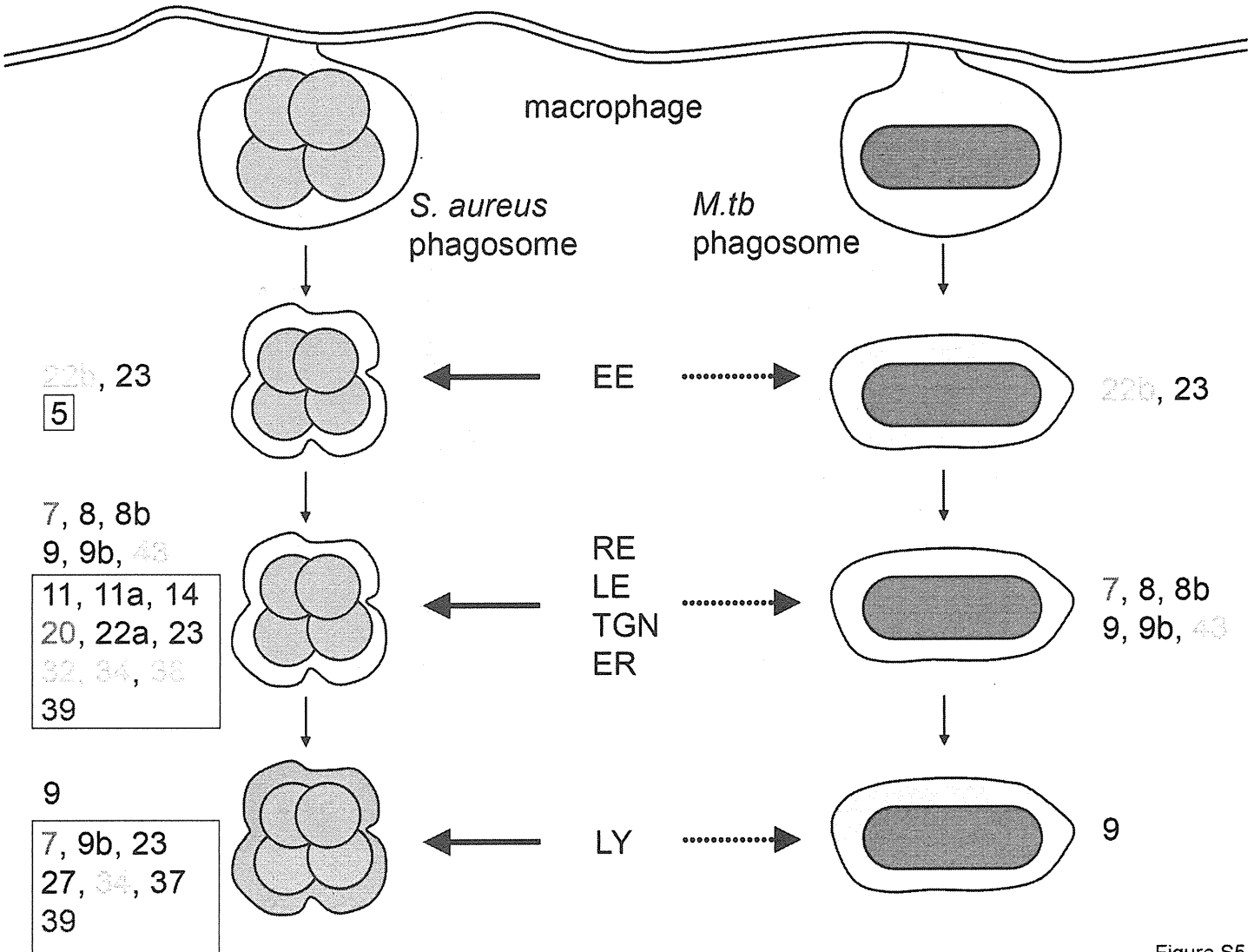
macrophage
S. aureus phagosome
M.tb phagosome
22b, 23
5
EE
22b, 23
7, 8, 8b
9, 9b, 43
11, 11a, 14
20, 22a, 23
32, 34, 36
39
RE
LE
TGN
ER
7, 8, 8b
9, 9b, 43
9
7, 9b, 23
27, 34, 37
39
LY
9

Figure S5

Table S1 Subcellular localization of Rab GTPases

	Localization	Acidification[a]	Cathepsin D[b]	LAMP2[c]	References
Rab1	Endoplasmic reticulum	N.T.	N.T.	-	(1)
Rab1b	Endoplasmic reticulum	N.T.	N.T.	-	(1)
Rab2	Endoplasmic reticulum	N.T.	N.T.	-	(1)
Rab2b	Endoplasmic reticulum	N.T.	N.T.	-	(1)
Rab3	Golgi	N.T.	N.T.	-	(2)
Rab3b	Golgi	N.T.	N.T.	-	(2)
Rab4	Early and recycling endosomes	N.T.	N.T.	+	(3)
Rab4b	Early and recycling endosomes	N.T.	N.T.	+	(3)
Rab5	Early endosomes	-	-	-	(4)
Rab5b	Early endosomes	N.T.	N.T.	-	(4)
Rab6	Golgi	N.T.	N.T.	-	(5)
Rab6b	Golgi	N.T.	N.T.	-	(5)
Rab7	Late endosomes, lysosomes	+	+	++	(6)
Rab7b	Late endosomes, lysosomes	-	-	++	(7)
Rab8	Golgi	-	-	-	(8)
Rab8b	Golgi	-	-	-	(8)
Rab9	Late endosomes	-	-	++	(9)
Rab9b	Late endosomes	-	-	++	(9)
Rab10	Golgi, early endosomes	N.T.	N.T.	+	(8, 10)
Rab11	Golgi, recycling endosomes	-	-	+	(11)
Rab11b	Golgi, recycling endosomes	-	-	+	(11)
Rab13	Golgi, plasma membrane	-	-	-	(12), this study
Rab14	Golgi, trans-Golgi	-	-	-	(13)
Rab16	Golgi	N.T.	N.T.	-	(14)
Rab18	Endoplasmic reticulum	N.T.	N.T.	-	(15)
Rab20	Endoplasmic reticulum	+	+	-	(16)
Rab21	Early endosomes	N.T.	N.T.	-	(17)
Rab22a	Early endosomes	-	-	+	(18)
Rab22b	Early endosomes	-	+	-	(19)
Rab23	Plasma membrane	-	-	+	(20)
Rab24	Perinuclear region	N.T.	N.T.	-	This study
Rab27	Lysosomes	-	-	++	(21)
Rab28		N.T.	N.T.	-	
Rab29		N.T.	N.T.	-	
Rab30	Golgi	N.T.	N.T.	-	(15)
Rab32	Golgi, mitochondria	-	+	-	(22)
Rab34	Golgi	-	+	+	(23)
Rab35	Plasma membrane	N.T.	N.T.	-	(24)
Rab37	Lysosomes	-	-	++	(25)
Rab38	Golgi, mitochondria	-	+	-	(22)
Rab39	Perinuclear region and lysosomes	+	-	++	This study
Rab43	Golgi	-	+	-	(15)

(a) Involvement of Rab GTPases in the phagosomal acidification (Figure 4). +; function, -; non-function, N.T.; not tested.
(b) Involvement of Rab GTPases in the recruitment of cathepsin D to the phagoosme (Figure 5). +; function, -; non-function, N.T.; not tested.

(c) Co-localization of Rab GTPases and LAMP2. Raw264.7macrophages transfected with EGFP-fused Rab GTPases were stained with anti-LAMP-2 antibody, followed by observation with lasar scanning confocal microscopy. Pearson's correlation (PC) of overlapping fluorescent areas of EGFP-fused Rab GTPases and LAMP-2 was assessed. -; PC < 0, +; 0 < PC < 0.3, ++; PC > 0.3.

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Table S2 Primer list for construction of plasmid of EGFP–fused Rab GTPases

Rab GTPase	Primer forward	Primer reverse
Rab1	CAGATCTatgtccagcatgaatcccgaatatg	CGGTACCttagcagcaacctccacctg
Rab1b	CAGATCTatgaaccccgaatatgactacctgtttaag	CGAATTCtagcagcagccaccgctagcaggct
Rab2	CAGATCTatggcgtacgcctatctcttcaag	CCCGAATTCtcaacagcagccgccccca
Rab2b	CAGATCTatgacttatgcttatctcttcaagtatatc	CGAATTCtcagcagcagccagagttggaccctatgtc
Rab3	CCTCGAGCTatggcatccgccacagactcgc	CGAATTCtcagcaggcgcagtcctggt
Rab3b	CCTCGAGCTatggcttcagtgacagatggtaaaactgg	CGAATTCCtagcatgagcagttctgctgcagcagc
Rab4	CAGATCTatgtcgcagacggccatgtccgaaacc	CGAATTCtaacaaccacactcctgagcgttcg
Rab4b	CAGATCTatggctgagacctacgacttcctct	CGAATTCagcagccacacggctgaggggcc
Rab5	CAGATCTatggctagtcgaggcgcaacaagac	CGAATTCttagttactacaacactgattcctgg
Rab5b	CCTCGAGCTatgactagcagaagcacagctaggcc	CGAATTCagttgctacaacactggctcttg
Rab6	CCTCGAGCTatgtccacgggcggagactt	CGAATTCttagcaggaacagcctccttcac
Rab6b	CAGATCTatgtccgcaggggagattttggga	CGAATTCttagcaggagcagccgccctcgctggc
Rab7b	CCTCGAGCTatgaatccccggaagaaggt	CGAATTCagcagcatctgctccttgactggtctgg
Rab8	CAGATCTatggcgaagacctacgattacctg	CGAATTCtcacagaagaacacatcggaaaaagctg
Rab8b	CAGATCTatggcgaagacgtacgattatctcttcaag	CGAATTCaaagtagcgagcaacgaaagaaactggtc
Rab9	CAGATCTatggcaggaaaatcatcacttttttaaag	CGGTACCtcaacagcaagatgagctaggc
Rab9b	CCTCGAGCTatgagtgggaaatccctgctcttaaag	CGAATTCttaacagcacgaagaccctgctttggagc
Rab10	CAGATCTatggcgaagaagacgtacgacctg	CGAATTCtcagcagcatttgctcttccagc
Rab11	CAGATCTatgggcacccgcgacgacgag	CGAATTCttagatgttctgacagcactgcacc
Rab11b	CCTCGAGCTatggggacccgggacgacgagtacg	CGAATTCacaggttctggcagcactgcagctt
Rab13	CAGATCTatggccaaagcctacgaccac	CGAATTCtcagcccagggagcacttgttg
Rab14	CAGATCTatggcaactgcaccatacaactactc	CGAATTCctagcagccacagccttctc
Rab16	CCTCGAGCTatggcatcagctggagacacc	CGAATTCctagcagctgcagctgctgg
Rab18	CAGATCTatggacgaggacgtgctaacca	CGAATTCttataacacagagcaataaccaccacag
Rab20	CCTCGAGCTatgaggaagcccgacagcaag	CGAATTCtcaggcacaacacccagatctg
Rab21	CAGATCTccgggaagcgacgggatggc	CGAATTCttatccagaagaacagcaccctcc
Rab22a	CAGATCTatggcgctgagggagctcaa	CGGTACCtcagcagcagctccgctttg
Rab22b	CAGATCTatgatggcgatacgggagctcaaagtg	CGAATTCaacagcaccggcggctggcttgc
Rab23	CCTCGAGCTatgttggaggaagatatggaagtcgc	CAAGCttagggtatgctacagctgctaaaagg
Rab24	CAGATCTatgagcgggcagcgcgtgga	CGAATTCtcagtgatgacaacagctgtagaag
Rab27	CAGATCTatgtctgatggagattatgattacctc	CGAATTCtcaacagccacatgccccttttctc
Rab28	CAGATCTatgtcggactctgaggaggag	CGAATTCtcactgaactgcacacatagagcttc
Rab29	CAGATCTatgggcagccgcgaccacct	CGAATTCctagcagcaggaccagctgg
Rab30	CCTCGAGCTatgagtatggaagattatgatttcctgttc	CGGTACCttagttgaaattacaacaagtcaaatagctg
Rab32	CCAGATCTatggcgggcggaggagccgg	CGAATTCtcagcaacactgggatttgttctctg
Rab34	CCTCGAGCTatgaacattctggcacccgtgc	CGGTACCtcatgggcaacatgtgggcttc
Rab35	CCTCGAGCTatggcccgggactacgacca	CGAATTCttagcagcagcgtttctttcgtttactg
Rab37	CCTCGAGCTatgacgggcacgccaggcgccgttg	CGAATTCacatgaaggagcagcagctggag
Rab38	CAGATCTatgcaggccccgcacaagga	CGAATTCctaggatttggcacagccagag
Rab39	CAGATCTatggagaccatctggatctaccag	CGAATTCtcagcagaagcattctttcctggg
Rab43	CAAGCTTCGcggcccttcggcttcttctag	CGAATTCggctctggagggctgggctt

Table S3 Primer list for site-directed mutagenesis

Rab GTPase	dominant negative	constitutive acitive	dominant negative-F	dominant negative-R	constitutive active-F	constitutive active-R
Rab5	S34N	Q79L	agagtccgctgttggcaaaAATagcctagtgcttcgtttt	aaaacgaagcactaggctATTtttgccaacagcggactct	gaaatatgggatacagctggtcTagaacgataccatagcctag	ctaggctatggtatcgttctAgaccagctgtatcccatatttc
Rab7b	T22N	Q67L	gccattggtgtgggaaagaActccctccctcaccaatatg	catattggtgagggagggagTtctttcccacaccaatggc	gatctgggacacgggcggtcTggagcggttccgctccatg	catggagcggaaccgctccAgaccgcccgtgtcccagatc
Rab8	T22N	Q67L	gactcgggggtgggggaagaActgtgtcctgttccgcttc	gaagcggaacaggacacagTtcttccccacccccgagtc	gatatgggacacagccggtcTggaacggtttcggacgatc	gatcgtccgaaaccgttccAgaccggctgtgtcccatatc
Rab8b	T22N	Q67L	ctcgggggtaggcaagaActgcctcctgttccgcttctc	gagaagcggaacaggaggcagTtcttgcctacccccgag	gatatgggacacagcgggtcTggaaagattccgaacaatc	gattgttcggaatctttccAgacccgctgtgtcccatatc
Rab9	S21N	Q66L	gatggtggagttgggaagaAttcacttatgaacagatatg	catatctgttcataagtgaaTtcttcccaactccaccatc	gggacacggcaggtcTggagcgattccgaagcctgaggac	gtcctcaggcttcggaatcgctccAgacctgccgtgtccc
Rab9b	S21N	Q66L	gatggtggagttgggaaaaACtcgcttatgaaccgttacg	cgtaacggttcataagcgaGTttttcccaactccaccatc	ctgggacactgcagggcTggaacgtttcaagagccttag	ctaaggctcttgaaacgttccAgccctgcagtgtcccag
Rab11	S25N	Q70L	gattctggtgttggaaagaAtaatctcctgtctcgatttac	gtaaatcgagacaggagattaTtctttccaacaccagaatc	gatatgggacacagcagggcTGgagcgatatcgagctataac	gttatagctcgatatcgctcCAgccctgctgtgtcccatatc
Rab11b	S25N	Q70L	gactcaggcgtgggcaagaAcaacctgctgtcgcgcttc	gaagcgcgacagcaggttgTtcttgcccacgcctgagtc	gatctgggacaccgctggccTggagcgctaccgccgcatc	gatgcggcggtagcgctccAggccagcggtgtcccagatc
Rab13	T22N	Q67L	gactcgggggtgggcaagaACtgtctgatcattcgctttg	caaagcgaatgatcagacaGTtcttgcccacccccgagtc	gtctgggacacggctggccTagagcggttcaagacaataac	gttattgtcttgaaccgctctAggccagccgtgtcccagac
Rab14	S25N	Q70L	gacatgggagtaggaaaaAAttgcttgcttcatcaatttac	gtaaattgatgaagcaagcaaTTttttcctactcccatgtc	gatttgggatacggcaggacTggagcgatttagggctgttac	gtaacagccctaaatcgctccAgtcctgccgtatcccaaatc
Rab20	T19N	R59L	catgaacgtggggaagaATtcgctgctgcagcggtatatg	catataccgctgcagcagcgaATtcttccccacgttcatg	gggacaccgcagggcTggagcagttccacggcctgggatc	gatcccaggccgtggaactgctccAgccctgcggtgtccc
Rab22a	S19N	Q64L	caggtgtaggtaaaAACagtattgtgtggcggtttgtgg	ccacaaaccgccacacaatactGTTtttacctacacctg	ctgggatacagctggacTCgaacgatttcgtgccttag	ctaaggcacgaaatcgttcGAgtccagctgtatcccag
Rab22b	S20N	Q65L	gacactggggttgggaaaAACagcatcgtgtgtcgatttgtc	gacaaatcgacacacgatgctGTTttttcccaaccccagtgtc	catctgggacactgctggtcTTgaacggtttcattcattgg	ccaatgaatgaaaccgttcAAgaccagcagtgtcccagatg
Rab23	S23N	Q68L	gaatggagcagttggaaaaAATagtatgattcagcgatattg	caatatcgctgaatcatactATTttttccaactgctccattc	gttatgggacactgcaggtcTTgaggaatttgatgcaattac	gtaattgcatcaaattcctcAAgacctgcagtgtcccataac
Rab27	T23N	Q78L	ctctggtgtagggaagaAcagtgtactttaccaatatac	gtatattggtaaagtacactgTtcttccctacaccagag	gttatgggacacagcagggcTggagaggtttcgtagcttaac	gttaagctacgaaacctctccAgccctgctgtgtcccataac
Rab32	T39N	Q85L	gagcttggcgtgggcaagaAcagcatcatcaagcgctacg	cgtagcgcttgatgatgctgTtcttgcccacgccaagctc	gctgtgggacatcgcgggggcTggagcgatttggcaacatg	catgttgccaaatcgctccAgccccgcgatgtcccacagc
Rab34	T66N	Q111L	gacctgtcggtggggaagaATtgcctcattaataggttc	gaacctattaatgaggcaaTtcttccccaccgacaggtc	ctttgggataccgctgggcTggagaggttcaaatgcattg	caatgcatttgaacctctccAgcccagcggtatcccaaag
Rab37	T43N	Q89L	gagacacaggcgtcggcaaaaACtgtttcctgatccaattc	gaattggatcaggaaacaGTttttgccgacgcctgtgtctc	gatctgggacaccgctgggcTggaacggttccgaagcgtc	gacgcttcggaaccgttccAgcccagcggtgtcccagatc
Rab38	T23N	Q69L	gacctgggcgtggggaagaAcagtatcatcaagcgctacg	cgtagcgcttgatgatactgTtcttccccacgcccaggtc	ctgggatatcgcaggtcTCgaaagatttggaaacatgac	gtcatgtttccaaatctttcGAgacctgcgatatcccag
Rab39	S22N	Q72L	gactccaccgtgggcaagAActgcctcctgcaccgcttc	gaagcggtgcaggaggcagTTcttgcccacggtggagtc	ctctgggacacggcgggacTggagcggttcagatcaataac	gttattgatctgaaccgctccAgtcccgccgtgtcccagag
Rab43	T32N	Q77L	cgacgcaagcgtgggcaagaACtgcgtggtgcagcgcttc	gaagcgctgcaccacgcaGTtcttgcccacgcttgcgtcg	gatctgggacacggccggccTggagcggttccgcaccatc	gatggtgcggaaccgctccAggccggccgtgtcccagatc

RESEARCH ARTICLE

A novel vaccine strategy to induce mycobacterial antigen-specific Th1 responses by utilizing the C-terminal domain of heat shock protein 70

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Keywords
Mycobacterium tuberculosis; heat shock protein; DNA vaccine; IFN-γ.

Abstract

Heat shock protein 70 (HSP70) is a member of a highly conserved superfamily of intracellular chaperones called stress proteins that can activate innate and adaptive immune responses. We evaluated the effect of a fusion DNA vaccine that encoded mycobacterial HSP70 and MPT51, a major secreted protein of *Mycobacterium tuberculosis*. Spleen cells from mice immunized with fusion DNA of full-length HSP70 and MPT51 produced a higher amount of interferon-γ (IFN-γ) in response to the CD4+, but not the CD8+ T-cell epitope peptide on MPT51 than those from mice immunized with MPT51 DNA. Furthermore, because HSP70 comprises the N-terminal ATPase domain and the C-terminal peptide-binding domain, we attempted to identify the domain responsible for its enhancing effect. The fusion DNA vaccine that encoded the C-terminal domain of HSP70 and MPT51 induced a higher MPT51-specific IFN-γ production by CD4+ T cells than the vaccine that encoded MPT51 alone, whereas that with the N-terminal domain did not. Similar results were obtained by immunization with the fusion proteins. These results suggest that the DNA vaccine that encodes a chimeric antigen molecule fused with mycobacterial HSP70, especially with its C-terminal domain, can induce a stronger antigen-specific T-helper cell type 1 response than antigen DNA alone.

Introduction

Tuberculosis is a major cause of death worldwide. There were an estimated 9.4 million incident and 11.1 million prevalent cases of tuberculosis, and 1.8 million people died of tuberculosis, in 2008 (World Health Organization, 2009). *Mycobacterium bovis* Bacillus Calmette–Guerin (BCG) is the only available vaccine against tuberculosis, but it has been reported to show variable protective efficacy (Colditz *et al.*, 1994). Although BCG can protect against tuberculosis in childhood, its efficacy in adults varies, especially in endemic countries (Sterne *et al.*, 1998; Kaufmann, 2004; Andersen, 2007). It is also known to represent a risk for immunocompromised patients. In addition, the emergence of multidrug-resistant strains of *Mycobacterium tuberculosis* has lent urgency to the search for novel therapeutic agents and the development of more effective vaccines capable of protecting adults (Kaufmann, 2000).

MPT51 is a major secreted protein of *M. tuberculosis*, which has a molecular weight of 27 kDa and a primary structure that is similar to the components of the antigen 85 complex (Nagai *et al.*, 1991; Ohara *et al.*, 1995, 1997). We demonstrated previously that MPT51 induces T-cell-mediated immune responses and protective immunity against challenge with *M. tuberculosis* in mice (Miki *et al.*, 2004), and have identified one CD8+ and two CD4+ T-cell epitopes that are presented by H2-D^d and H2-A^b, respectively (Suzuki *et al.*, 2004). MPT51 is recognized by T cells from patients with active tuberculosis and is also considered to be immunogenic in humans (de Araujo-Filho *et al.*, 2008).

Heat shock protein70 (HSP70) is a member of a highly conserved superfamily of intracellular chaperones called

stress proteins (Gething *et al.*, 1995). In addition, HSP70 appears to play important roles in the innate and adaptive immune responses, such as receptor-mediated antigen internalization by sentinel antigen-presenting cells (APCs), stimulation of production of various cytokines, and maturation of dendritic cells (DCs) (Suto & Srivastava, 1995; Basu *et al.*, 2000; Binder *et al.*, 2000; Castellino *et al.*, 2000; Singh-Jasuja *et al.*, 2000). Collectively, the ability of HSP70 to bind antigenic peptides and deliver them to APCs profoundly contributes to the generation of antigen-specific T-cell responses.

In this study, we compared the effect of a DNA vaccine that encoded a fusion protein that consisted of MPT51, a protective antigen against *M. tuberculosis* (Miki *et al.*, 2004), and *M. tuberculosis* HSP70 on the induction of MPT51-specific T-cell responses, with that of MPT51 DNA alone. After showing superior MPT51-specific T-cell induction by the fusion molecule, we attempted to establish the domain of HSP70 that was responsible for this enhancing effect.

Materials and methods

Construction of fusion genes for DNA vaccines

Mycobacterium tuberculosis HSP70 gene was cloned by PCR from genomic DNA of the H37Rv strain. The primers used for PCR were as follows:

HSP70F (full-length HSP70: residues 1–625)

5′-TATGAATTCACCATGGCTCGTGCGGTCGGG-3′ (forward)

5′-AATGGTACCCTTGGCCTCCCGGCCGT-3′ (reverse)

HSP70N (N-terminal domain of HSP70: residues 1–360)

5′-TATGAATTCACCATGGCTCGTGCGGTCGGG-3′ (forward)

5′-AATGGTACCCACCTCGCCCTTGAGGA-3′ (reverse)

HSP70C (C-terminal domain of HSP70: residues 354–625)

5′-TATGAATTCACCATGGCGTCCTCAAGGGC-3′ (forward)

5′-AATGGTACCCTTGGCCTCCCGGCCGT-3′ (reverse)

Forward and reverse primers contained EcoRI and KpnI restriction sites (underlined), respectively. PCR products were purified and cloned into the EcoRI/KpnI sites of the pCI vector (Promega, Madison, WI) that contained MPT51 DNA at the XbaI site (Suzuki *et al.*, 2004). A nucleotide sequence for a 12-amino-acid (GGGSGGGSGGGS) linker was then inserted into the KpnI sites of pCI vectors that contained chimeric MPT51 DNA. The chimeric DNA constructs thus prepared were designated *HSP70F-MPT51*, *HSP70N-MPT51*, and *HSP70C-MPT51*. As a control, *HSP70F* was amplified by PCR using a primer set as follows: 5′-TATGAATTCACCATGGCTCGTGCGGTCGGG-3′ (forward, an underline indicates the EcoRI site) and 5′-AATGGTACCTCACTTGGCCTCCCGGCCGT-3′ (reverse, an underline indicates the KpnI site). The PCR product was purified and cloned into the EcoRI/KpnI sites of the pCI vector. The pCI plasmids containing these constructs were propagated in *Escherichia coli* strain XL1-Blue (Stratagene, La Jolla, CA) and purified by EndoFree Plasmid Maxi Kit (Qiagen GmbH, Hilden, Germany). The concentration of endotoxin was tested using the Endospecy ES-24S kit and the Toxicolor DIA kit (both from Seikagaku Biobusiness Corporation, Tokyo, Japan), and all plasmid solutions were found to contain < 0.1 EU endotoxin μg^{-1} DNA.

Preparation of fusion proteins

For protein preparation, *MPT51*, *HSP70F-MPT51*, *HSP70N-MPT51*, and *HSP70C-MPT51* were 6 × histidine-tagged by PCR using the corresponding forward primers listed above and a reverse primer (CAAGCTTTTAATGATGATGATGATGATGGCGGATCGCACCGACGATAT) containing nucleotide sequences for the extreme C-terminal of MPT51, the histidine-tag (double underlined), and the HindIII site (underlined). The PCR products were purified and cloned into the EcoRI/HindIII sites of the pRSET expression vector (Invitrogen, Carlsbad, CA). *Escherichia coli* JM109 competent cells were transformed with the expression vectors, and proteins were induced according to the manufacturer's instructions. Proteins were extracted and purified by Ni^{2+}-nitrilotriacetic acid (Ni-NTA) agarose (Qiagen GmbH) in the presence of 7 M urea, according to the manufacturer's instructions. Purified proteins were refolded by decreasing the concentration of urea while immobilized on the Ni-NTA matrix and then eluted by phosphate-buffered saline (PBS) (pH 7.4) containing 250 mM imidazole. The buffer was finally exchanged with PBS (pH 7.4) using a PD-10 desalting column (GE Healthcare, Uppsala, Sweden). The purity of recombinant proteins was checked by sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE). The concentration of endotoxin was tested using the Endospecy ES-24S kit and the Toxicolor DIA kit, and recombinant protein solutions contained < 10 EU endotoxin mg^{-1} protein.

Preparation of anti-MPT51 monoclonal antibody (mAbs)

Anti-MPT51 mAbs were prepared as described previously (Harlow & Lane, 1988). Briefly, purified recombinant MPT51 protein (50 μg per mouse) was mixed with the RIBI Adjuvant System (Corixa, Hamilton, MT) and injected subcutaneously into BALB/c mice three times at 3-week intervals. Spleen cells from immunized mice were fused with SP2/0, and stably hybridized cells were selected using HAT medium (Invitrogen). Hybridomas that produced anti-MPT51 mAbs were screened by enzyme-linked immunosorbent assay (ELISA), and two clones (2B11F5 and 2D9H2) were established by limiting dilution. Both clones produced

anti-MPT51 mAbs of the IgG1 isotype, as determined using a Mouse Immunoglobulin Isotype Kit (BD Biosciences Pharmingen, San Diego, CA).

Western blotting detection of chimeric MPT51 proteins

HEK293T cells were transfected with pCI plasmids that encoded MPT51 DNA of various forms using FuGENE 6 (Roche Diagnostics GmbH, Mannheim, Germany). Cells were collected 24 h after transfection and lysed in the radioimmunoprecipitation assay buffer (25 mM Tris-HCl, pH 7.6, 150 mM NaCl, 1% NP-40, 1% sodium deoxycholate, 0.1% SDS), and Western blotting was performed with mouse anti-MPT51 mAb (from 2B11F5), HRP-conjugated goat anti-mouse immunoglobulins (Zymed Laboratories/Invitrogen), and West Pico Chemiluminescent Substrate (Pierce, Rockford, IL).

Animals and immunization

Female BALB/c and C57BL/6 mice (between 7 and 9 weeks of age) were purchased from Japan SLC (Hamamatsu, Japan) and maintained at the Institute for Experimental Animals, Hamamatsu University School of Medicine. All animal experiments were performed according to the Guidelines for Animal Experimentation, Hamamatsu University School of Medicine.

Mice were epidermally immunized with plasmids (2 μg per mouse per immunization) using the Helios gene gun system (Bio-Rad Laboratories, Hercules, CA) as described previously (Suzuki *et al.*, 2004) or recombinant proteins (50 μg per mouse) emulsified with incomplete Freund's adjuvant (Difco Laboratories/BD Diagnostic Systems, Sparks, MD) by injecting subcutaneously three times at 10-day intervals.

ELISA for interferon-γ (IFN-γ)

Two weeks after the last immunization, spleen cells from immunized BALB/c and C57BL/6 mice were cultured in a 96-well plate (1×10^6/0.2 cells mL^{-1}) in the presence of MPT51 peptides (1 μM) for 2 and 4 days, respectively. Antigenic peptides P24-32 and P171-190 (a dominant H2-A^b-restricted epitope) (Suzuki *et al.*, 2004) were used for CD8+ and CD4+ T-cell stimulation, respectively. For protein immunization, spleen cells from immunized or naïve C57BL/6 mice were stimulated with an antigenic peptide P171-190 (1 μM) for 4 days as described above. The IFN-γ concentration of the culture supernatants was determined by a sandwich ELISA as described previously (Yoshida *et al.*, 1995).

Preparation of total RNA and semi-quantitative reverse transcriptase (RT)-PCR

Two weeks after the last immunization, spleen cells from immunized C57BL/6 mice were cultured in a 12-well plate (1×10^7 cells mL^{-1} per well) in the presence of 1 μM MPT51 peptide (P171-190) for 16 h. Total RNA was prepared using ISOGEN (Nippon Gene, Tokyo, Japan), and semi-quantitative RT-PCR was performed as described previously (Uchijima *et al.*, 2005) using primers as follows:

inducible nitric oxide synthase (iNOS)
5′-TACAAGATGACCCTAAGAGT-3′ (forward)
5′-ACATGGCCGAGCGTCAAAGA-3′ (reverse)
IFN-γ
5′-TCTGAGACAATAAACGCTAC-3′ (forward)
5′-GAATCAGCAGCGACTCCTTT-3′ (reverse)
glycerol-3-phosphate dehydrogenase (G3PDH)
5′-ACCACAGTCCAT CCATCAC-3′ (forward)
5′-TCCACCACCCTGTTGCTGTA-3′ (reverse)

Statistical analysis

Statistical analyses were performed using STATVIEW-J 5.0 statistics program (SAS Institute Inc., Cary, NC). The Mann–Whitney test was used to calculate *P*-values.

Results

Enhancement of MPT51-specific T-cell responses by full-length HSP70

We first examined the enhancing effect of full-length HSP70 (HSP70F) for the induction of MPT51-specific T-cell responses. Because MPT51 induces only CD4+ or CD8+ T-cell response in C57BL/6 or BALB/c, respectively (Suzuki *et al.*, 2004), we used both strains to investigate their corresponding T-cell responses. C57BL/6 and BALB/c mice were immunized with a fusion gene of HSP70F and MPT51 (*HSP70F-MPT51*) or *MPT51* using the Helios gene gun system. Spleen cells from immunized C57BL/6 and BALB/c mice were used for IFN-γ production assays of CD4+ and CD8+ T cells, respectively, in response to corresponding antigenic peptides. CD4+ T cells from C57BL/6 mice immunized with *HSP70F-MPT51* produced a significantly higher amount of IFN-γ than those immunized with *MPT51* (Fig. 1). The addition of HSP70F to MPT51 did not show a significant enhancing effect on the antigen-specific CD8+ response, although CD8+ T cells from BALB/c mice immunized with *HSP70F-MPT51* showed a slightly higher IFN-γ production than those immunized with *MPT51*. Immunization with HSP70F DNA alone did not induce MPT51-specific immune responses in C57BL/6 and BALB/c mice, and the amounts of IFN-γ production from spleen cells of immunized mice in response to corresponding

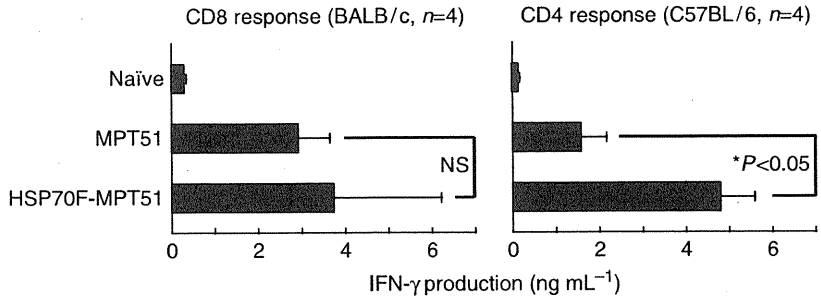

Fig. 1. Enhancing effect of HSP70 conjugation on MPT51-specific immune response. BALB/c (for CD8+ T-cell response) and C57BL/6 (for CD4+ T-cell response) mice were immunized with plasmids that encoded *HSP70F-MPT51* or *MPT51* alone, and their spleen cells were stimulated with the corresponding antigenic peptides. The IFN-γ concentration of the culture supernatants was determined by ELISA. The results of four mice per group are presented as mean ± SD. NS, not significant; $*P < 0.05$. IFN-γ productions from unstimulated spleen cells were nearly undetectable in all groups.

peptides were similar to those of naïve mice (data not shown). In contrast to IFN-γ production, *HSP70F-MPT51* showed no enhancing effect on MPT51-specific interleukin-4 (IL-4) production in both strains, although spleen cells from both strains similarly produced IL-4 in response to anti-CD3 mAb stimulation (data not shown). Taken together, the addition of HSP70 to MPT51 enhanced antigen-specific T-helper cell type 1 (Th1), but not Th2 responses.

Identification of the domain of HSP70 responsible for its enhancing effect on MPT51-specific T-cell response

Because HSP70 comprises two major domains, that is, the N-terminal ATPase domain (44 kDa) and the C-terminal peptide-binding domain (27 kDa), we next attempted to identify the domain that was responsible for the enhancement of the MPT51-specific T-cell response. For this purpose, we prepared additional fusion genes, *HSP70N-MPT51* and *HSP70C-MPT51* (Fig. 2a).

Before immunization, 293 T cells were transfected transiently with plasmids that encoded these chimeric MPT51 DNAs, to confirm the protein expression *in vitro*. Both fusion proteins, as well as HSP70F-MPT51 and MPT51, were detected at around the expected molecular sizes by Western blotting with anti-MPT51 mAb (Fig. 2b), indicating the proper amino acid sequences of expressed proteins.

BALB/c and C57BL/6 mice were then immunized with the plasmids containing *HSP70N-MPT51*, *HSP70C-MPT51*, or *MPT51* by gene-gun and their spleen cells were tested for MPT51-specific T-cell responses. A stronger IFN-γ production from CD4+ T cells was induced by *HSP70C-MPT51* compared with that by *HSP70N-MPT51* and *MPT51* alone (Fig. 3). However, *HSP70C-MPT51* showed no enhancing effect on MPT51-specific IL-4 production (data not shown). Although the CD4+ T-cell response induced by *HSP70N-MPT51* seemed stronger than that induced by *MPT51*, the difference was not statistically significant. In contrast, the addition of either HSP70N or HSP70C did not have any effect on the induction of CD8+ T-cell responses, which confirmed the results with HSP70F. The enhancing effect of HSP70C was confirmed by semi-quantitative RT-PCR (Fig. 4). The expression of mRNA for IFN-γ was increased considerably, which resulted in the upregulation of mRNA for iNOS, probably in APCs. These results together indicate that the C-terminal domain of *M. tuberculosis* HSP70 contributes to the enhancement of antigen-specific Th1 responses.

Induction of MPT51-specific CD4+ T-cell responses by MPT51-HSP70 fusion proteins

We finally prepared fusion MPT51 proteins and examined their effects on the induction of MPT51-specific CD4+ T-cell responses. Although SDS-PAGE analysis showed all Ni-NTA-purified proteins to have molecular sizes slightly smaller than those algorithmically expected (Fig. 5a), they were confirmed to have proper amino acid sequences by sequencing analyses (data not shown). When mice were immunized with these recombinant proteins, HSP70F-MPT51 and HSP70C-MPT51 again induced stronger immune responses than HSP70N-MPT51 and MPT51, and the effect of HSP70C-MPT51 was superior to that of HSP70F-MPT51 (Fig. 5b). These results confirm the evidence obtained by DNA vaccination that *M. tuberculosis* HSP70, especially its C-terminal domain, facilitates the induction of antigen-specific CD4+ T-cell responses.

Discussion

In DNA vaccines, the plasmid DNA is delivered into somatic cells (such as keratinocytes or myocytes) and professional APCs (such as DCs), but the former cells serve as a predominant reservoir for antigen (Gurunathan *et al.*, 2000; Kutzler & Weiner, 2008). DNA vaccines express a low amount of antigen at the restricted site of inoculation, and the frequency of DC bearing vaccinated DNA is very low

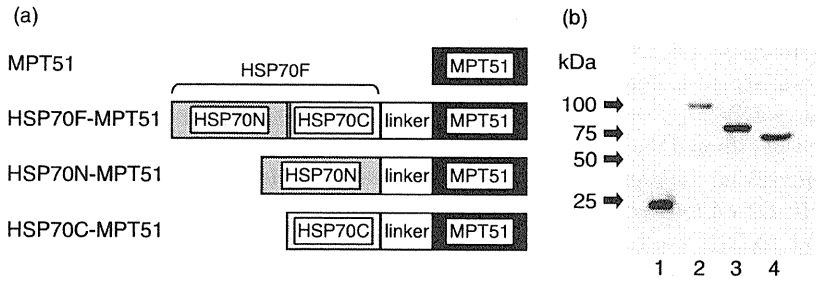

Fig. 2. Chimeric HSP70-MPT51 molecules. (a) Schematic diagram of chimeric molecules. HSP70F, HSP70N, and HSP70C mean full-length, the N-terminal domain, and the C-terminal domain of HSP70, respectively. (b) Expression of chimeric proteins in HEK293T cells. Cells were transfected with plasmids that encoded DNA for various MPT51 molecules, and the protein expression was detected by Western blotting using anti-MPT51 mAb (derived from a clone 2B11F5). 1, MPT51 (expected molecular weight: 27 979.17); 2, HSP70F-MPT51 (95 570.65); 3, HSP70N-MPT51 (67 382.45); and 4, HSP70C-MPT51 (57 774.05). Expected molecular sizes were calculated by an algorithm termed 'COMPUTE PI/MW TOOL' in EXPASY (http://expasy.org/tools/pi_tool.html).

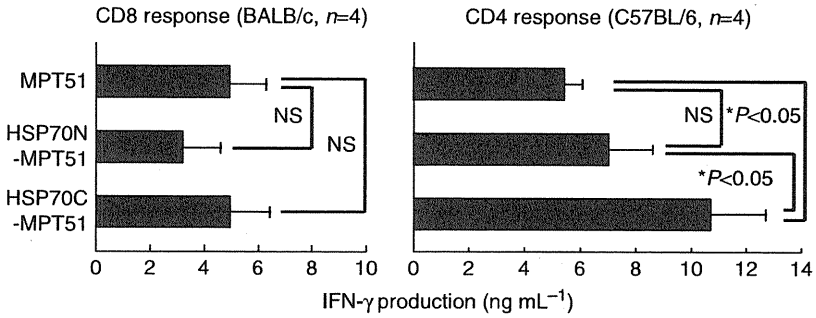

Fig. 3. Comparison of the enhancing effects of the N- and C-domains of HSP70 in DNA vaccination. BALB/c and C57BL/6 mice were immunized with plasmids that encoded *HSP70N-MPT51*, *HSP70C-MPT51*, or *MPT51* alone, and the effects were determined by an IFN-γ production assay using MPT51 peptides for stimulation. The results of four mice per group are presented as mean ± SD. NS, not significant; $*P < 0.05$. IFN-γ productions from unstimulated spleen cells were nearly undetectable in all the groups.

(Casares *et al.*, 1997; Barouch *et al.*, 2004). Therefore, intercellular antigen spreading seems particularly important to increase the number of APCs. In the present study, we attempted to establish a new fusion DNA vaccine against MPT51 using *M. tuberculosis* HSP70 as a partner to facilitate the receptor-mediated uptake of shed antigens from transfected somatic cells that underwent apoptosis and/or necrosis by professional APCs. With this new vaccine construct, we demonstrated that HSP70, especially its C-terminal domain, had an enhancing effect on the induction of MPT51-specific CD4+ (but not CD8+) T-cell responses.

Microbial and mammalian HSP70s effectively induce antigen-specific immune responses in various ways (Asea *et al.*, 2000; Kuppner *et al.*, 2001; Somersan *et al.*, 2001), and several receptors have been identified for them, that is, CD91 (Basu *et al.*, 2001), CD40 (Wang *et al.*, 2001; Becker *et al.*, 2002), CCR5 (Floto *et al.*, 2006), TLR-2, and TLR-4 (Asea *et al.*, 2002). Tobian *et al.* (2004a) have reported that exogenous *M. tuberculosis* HSP70 can CD91-dependently enhance the presentation capacity for ovalbumin (OVA)-derived major histocompatibility complex (MHC) class I peptides in macrophages and DCs. This has established CD91 as a receptor for prokaryotic as well as mammalian HSPs. On the other hand, they have also reported that the enhancing effect of *M. tuberculosis* HSP70 on the presentation of MHC class II peptides is CD91-independent (Tobian *et al.*, 2004b). HSP70 has also been reported to bind to a chemokine receptor CCR5 (Whittall *et al.*, 2006) and transduce various signals into DCs to enhance immune responses (Floto *et al.*, 2006). We reported previously that a fusion protein of MIP-1α and MPT51 is internalized preferentially into DCs via CCR5, and consequently, induces stronger MPT51-specific CD8+ and CD4+ T-cell responses than MPT51 alone (Uchijima *et al.*, 2008 and unpublished data). It is possible that *M. tuberculosis* HSP70 exerts its enhancing effect in the same way, although further analysis is necessary. Alternatively, additional signals via other HSP70 receptors, such as CD40 and/or TLRs, may contribute to the enhancing effects. Taken together, these observations suggest that activation signals transduced via HSP70 receptors other than CD91 play pivotal roles in the enhancement of immune responses, although CD91 may contribute to the internalization of MPT51 fusion proteins conjugated with HSP70.

The domain of HSP70 that is responsible for its enhancing effect is still a controversial subject. Some groups have reported that the C-terminal peptide-binding domain might act as a microbial adjuvant (Wang *et al.*, 2002; Qazi *et al.*, 2005). Wang and colleagues showed that the C-, but not the N-terminal domain upregulates the expression of cytokines and their receptors (IL-12, tumor necrosis factor-α, NO, C–C chemokines, and CCR7), costimulatory molecules (CD83, CD86, and CD80), and HLA class II molecules in human hematopoietic cells. Of these upregulated molecules, IL-12 is known to be a very potent cytokine for Th1 polarization (Trinchieri, 1994), but they showed Th1 skewing of immune responses only by an isotype analysis of immunoglobulins specific for HSP70 itself. Qazi and colleagues also described the effectiveness of the C-terminal domain, but they did not compare its effect with that of the N-terminal domain. Together with these observations, our current findings showing the enhancing effect on targeted-antigen-specific IFN-γ production by CD4+ T cells strengthen the rationale for the use of the C-terminal domain of HSP70 as a Th1-polarizing adjuvant. The enhancing effect of C-terminal domain of HSP70 is more prominent when used in protein immunization. As shown in Fig. 5b, the addition of HSP70C (and HSP70F) to MPT51 effectively induced antigen-specific immune responses, even if the antigen alone could not induce the response. In contrast, Udono *et al.* (2001) have identified amino acid residues 280–385 in the N-terminal ATPase domain of HSP70 as the most important region for cytotoxic T lymphocyte (CTL) induction. Huang *et al.* (2000) have also shown that the N-terminal domain of HSP70 (residues 160–370) is sufficient to stimulate the substantial generation of anti-OVA CTL in the absence of an adjuvant. At present, we have no evidence to explain why HSP70N did not show an enhancing effect on CD8+ T-cell responses in our system. Our construct contains the entire structure of the N-terminal domain while other effective constructs lack the extreme N-terminus, and this portion might have an inhibitory effect. Alternatively, the difference(s) in the immunogenicity of antigens (OVA vs. MPT51) and/or strain (C57BL/6 vs. BALB/c) may be accountable for the ineffectiveness. Besides the enhancing effect of the N-terminal domain on immune responses, however, its immunosuppressive role by the production of IL-10 and transforming growth factor-β has also been demonstrated in rats (Kimura *et al.*, 1998; Wendling *et al.*, 2000). In general, the C-terminal peptide-binding domain of HSP70 tends to facilitate CD4+ T-cell responses more effectively than CD8+ T-cell responses, which skews the cytokine milieu toward Th1.

IFN-γ-secreting CD4+ T cells known as Th1 cells are important mediators of tuberculosis protection (Cooper *et al.*, 1993; Flynn *et al.*, 1993), and attempts to induce tuberculosis antigen-specific Th1 cells have been the

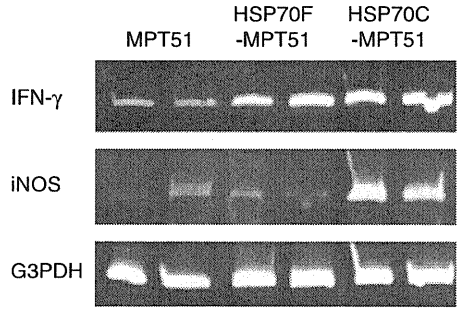

Fig. 4. Semi-quantitative RT-PCR for iNOS and IFN-γ. Spleen cells from immunized C57BL/6 mice were stimulated with MPT51 peptide (P171-190), and the expression of iNOS and IFN-γ was tested by semi-quantitative RT-PCR. G3PDH was used as a control.

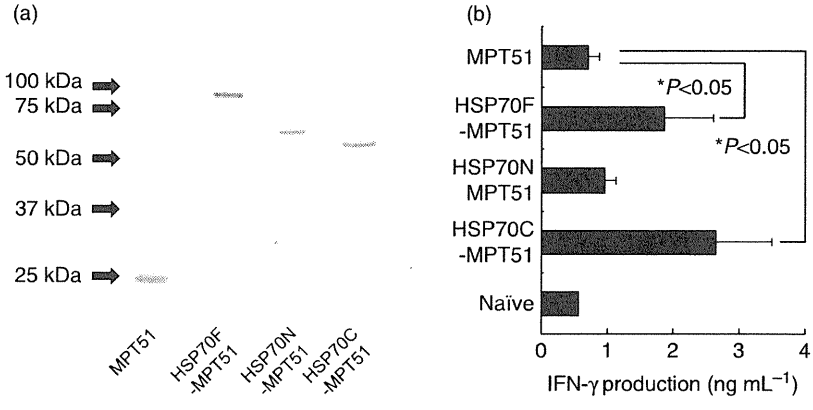

Fig. 5. Comparison of the enhancing effects of the N- and C-domains of HSP70 in protein vaccination. (a) SDS-PAGE analysis of recombinant proteins. Proteins were purified with Ni-NTA agarose, subjected to SDS-PAGE, and stained with Coomassie Brilliant Blue R-250. For the expected molecular sizes, see the legend for Fig. 2b. (b) MPT51-specific IFN-γ production. C57BL/6 mice were immunized with recombinant proteins, and their spleen cells were used for an IFN-γ production assay in response to the MPT51 peptide (P171–190). The results of four mice per group are presented as mean ± SD. $^*P < 0.05$. IFN-γ productions from unstimulated spleen cells were nearly undetectable in all the groups.

dominant theme of most tuberculosis-vaccine development (Skeiky & Sadoff, 2006). Although CD8+ CTLs have also been reported to contribute to disease resistance (Flynn & Chan, 2001; Kaufmann, 2003), our current findings may pave the way for the establishment of a novel vaccine against *M. tuberculosis*.

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