	Max Planck/TBVI
Phase I	Hyvac 4/AERAS-404	Fusion protein + adjuvant	SSI/Sanofi/AERAS
Phase I	RUTI	Fragmented Mtb cell	Archivel Farma
Phase I	Hybrid-I + CAF01	Ag85B/ESAT6 + adjuvant	SSI

Abbreviations in the sponsors: AERAS, AERAS Global TB Vaccine Foundation; GSK, GlaxoSmithKline; OETC, The Oxford-Emergent Tuberculosis Consortium Ltd.; SSI, Staten Serum Institute; TBVI, Tuberculosis Vaccine Initiative.

Therefore, the first choice of strategy may be improving BCG by using recombinant DNA technology even though it may imply safety issue of vaccination in HIV-infected individuals. Overproduction against a protective antigen of TB in BCG (rBCG30) exhibited enhanced immunogenicity in humans [16]. Moreover, the expression of the listeriolysin gene in BCG (rBCG/*hly*$^+$::Δ*ureC*) is proven to be more potent in the induction of TB-specific cellular immune responses [17]. Another strategy for improving BCG vaccines is boosting BCG immunity with protein [18, 19] or viral vector vaccine such as modified vaccinia virus Ankara (MVA) strain [20] and adenovirus type 35 [21]. BCG-prime and recombinant MVA-antigen 85A boost regimen [22] exhibited efficient immune responses in humans and have entered the first phase IIb trial in newborns. Furthermore, a combination of such strategies in which 3 major antigens are overproduced and the perfringolysin gene is incorporated into BCG and boosted with a recombinant adenovirus vaccine has been developed [23]. However, it is unknown whether such strategies are relevant for developing vaccines that are effective against adult pulmonary TB. It is necessary to test whether these candidate vaccines effectively induce mucosal immunity and protect against lung disease.

4. HIV/AIDS Vaccine

4.1. Background of the Global HIV Epidemic. In 2009, there were an estimated 2.6 million people who became newly infected with HIV. This is more than 21% less than the estimated 3.2 million who became infected in 1997, the year in which annual new infections peaked. In 33 countries, the incidence of HIV has decreased by more than 25% between 2001 and 2009; 22 of these countries are in sub-Saharan Africa. This trend reflects a combination of factors including the impact of HIV prevention efforts and the natural course of HIV epidemics [24].

Although highly activated antiretroviral therapy apparently contributes to control HIV replication in infected individuals [25], several problems remain to be resolved. These problems include: (i) the following viral load recovers soon after the interruption of treatment; (ii) chronic toxicities cause abnormalities in lipid metabolism and mitochondria; (iii) drug-resistant viruses increase during long period of treatment; (iv) long-term treatment carries a risk of carcinogenesis [26]; (v) expensive drugs are still difficult to access in developing countries. Even in developed countries, the high cost of antiretroviral drugs produces a sense of impending crisis in public health policy [27]. In such circumstances, although the rate of new infections with HIV-1 is gradually decreasing, an effective preventive vaccine is still urgently needed to stem further spread of the virus [28]. Even though considerable recent progress has been made in the development of an HIV vaccine [29, 30], the immune correlate of viral protection is not fully elucidated due to the complicated interaction of viral, immunological, and genetic factors [31, 32]. Since it is known that some populations of HIV-1-infected people do not present disease progression when HIV-1 replication is regulated by host immunity [33, 34], targeted vaccine immunogens are designed to closely mimic the long-lasting protective immunity induced in the long-term human survivors of natural infection [35, 36]. Due to safety issues, a live-attenuated HIV vaccine is not practical. This inevitably led the trend of HIV vaccine development to component- and vector-based vaccines.

4.2. Current Trends in HIV/AIDS Vaccine Research. The first large-scale efficacy trial of an HIV/AIDS vaccine was conducted by a US company, Vaxgen Co., in which a genetically engineered surface envelope (Env) glycoprotein, gp120, vaccine was tested in humans. Although the vaccine was targeted toward inducing effective virus-neutralizing antibodies, the phase III efficacy trial revealed its ineffectiveness [37, 38]. The failure of the gp120 vaccine changed the trend of HIV/AIDS vaccine research from an antibody-targeted strategy to a cell-mediated immunity-targeted strategy. Because HIV-1 causes chronic infection due to its cell-associated features, cellular immunity especially virus-specific cytotoxic T lymphocyte (CTL) should be a more important arm of the host immune system. Indeed, immune deficiency virus-specific cell-mediated immunity has been suggested to effectively control viral replication during the natural course of viral infections [39–41]. Based on these findings, various vaccine modalities, including live viral vectors and DNA vaccines, have been used to elicit strong CTL and Th1 type

responses in nonhuman primate models. Although single-vaccine delivery systems sometimes exhibit insufficient immune responses, boosting with viral vector vaccines such as vaccinia virus [40, 41], adenovirus [42, 43], and Sendai virus [44] in DNA-primed individuals strongly amplified CTL responses and resulted in the effective control of simian immunodeficiency virus (SIV) replication. Among such viral vectors, adenovirus type 5 (Ad5) had the strongest CTL enhancement effect, and the DNA-prime and recombinant Ad5 boost vaccine strategy is recognized as the most promising. However, in 2007, Merck Co. reported that a recombinant Ad5 vaccine expressing HIV-1 Gag, Pol, and Nef antigens did not demonstrate any protective efficacy in a phase IIB clinical trial [45]. Surprisingly, the vaccinated group exhibited a significantly higher HIV-1 infection rate than the placebo group [45], suggesting that the recombinant Ad5 immunization may have some unknown effect in enhancing HIV-1 infection. Thus, we were aware that T-cell vaccine approaches may involve certain risks and limitations; this paradigm appears to have reached an impasse.

In September 2009, there was ground-breaking news that the RV144 large-scale efficacy trial in Thailand demonstrated a partial effect of reducing HIV-1 infection rate in the recipients of ALVAC (canarypox)/gp120 prime-boost vaccine [46]. Although the results demonstrated limited effects, they demonstrated the possibility of preventing HIV infection with the active immunization for the first time. Furthermore, although there was no apparent correlation between protection and virus-specific cellular immune response or neutralizing antibody levels in the vaccinees, more detailed analyses of the total host responses are expected in the future. Taking the vaccine formulation with the gp120 protein boost into account, some antibody-mediated reactions may be involved in this partial protection. On the other hand, a new T-cell-targeted vaccine also demonstrated protective efficacy in a macaque study in the same year. A rhesus cytomegalovirus-vectored vaccine expressing SIV Gag, Rev-Tat-Nef, and Env persistently infected rhesus macaques, primed, and maintained robust SIV-specific $CD4^+$ and $CD8^+$ effector memory T-cell responses in the absence of neutralizing antibodies [47]. The report suggests that T cell vaccines may have greater potential than previously estimated. Although the importance of broadly neutralizing antibody production would not change despite tremendous difficulties, cellular immunity-targeted candidate vaccines should be also clinically tested for proofs of concept.

4.3. BCG-Vectored HIV Vaccine. The most practical advantage of the BCG vector is its high safety. In addition to being effective at inducing protective immunity, an HIV-1 vaccine regimen must be shown to be safe, affordable, and compatible with other vaccines before it can be considered promising [39]. In this respect, vectors that have already been used in humans without serious complications and with low cost should be utilized for HIV vaccines. BCG is a unique live vaccine vector because of its easy antigen delivery to the professional APC to be presented to T cells. Therefore, this bacterium is expected to be an important vector for HIV vaccine development.

At the early stage of rBCG research in the 1990s, Aldovini and Young [48] demonstrated immunogenicity of rBCG against genetically engineered HIV-1 antigens in mice. We independently worked on an rBCG-vectored anti-HIV vaccine simultaneously. First, we demonstrated effective cellular immune induction against SIV Gag antigen by the rBCG vector in rhesus macaques [49, 50]. Furthermore, we cloned an extracellular α antigen (antigen 85B) gene from both BCG [51] and *Mycobacterium kansasii* [52], and established a foreign antigen secretion system in mycobacteria [53]. Based on this system, we extensively evaluated several rBCG constructs for candidate HIV vaccines and reported that an rBCG-HIV vaccine could induce protective humoral immune responses in guinea pigs [54]. These studies suggest that rBCG-based vaccines are feasible as AIDS vaccines. However, the CTL activity did not reach protective levels with a single injection of rBCG-HIV vaccine in the macaque model. To overcome the low immunogenicity of the rBCG vaccine in CTL induction, we utilized various strategies for enhancing the immune potential of the BCG vector.

4.4. Prime-Boost Regimen for Enhancing Immune Responses. The first strategy by which we tried to improve the potential of the rBCG-HIV vaccine was the use of a safe recombinant viral vector for a booster vaccine. With respect to safety, traditional live vaccines, which have been administered safely to both the healthy and the HIV-infected individuals, may be the vectors of choice for HIV-1 vaccines. To fully take advantage of the benefits of such traditional vaccines in the development of anti-HIV vaccines, we studied BCG Tokyo 172 strain and the replication-deficient vaccinia vaccine strain DIs [55, 56] both of which have been shown to be nonpathogenic when inoculated into immune-deficient animals as live recombinant vaccine vehicles [57]. The vaccinia virus DIs have been tested clinically as a smallpox vaccine in Japanese infants and proved to be quite safe. We chose this highly attenuated virus as a booster vaccine vector and constructed recombinant DIs (rDIs) expressing the HIV *gag* [58] or SIV *gag-pol* gene [59]. Both rDIs constructs were found to be effective in eliciting HIV- or SIV-Gag-specific immunity in mice. When they were administered as a booster antigen after priming with an SIV-DNA vaccine, the cellular immunity to SIV Gag was greatly enhanced [59]. In brief, we tested a new combination regimen: priming with rBCG-SIV Gag followed by boosting with rDIs-SIV Gag.

In the macaque study, we found that BCG/DIs vaccination induced a long-lasting and effective cellular immunity that was able to control a highly pathogenic virus SHIV C2/1 [60], after mucosal challenge [61]. A possible mechanism of effective Gag-specific cell-mediated immunity is shown in Figure 2. The strong Th1 response induced by the BCG vector may contribute to eliciting the Gag-specific CTL response. How these immune inductions are correlated with protective efficacy requires further investigation. In this study, the BCG/DIs vaccination developed high levels of cellular immunity in the macaques that were protected against the loss of $CD4^+$ T lymphocytes with reduced viral RNA levels after virus challenge. Furthermore, the BCG/DIs group showed no evidence of clinical diseases or mortality

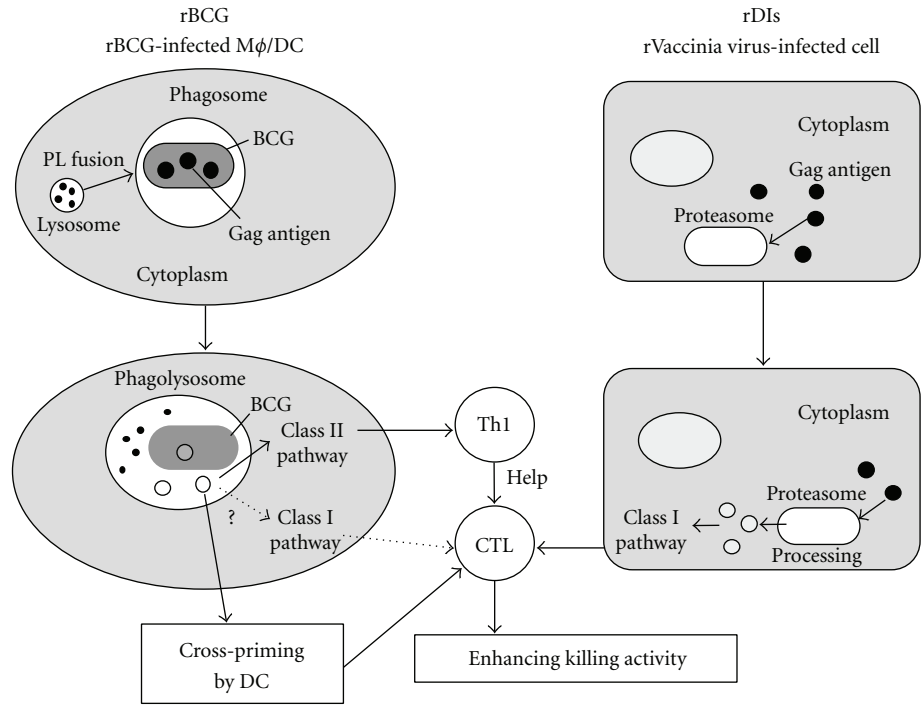

Figure 2: A possible mechanism of effective Gag-specific cell-mediated immunity induction with the rBCG/rDIs prime-boost vaccine. Abbreviations: DC, dendritic cell; Mϕ, macrophage; PL, phagosome-lysozome; Th1, type 1 helper T cell; CTL, cytotoxic T lymphocyte.

after viral challenge during the 1-year observation period [61]. These results suggest that the BCG/DIs prime-boost regimen might be a potential candidate for an effective and safe anti-HIV vaccine. Recent studies in macaques subjected to BCG/Ad5 [62] and BCG/MVA [63] regimens strongly support the effectiveness of the BCG vector. In the latter study, a hemolysin-expressing BCG strain, which was devised for more efficient antigen presentation to the CTL precursor, elicited a robust and broad range of HIV-1 specific T-cell responses along with recruitment of multiple T-cell clonotypes into the memory pool.

4.5. Codon Optimization Strategy. The major issue with BCG vehicle vaccines is the low expression level of the foreign antigen gene in BCG cells. In general, sufficient levels of foreign antigen-specific immune responses are obtained with high doses of rBCG between 10- and 100-fold greater than that needed for a practical dose against TB in humans [54]. This is considered the main limitation for the clinical use of rBCG-based vaccines. To address this substantial issue, we applied a codon optimization strategy for foreign genes in the rBCG system to increase its expression level. The aims of the study were to increase the immunogenicity of the foreign antigen, decrease inoculation dosages as small as the conventional BCG vaccine against TB, avoid adverse reactions, prevent possible association with Th2-type immune responses, and ward off the exacerbation of retroviral infections.

First, we determined the in vitro effects of codon optimization of the HIV gene in rBCG. Although the effect of codon optimization in mammalian cells is well documented [64–66], its effect in rBCG vehicle had never been fully elucidated. We targeted the HIV-1 *gag p24* gene as a model antigen to clarify the effect of codon optimization in the rBCG system. A specially designed synthetic p24 gene consisting of mycobacterial-preferred codons resulted in an increase in their GC content from 43.4% to 67.4%. Furthermore, codon-optimized rBCG was generated without any detectable changes in its characters including the growth rate. This rBCG exhibited a dramatic increase in Gag p24 antigen production approximately 40-fold greater than the non-optimized rBCG. Moreover, we successfully obtained data regarding the enhancement of immune responses in codon-optimized rBCG-immunized mice [67]. Inoculation of mice with a single low dose of the codon-optimized bacteria elicited effective cellular immunity. In the ELISPOT assay, the number of Gag-specific IFN-γ spot-forming cells elicited by codon-optimized rBCG was significantly greater than that elicited by non-optimized recombinants [67]. These cellular immune responses would decrease if the $CD8^+$ T cells were depleted. The results also suggest that effective MHC-class I-restricted CTL responses are inducible by vaccination with codon-optimized rBCG. Furthermore, Gag-specific lymphocyte proliferative responses were also detected in the codon-optimized rBCG-immunized mice [67].

We also applied this strategy to an SIV Gag construct and successfully generated an rBCG harboring the codon-optimized SIV *gag* gene with an expression 10-fold greater than that of the native *gag* gene. In the macaque study, compared with a native *gag* gene construct, a low-dose (10^6 bacilli) injection of this construct induced optimal priming of Gag-specific $CD4^+$ and $CD8^+$ T cells and prolonged the maintenance of memory T-cell response after vaccinia DIs

boost [68]. These results imply that the quality of the priming vaccine is a critical factor for inducing a desirable immune response against immunodeficiency viruses. Thus, the codon optimization strategy should generally be applied to other foreign genes in rBCG-based vaccine development.

5. Vaccine for Other Infectious Diseases

There were various candidate rBCG vaccines targeting infectious diseases other than TB or HIV. Stover et al. [69] reported that the rBCG system would be useful in Lyme disease vaccine development; the vaccine incorporated with the surface protein of *Borrelia burgdorferi* first reached clinical phase I trials. However, the vaccine was rejected due to its low antibody production response [70]. Two groups [71, 72] applied rBCG in malaria vaccine development and demonstrated efficacy in a mouse model. Malaria is recognized as one of the three major infectious diseases as well as TB and AIDS. Although there is a long history of malaria vaccine development, we have not seen any licensed vaccine. The strategy to induce cellular immunity against conserved antigens using BCG vector could be effective to overcome substantial difficulties in producing vaccine due to antigenic diversity and unique life cycle of this parasite. In addition, BCG vector was tested for vaccine discovery against some viral diseases. A rBCG expressing the measles virus nucleoprotein demonstrated protection against measles virus pneumonia in macaques [73]. Furthermore, we demonstrated that a rBCG with a single hepatitis C virus (HCV) NS5 CTL epitope into antigen 85B induced HCV-specific CTL response in mice [74]. HCV is recognized as one of the major infectious pathogens of which the global infection rate is ~3%. Although the priority for preventive HCV vaccine development has become lower because of the remarkable progress in the treatment, BCG vector of targeting CTL induction may have implication for therapeutic vaccine against this disease. All these candidates at the early stage of rBCG study could not proceed to further development stages at those times. The rBCG-based vaccine development for these diseases should be reconsidered because the advanced technology that enhances the potential of BCG vectors has become currently available.

6. Conclusion and Future Perspective

As described in Section 3, several rBCG-based candidate vaccines are currently being evaluated for the development of TB vaccines. Such human trials would provide a greater insight into the paradigm of immune correlation in *M. tuberculosis* infection. In addition, the application of the codon optimization strategy enables us to utilize this bacterial vector as a primer of a heterologous prime-boost regimen for a preventive HIV vaccine. These results could suggest that the BCG vector is possible divalent vaccine controlling both TB and HIV/AIDS with a single construct; such study may help resolve the serious public health problem in the sub-Saharan African countries in which both diseases are highly prevalent [14].

Another potential outcome is the utility of the BCG vector for infant vaccines. One of the largest advantages of rBCG vaccines is their applicability to newborns. Because BCG as a TB vaccine is integrated into the expanded program on immunization in many countries, we have the earliest chance to immunize newborns with BCG within 3 months of birth before they are exposed to a variety of infectious pathogens. Substituting the current BCG with a novel rBCG vaccine possessing protective antigens against pathogens that cause serious diseases in infants, such as severe diarrhea and respiratory diseases, could be effective in developing countries. Such vaccine concepts should be also tested in appropriate animal models before they are tested in humans. Thus, after much trial and error in the last 2 decades, rBCG-based vaccines may contribute to the control of global infectious diseases in the near future.

Acknowledgements

The authors thank Drs. Yasushi Ami, Masaru Kanekiyo, and Mitsuo Honda for their helpful discussion. They also thank Dr. Naoki Yamamoto for supervising the study on HIV vaccine development.

References

[1] L. C. Rodrigues, V. K. Diwan, and J. G. Wheeler, "Protective effect of BCG against tuberculous meningitis and miliary tuberculosis: a metaanalysis," *International Journal of Epidemiology*, vol. 22, no. 6, pp. 1154–1158, 1993.

[2] G. A. Colditz, T. F. Brewer, C. S. Berkey et al., "Efficacy of BCG vaccine in the prevention of tuberculosis: meta-analysis of the published literature," *Journal of the American Medical Association*, vol. 271, no. 9, pp. 698–702, 1994.

[3] R. Brosch, S. V. Gordon, T. Garnier et al., "Genome plasticity of BCG and impact on vaccine efficacy," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 104, no. 13, pp. 5596–5601, 2007.

[4] S. M. Irwin, A. Goodyear, A. Keyser et al., "Immune response induced by three *Mycobacterium bovis* BCG substrains with diverse regions of deletion in a C57BL/6 mouse model," *Clinical and Vaccine Immunology*, vol. 15, no. 5, pp. 750–756, 2008.

[5] M. Seki, I. Honda, I. Fujita, I. Yano, S. Yamamoto, and A. Koyama, "Whole genome sequence analysis of *Mycobacterium bovis* bacillus Calmette-Guérin (BCG) Tokyo 172: a comparative study of BCG vaccine substrains," *Vaccine*, vol. 27, no. 11, pp. 1710–1716, 2009.

[6] W. R. Jacobs, M. Tuckman, and B. R. Bloom, "Introduction of foreign DNA into mycobacteria using a shuttle phasmid," *Nature*, vol. 327, no. 6122, pp. 532–535, 1987.

[7] R. Hernàndez-Pando, M. Castañòn, C. Espitia, and Y. Lopez-Vidal, "Recombinant BCG vaccine candidates," *Current Molecular Medicine*, vol. 7, no. 4, pp. 365–372, 2007.

[8] R. G. Bastos, S. Borsuk, F. K. Seixas, and O. A. Dellagostin, "Recombinant *Mycobacterium bovis* BCG," *Vaccine*, vol. 27, no. 47, pp. 6495–6503, 2009.

[9] J. Uehori, M. Matsumoto, S. Tsuji et al., "Simultaneous blocking of human toll-like receptors 2 and 4 suppresses myeloid dendritic cell activation induced by *Mycobacterium*

bovis bacillus Calmette-Guérin peptidoglycan," *Infection and Immunity*, vol. 71, no. 8, pp. 4238–4249, 2003.

[10] J. M. Roda, R. Parihar, and W. E. Carson III, "CpG-containing oligodeoxynucleotides act through TLR9 to enhance the NK cell cytokine response to antibody-coated tumor cells," *Journal of Immunology*, vol. 175, no. 3, pp. 1619–1627, 2005.

[11] T. Kawashima, Y. Norose, Y. Watanabe et al., "Cutting edge: major CD8 T cell response to live bacillus Calmette-Guérin is mediated by CD1 molecules," *Journal of Immunology*, vol. 170, no. 11, pp. 5345–5348, 2003.

[12] N. P. Goonetilleke, H. McShane, C. M. Hannan, R. J. Anderson, R. H. Brookes, and A. V. S. Hill, "Enhanced immunogenicity and protective efficacy against *Mycobacterium tuberculosis* of bacille Calmette-Guérin vaccine using mucosal administration and boosting with a recombinant modified vaccinia virus Ankara," *Journal of Immunology*, vol. 171, no. 3, pp. 1602–1609, 2003.

[13] E. A. Ramsburg, J. M. Publicover, D. Coppock, and J. K. Rose, "Requirement for CD4 T cell help in maintenance of memory CD8 T cell responses is epitope dependent," *Journal of Immunology*, vol. 178, no. 10, pp. 6350–6358, 2007.

[14] Global Tuberculosis Control Report, 2010, http://whqlibdoc.who.int/publications/2010/9789241564069_eng.pdf.

[15] The Global Plan to Stop TB 2011–2015, pp 81-88, 2010, http://www.stoptb.org/global/plan.

[16] D. F. Hoft, A. Blazevic, G. Abate et al., "A new recombinant bacille Calmette-Guérin vaccine safely induces significantly enhanced tuberculosis-specific immunity in human volunteers," *Journal of Infectious Diseases*, vol. 198, no. 10, pp. 1491–1501, 2008.

[17] L. Grode, P. Seiler, S. Baumann et al., "Increased vaccine efficacy against tuberculosis of recombinant *Mycobacterium bovis* bacille Calmette-Guérin mutants that secrete listeriolysin," *Journal of Clinical Investigation*, vol. 115, no. 9, pp. 2472–2479, 2005.

[18] K. Von Eschen, R. Morrison, M. Braun et al., "The candidate tuberculosis vaccine Mtb72F/AS02A: tolerability and immunogenicity in humans," *Human Vaccines*, vol. 5, no. 7, pp. 475–482, 2009.

[19] J. T. van Dissel, S. M. Arend, C. Prins et al., "Ag85B-ESAT-6 adjuvanted with IC31 promotes strong and long-lived *Mycobacterium tuberculosis* specific T cell responses in naïve human volunteers," *Vaccine*, vol. 28, no. 20, pp. 3571–3581, 2010.

[20] H. McShane, A. A. Pathan, C. R. Sander et al., "Recombinant modified vaccinia virus Ankara expressing antigen 85A boosts BCG-primed and naturally acquired antimycobacterial immunity in humans," *Nature Medicine*, vol. 10, no. 11, pp. 1240–1244, 2004.

[21] B. Abel, M. Tameris, N. Mansoor et al., "The novel tuberculosis vaccine, AERAS-402, induces robust and polyfunctional $CD4^+$ and $CD8^+$ T cells in adults," *American Journal of Respiratory and Critical Care Medicine*, vol. 181, no. 12, pp. 1407–1417, 2009.

[22] T. J. Scriba, M. Tameris, N. Mansoor et al., "Modified vaccinia Ankara-expressing Ag85A, a novel tuberculosis vaccine, is safe in adolescents and children, and induces polyfunctional CD4+ T cells," *European Journal of Immunology*, vol. 40, no. 1, pp. 279–290, 2010.

[23] R. Sun, Y. A. W. Skeiky, A. Izzo et al., "Novel recombinant BCG expressing perfringolysin O and the over-expression of key immunodominant antigens; pre-clinical characterization, safety and protection against challenge with *Mycobacterium tuberculosis*," *Vaccine*, vol. 27, no. 33, pp. 4412–4423, 2009.

[24] UNAIDS Report on the Global AIDS Epidemic, 2010, http://www.unaids.org/documents/20101123_GlobalReport_em.pdf.

[25] R. Granich, S. Crowley, M. Vitoria et al., "Highly active antiretroviral treatment as prevention of HIV transmission: review of scientific evidence and update," *Current Opinion in HIV and AIDS*, vol. 5, no. 4, pp. 298–304, 2010.

[26] A. E. Grulich, M. T. van Leeuwen, M. O. Falster, and C. M. Vajdic, "Incidence of cancers in people with HIV/AIDS compared with immunosuppressed transplant recipients: a meta-analysis," *Lancet*, vol. 370, no. 9581, pp. 59–67, 2007.

[27] K. A. Gebo, J. A. Fleishman, R. Conviser et al., "HIV Research Network. Contemporary costs of HIV healthcare in the HAART era," *AIDS*, vol. 24, no. 17, pp. 2705–2715, 2010.

[28] N. L. Letvin, D. H. Barouch, and D. C. Montefiori, "Prospects for vaccine protection against HIV-1 infection and AIDS," *Annual Review of Immunology*, vol. 20, pp. 73–99, 2002.

[29] S. H. E. Kaufmann and A. J. McMichael, "Annulling a dangerous liaison: vaccination strategies against AIDS and tuberculosis," *Nature Medicine*, vol. 11, no. 4, pp. S33–S44, 2005.

[30] N. L. Letvin, "Progress toward an HIV vaccine," *Annual Review of Medicine*, vol. 56, pp. 213–223, 2005.

[31] G. Pantaleo and R. A. Koup, "Correlates of immune protection in HIV-1 infection: what we know, what we don't know, what we should know," *Nature Medicine*, vol. 10, no. 8, pp. 806–810, 2004.

[32] M. Z. Smith and S. J. Kent, "Genetic influences on HIV infection: implications for vaccine development," *Sexual Health*, vol. 2, no. 2, pp. 53–62, 2005.

[33] A. S. Fauci, S. M. Schnittman, G. Poli, S. Koenig, and G. Pantaleo, "Immunopathogenic mechanisms in human immunodeficiency virus (HIV) infection," *Annals of Internal Medicine*, vol. 114, no. 8, pp. 678–693, 1991.

[34] A. J. McMichael and T. Hanke, "HIV vaccines 1983–2003," *Nature Medicine*, vol. 9, no. 7, pp. 874–880, 2003.

[35] M. D. Daniel, F. Kirchhoff, S. C. Czajak, P. K. Sehgal, and R. C. Desrosiers, "Protective effects of a live attenuated SIV vaccine with a deletion in the nef gene," *Science*, vol. 258, no. 5090, pp. 1938–1941, 1992.

[36] J. D. Lifson, M. Piatak, J. L. Rossio et al., "Whole inactivated SIV virion vaccines with functional envelope glycoproteins: safety, immunogenicity, and activity against intrarectal challenge," *Journal of Medical Primatology*, vol. 31, no. 4-5, pp. 205–216, 2002.

[37] J. S. James, "First AIDS vaccine tested did not protect, but gives scientific leads," *AIDS Treatment News*, no. 389, p. 6, 2003.

[38] D. P. Francis, W. L. Heyward, V. Popovic et al., "Candidate HIV/AIDS vaccines: Lessons learned from the world's first phase III efficacy trials," *AIDS*, vol. 17, no. 2, pp. 147–156, 2003.

[39] R. R. Amara and H. L. Robinson, "A new generation of HIV vaccines," *Trends in Molecular Medicine*, vol. 8, no. 10, pp. 489–495, 2002.

[40] R. R. Amara, F. Villinger, J. D. Altman et al., "Control of a mucosal challenge and prevention of AIDS by a multiprotein DNA/MVA vaccine," *Science*, vol. 292, no. 5514, pp. 69–74, 2001.

[41] I. Ourmanov, C. R. Brown, B. Moss et al., "Comparative efficacy of recombinant modified vaccinia virus Ankara expressing simian immunodeficiency virus (SIV) Gag-Pol and/or Env in macaques challenged with pathogenic SIV," *Journal of Virology*, vol. 74, no. 6, pp. 2740–2751, 2000.

[42] J. W. Shiver, T. M. Fu, L. Chen et al., "Replication-incompetent adenoviral vaccine vector elicits effective anti-immunodeficiency-virus immunity," *Nature*, vol. 415, no. 6869, pp. 331–335, 2002.

[43] M. S. Seaman, L. Xu, K. Beaudry et al., "Multiclade human immunodeficiency virus type 1 envelope immunogens elicit broad cellular and humoral immunity in rhesus monkeys," *Journal of Virology*, vol. 79, no. 5, pp. 2956–2963, 2005.

[44] T. Matano, M. Kobayashi, H. Igarashi et al., "Cytotoxic T lymphocyte-based control of simian immunodeficiency virus replication in a preclinical AIDS vaccine trial," *Journal of Experimental Medicine*, vol. 199, no. 12, pp. 1709–1718, 2004.

[45] J. Cohen, "Did Merck's failed HIV vaccine cause harm?" *Science*, vol. 318, no. 5853, pp. 1048–1049, 2007.

[46] S. Rerks-Ngarm, P. Pitisuttithum, S. Nitayaphan et al., "Vaccination with ALVAC and AIDSVAX to prevent HIV-1 infection in Thailand," *The New England Journal of Medicine*, vol. 361, no. 23, pp. 2209–2220, 2009.

[47] S. G. Hansen, C. Vieville, N. Whizin et al., "Effector memory T cell responses are associated with protection of rhesus monkeys from mucosal simian immunodeficiency virus challenge," *Nature Medicine*, vol. 15, no. 3, pp. 293–299, 2009.

[48] A. Aldovini and R. A. Young, "Humoral and cell-mediated immune responses to live recombinant BCG-HIV vaccines," *Nature*, vol. 351, no. 6326, pp. 479–482, 1991.

[49] Y. Yasutomi, S. Koenig, S. S. Haun et al., "Immunization with recombinant BCG-SIV elicits SIV-specific cytotoxic T lymphocytes in rhesus monkeys," *Journal of Immunology*, vol. 150, no. 7, pp. 3101–3107, 1993.

[50] Y. Yasutomi, S. Koenig, R. M. Woods et al., "A vaccine-elicited, single viral epitope-specific cytotoxic T lymphocyte response does not protect against intravenous, cell-free simian immunodeficiency virus challenge," *Journal of Virology*, vol. 69, no. 4, pp. 2279–2284, 1995.

[51] K. Matsuo, R. Yamaguchi, A. Yamazaki, H. Tasaka, and T. Yamada, "Cloning and expression of the *Mycobacterium bovis* BCG gene for extracellular α antigen," *Journal of Bacteriology*, vol. 170, no. 9, pp. 3847–3854, 1988.

[52] K. Matsuo, R. Yamaguchi, A. Yamazaki, H. Tasaka, K. Terasaka, and T. Yamada, "Cloning and expression of the gene for the cross-reactive α antigen of *Mycobacterium kansasii*," *Infection and Immunity*, vol. 58, no. 2, pp. 550–556, 1990.

[53] K. Matsuo, R. Yamaguchi, A. Yamazaki et al., "Establishment of a foreign antigen secretion system in mycobacteria," *Infection and Immunity*, vol. 58, no. 12, pp. 4049–4054, 1990.

[54] M. Honda, K. Matsuo, T. Nakasone et al., "Protective immune responses induced by secretion of a chimeric soluble protein from a recombinant *Mycobacterium bovis* bacillus Calmette-Guerin vector candidate vaccine for human immunodeficiency virus type 1 in small animals," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 92, no. 23, pp. 10693–10697, 1995.

[55] I. Tagaya, T. Kitamura, and Y. Sano, "A new mutant of dermovaccinia virus," *Nature*, vol. 192, no. 4800, pp. 381–382, 1961.

[56] T. Kitamura, Y. Kitamura, and I. Tagaya, "Immunogenicity of an attenuated strain of vaccinia virus on rabbits and monkeys," *Nature*, vol. 215, no. 5106, pp. 1187–1188, 1967.

[57] K. Takeya, K. Nomoto, S. Muraoka, S. Shimotori, T. Taniguchi, and T. Miyake, "Growth of two strains of *Mycobacterium bovis* (BCG) in a thymic mice," *Journal of General Microbiology*, vol. 100, no. 2, pp. 403–405, 1977.

[58] K. Ishii, Y. Ueda, K. Matsuo et al., "Structural analysis of vaccinia virus DIs strain: application as a new replication-deficient viral vector," *Virology*, vol. 302, no. 2, pp. 433–444, 2002.

[59] K. Someya, K-Q Xin, K. Matsuo, K. Okuda, N. Yamamoto, and M. Honda, "A consecutive priming-boosting vaccination of mice with simian immunodeficiency virus (SIV) gag/pol DNA and recombinant vaccinia virus strain DIs elicits effective anti-SIV immunity," *Journal of Virology*, vol. 78, no. 18, pp. 9842–9853, 2004.

[60] K. Shinohara, K. Sakai, S. Ando et al., "A highly pathogenic simian/human immunodeficiency virus with genetic changes in cynomolgus monkey," *Journal of General Virology*, vol. 80, no. 5, pp. 1231–1240, 1999.

[61] Y. Ami, Y. Izumi, K. Matsuo et al., "Priming-boosting vaccination with recombinant *Mycobacterium bovis* bacillus Calmette-Guérin and a nonreplicating vaccinia virus recombinant leads to long-lasting and effective immunity," *Journal of Virology*, vol. 79, no. 20, pp. 12871–12879, 2005.

[62] M. J. Cayabyab, B. Korioth-Schmitz, Y. Sun et al., "Recombinant *Mycobacterium bovis* BCG prime-recombinant adenovirus boost vaccination in rhesus monkeys elicits robust polyfunctional simian immunodeficiency virus-specific T-cell responses," *Journal of Virology*, vol. 83, no. 11, pp. 5505–5513, 2009.

[63] M. Rosario, J. Fulkerson, S. Soneji et al., "Safety and immunogenicity of novel recombinant BCG and modified vaccinia virus Ankara vaccines in neonate rhesus macaques," *Journal of Virology*, vol. 84, no. 15, pp. 7815–7821, 2010.

[64] S. André, B. Seed, J. Eberle, W. Schraut, A. Bültmann, and J. Haas, "Increased immune response elicited by DNA vaccination with a synthetic gp120 sequence with optimized codon usage," *Journal of Virology*, vol. 72, no. 2, pp. 1497–1503, 1998.

[65] M. Uchijima, A. Yoshida, T. Nagata, and Y. Koide, "Optimization of codon usage of plasmid DNA vaccine is required for the effective MHC class I-restricted T cell responses against an intracellular bacterium," *Journal of Immunology*, vol. 161, no. 10, pp. 5594–5599, 1998.

[66] D. L. Narum, S. Kumar, W. O. Rogers et al., "Codon optimization of gene fragments encoding Plasmodium falciparum merzoite proteins enhances DNA vaccine protein expression and immunogenicity in mice," *Infection and Immunity*, vol. 69, no. 12, pp. 7250–7253, 2001.

[67] M. Kanekiyo, K. Matsuo, M. Hamatake et al., "Mycobacterial codon optimization enhances antigen expression and virus-specific immune responses in recombinant *Mycobacterium bovis* bacille Calmette-Guérin expressing human immunodeficiency virus type 1 Gag," *Journal of Virology*, vol. 79, no. 14, pp. 8716–8723, 2005.

[68] M. Kanekiyo, Y. Ami, K. Matsuo et al., "A low-dose codon-optimized recombinant BCG-based HIV vaccine: prime-boost vaccination with recombinant BCG and replication-defective recombinant vaccinia virus DIs evokes SIV-specific immunity which overcomes the anamnestic BCG immunity in macaques," in *Proceedings of the 16th International AIDS Conference*, Toronto, Canada, August 2006.

[69] C. K. Stover, G. P. Bansal, M. S. Hanson et al., "Protective immunity elicited by recombinant bacille Calmette-Guerin (BCG) expressing outer surface protein A (OspA) lipoprotein: a candidate Lyme disease vaccine," *Journal of Experimental Medicine*, vol. 178, no. 1, pp. 197–209, 1993.

[70] R. Edelman, K. Palmer, K. G. Russ et al., "Safety and immunogenicity of recombinant Bacille Calmette-Guerin (rBCG) expressing Borrelia burgdorferi outer surface protein A (OspA) lipoprotein in adult volunteers: a candidate Lyme disease vaccine," *Vaccine*, vol. 17, no. 7-8, pp. 904–914, 1999.

[71] S. Matsumoto, H. Yukitake, H. Kanbara, and T. Yamada, "Recombinant *Mycobacterium bovis* bacillus Calmette-Guerin secreting merozoite surface protein 1 (MSP1) induces protection against rodent malaria parasite infection depending on MSP1-stimulated interferon γ and parasite-specific antibodies," *Journal of Experimental Medicine*, vol. 188, no. 5, pp. 845–854, 1998.

[72] C. Zheng, P. Xie, and Y. Chen, "Recombinant *Mycobacterium bovis* BCG producing the circumsporozoite protein of Plasmodium falciparum FCC-1/HN strain induces strong immune responses in BALB/c mice," *Parasitology International*, vol. 51, no. 1, pp. 1–7, 2002.

[73] Y. D. Zhu, G. Fennelly, C. Miller et al., "Recombinant bacille Calmette-Guérin expressing the measles virus nucleoprotein protects infant rhesus macaques from measles virus pneumonia," *Journal of Infectious Diseases*, vol. 176, no. 6, pp. 1445–1453, 1997.

[74] S. Uno-Furuta, K. Matsuo, S. Tamaki et al., "Immunization with recombinant Calmette-Guerin bacillus (BCG)-hepatitis C virus (HCV) elicits HCV-specific cytotoxic T lymphocytes in mice," *Vaccine*, vol. 21, no. 23, pp. 3149–3156, 2003.