Brief Definitive Report

Tuberculosis Toxin Blocking Phagosome Maturation Inhibits a Novel Ca\(^{2+}\)/Calmodulin–PI3K hVPS34 Cascade

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Abstract

The capacity of Mycobacterium tuberculosis to infect latently over one billion people and cause two million fatalities annually rests with its ability to block phagosomal maturation into the phagolysosome in infected macrophages. Here we describe how M. tuberculosis toxin lipoolarabinomannan (LAM) causes phagosome maturation arrest, interfering with a new pathway connecting intracellular signaling and membrane trafficking. LAM from virulent M. tuberculosis, but not from avirulent mycobacteria, blocked cytosolic Ca\(^{2+}\) increase. Ca\(^{2+}\) and calmodulin were required for a newly uncovered Ca\(^{2+}\)/calmodulin phosphatidylinositol (PI)3 kinase hVPS34 cascade, essential for production of PI 3 phosphate (PI3P) on liposomes in vitro and on phagosomes in vivo. The interference of the trafficking toxin LAM with the calmodulin-dependent production of PI3P described here ensures long-term M. tuberculosis residence in vacuoles sequestered away from the bactericidal and antigen-processing organelles in infected macrophages.

Key words: phosphatidylinositol 3-kinase • calmodulin • calcium • Mycobacterium tuberculosis • EEA1

Introduction

Phagolysosome biogenesis depends on interactions of the phagosome with the intracellular sorting pathways delivering late endosomal and lysosomal constituents to the maturing phagosome (1, 2). It has been shown that two specific rab5 effectors play an essential role in phagosomal maturation (2, 3): the phosphatidylinositol (PI)3 kinase hVPS34 (4), and the endosomal tethering molecule EEA1, which associates with endosomal membranes via its PI3 phosphate (PI3P) binding FYVE domain (5). It has been reported that by a hitherto unknown mechanism, Mycobacterium tuberculosis inhibits EEA1 recruitment to phagosomes in infected macrophages, thus precluding phagolysosome formation (3). The inhibition by M. tuberculosis of EEA1 recruitment to the phagosome obstructs a pathway, dependent on EEA1 and Syntaxin 6, of delivery to phagosomes of lysosomal hydrolases and V\(_r\)-ATPase proteolipid (6). The resulting block in phagosomal maturation contributes to the long-term survival and persistence of the tubercle bacillus in host macrophages (7).

It has been established that Ca\(^{2+}\) affects phagosomal maturation (8, 9). However, the mechanism of how Ca\(^{2+}\) affects phagolysosome formation remains to be delineated. The initial clues come from the studies showing that inhibition of cytosolic Ca\(^{2+}\) rise blocks phagosomal acquisition of late endosomal and lysosomal markers and lumenal acidification of the phagosome (8, 10). Significantly, infection of macrophages with M. tuberculosis prevents Ca\(^{2+}\) fluxes and inhibits activation of the downstream Ca\(^{2+}\)/calmodulin effectors such as Ca\(^{2+}\)/calmodulin kinase II (CaMKII; 8, 9). Here, we investigated potential connections between M. tuberculosis effects on Ca\(^{2+}\) fluxes and our previous reports that the M. tuberculosis glycosylated PI lipoarabinomannan (LAM) prevents EEA1 recruitment to phagosomes, which in turn leads to a block in phagosome maturation (3, 6). We examined whether the M. tuberculosis product LAM affected Ca\(^{2+}\) fluxes and whether and how Ca\(^{2+}\) signaling influenced EEA1 recruitment to phagosomes.

Materials and Methods

Ratiometric [Ca\(^{2+}\)]\(\text{Imaging.} \) J774 cells were loaded for 30 min with 5 μM Fura-2 acetoxy-methyl ester. The cells were illuminated at 340 nm for 250 msec and 380 nm for 100 msec in 5-s intervals using a TILL Polychrome monochromator, and 340 380 fluorescence ratios were calculated using TILL software. For FcR clustering-induced [Ca\(^{2+}\)]\(\text{rise, Fura-2–preloaded J774 cells were incubated at 4°C with 55 μg/ml mouse IgG for 30 min in HBSS,} \)
in the presence of 0.5 mM CaCl$_2$.

The cells were treated with W7 at indicated time points. Video 1 is available at http://www.jem.org/cgi.

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Hopkins, Baltimore, MD), and hVPS34 and p150 (provided by J. Corvera, University of Massachusetts, Amherst, MA), Syntaxin 8 (provided by W. Hong, Institute of Molecular and Cell Biology previously described (3). Antibodies were: EEA1 (provided by S. Lee, University of California, San Francisco), Syntaxin 8 (provided by W. Hong, Institute of Molecular and Cell Biology previously described (12, 13). Immunoblotting was performed as

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Results

M. tuberculosis Glycosylated Phosphatidylinositol LAM Inhibits Cytosolic Ca$^{2+}$ Rise in Macrophages. We considered two separate lines of investigation demonstrating: (a) that M. tuberculosis LAM blocks phagosome maturation (3) by inhibiting EEA1-dependent trafficking pathway from TGN to phagosomes (6), and (b) that M. tuberculosis-engendered inhibition of Ca$^{2+}$ fluxes in macrophages leads to phagosome maturation arrest (8, 9). This led us to hypothesize that the phagosome maturation block might be mediated by LAM action on cytosolic Ca$^{2+}$. We tested this possibility by measuring intracellular Ca$^{2+}$ concentrations ([Ca$^{2+}$]) in J774 murine macrophage cell line after the addition of the Ca$^{2+}$ ionophore A23187. Cells were preincubated for 30 min in Ca$^{2+}$ containing HBSS with or without 20 μg/ml M. tuberculosis LAM. In a separate set of samples, the LAM equivalent from a nonpathogenic mycobacterial species, Mycobacterium smegmatis, was used instead of M. tuberculosis LAM. Fig. 1, A–D, shows that LAM from M. tuberculosis inhibits both the rate and the maximum [Ca$^{2+}$], rise. This effect is specific for M. tuberculosis LAM, as the LAM equivalent from M. smegmatis did not block [Ca$^{2+}$], increase (Fig. 1, A–D). These observations demonstrate that LAM, a product of M. tuberculosis, prevents increase of [Ca$^{2+}$]. This finding, combined with the previous demonstrations that LAM inhibits phagosomal maturation (3, 6) and that inhibition of Ca$^{2+}$ fluxes is responsible for M. tuberculosis phagosome maturation block (8, 9), indicates that mycobacterial phagosome maturation arrest is caused by LAM-mediated inhibition of [Ca$^{2+}$], increases.

To complement ionophore studies, we tested effects of LAM on [Ca$^{2+}$], rise using FcR clustering as a physiological stimulus (14). J774 cells were split and left to adhere to coverslips for 2 h. Cytosolic Ca$^{2+}$ rise, elicited by FcR clustering (14), showed strong sphingosine kinase (SK) dependence as DMS, an SK inhibitor, reduced by 60% the increase of [Ca$^{2+}$], (Fig. 1, E and F). Next, we tested the effects of M. tuberculosis LAM by adding it 5 min before inducing FcR clustering. Fig. 1, E and F, show that LAM reduced the increase of [Ca$^{2+}$], without affecting receptor clustering (Fig. 1 E, E’ and E”). These results show that M. tuberculosis LAM inhibits Ca$^{2+}$ signaling induced by physiological stimuli. Furthermore, a significant portion of LAM-induced inhibition overlapped with the SK-dependent [Ca$^{2+}$], rise. In this context, it is noteworthy that a recent report suggests that M. tuberculosis affects Ca$^{2+}$ increases by interfering with SK signaling (15).

Calmodulin and CaMKII Are Required for EEA1 Recruitment to Phagosomal Membrane. Next, we investigated whether the LAM-mediated block of Ca$^{2+}$ increase inhibited EEA1 recruitment to phagosomes. Previous studies have implicated calmodulin and its downstream effector CaMKII as the Ca$^{2+}$ responsive elements affected by M. tuberculosis (9). Following this lead, we investigated whether calmodulin played a role in EEA1 recruitment to phagosomes. Macrophages were allowed to phagocytose complement opsonized latex beads for different periods of time in the presence or absence of W7, a specific inhibitor of Ca$^{2+}$/calmodulin interactions with its binding partners. After phagocytosis, LBC were purified, using established protocols of flotation in sucrose gradients (3, 12, 13), and probed for EEA1 by immunoblotting (Fig. 2 A). W7 treatment decreased the amount of EEA1 associated with phagosomes (Fig. 2 A). The role of calmodulin in EEA1 recruitment to phagosomes was confirmed by immunofluorescence microscopy (Fig. 2, B–E). Quantitation of EEA1 association with phagosomes (Fig. 2 F) showed a decrease in the num-
bers of LBC positive for EEA1 in W7-treated macrophages. As a control, LBC were also stained for Syntaxin 8, an endosomal SNARE (16) previously used as an EEA1-independent control for phagosomes (3, 17). W7 did not affect Syntaxin 8 association with LBC, indicating that decrease in EEA1, observed in the presence of the calmodulin inhibitor, was not a result of phagocytosis inhibition but was due to diminished EEA1 recruitment. These experiments demonstrate that calmodulin promotes association of EEA1 with phagosomes in vivo.

One of the major effectors of Ca²⁺/calmodulin is the multifunctional Ser/Thr kinase, CaMKII. An increase of [Ca²⁺], induces the binding of Ca²⁺/calmodulin to CaMKII, which in turn relieves CaMKII from autoinhibition, resulting in autophosphorylation of CaMKII and activation of the kinase (18). The role of CaMKII in EEA1 recruitment to phagosomes was investigated using LBC isolated from macrophages treated with the CaMKII-specific inhibitor KN62. KN62 interferes with the binding of Ca²⁺/calmodulin specifically to CaMKII, thus preventing activation of CaMKII. Fig. 2 G shows that treatment of macrophages with KN62 for 1 h decreased the amount of EEA1 on phagosomes. Syntaxin 3 was used as a loading control. This result indicates that CaMKII is necessary for EEA1 recruitment to phagosomes.

Ca²⁺/Calmodulin Affects Generation of PI3P In Vitro. How does calmodulin affect EEA1 recruitment to phagosomes? Ca²⁺/calmodulin binds directly to EEA1 via its IQ domain, but this association has been reported to repel EEA1 from membranes (19). Interestingly, Ca²⁺/calmodulin has been shown to positively regulate the levels of PI3P in CHO cells (20). Next, we examined whether calmodulin acted directly on EEA1, or affected EEA1 binding to membranes indirectly, via a PI3 kinase. Two types of liposomes, PS/PI and PS/PI3P were prepared and then incubated with cytosol. After 30 min of incubation, liposomes were pelleted and probed for EEA1 by immunoblotting. Wortmannin, a specific inhibitor of PI3 kinase, inhibited EEA1 binding to PS/PI liposomes (Fig. 3 A), indicating the importance of PI3 kinase activity in this assay. Next, the liposomes were incubated with J774 cytosol in the presence or absence of W7. After 15 min of incubation, liposomes were pelleted and probed for EEA1 by immunoblotting (Fig. 3 A). The association of EEA1 with PI containing liposomes was reduced in the presence of W7, whereas its association with liposomes containing preformed PI3P li-
posomes was not affected (Fig. 3 A). These results show that calmodulin enhancement of EEA1 recruitment to membranes occurs at a PI3 kinase step, as W7 inhibited the binding of EEA1 to liposomes containing the PI3 kinase substrate PI, but did not affect its binding to liposomes with preexisting PI3P.

**Ca^{2+}/calmodulin and CaMKII positively regulate EEA1 recruitment to phagosomes.** (A) Immunoblotting analysis and quantitation (mean ± SE) of EEA1 on purified LBC isolated from 25 μM W7-treated or -untreated macrophages. (B–E) Immunofluorescence images of EEA1 recruited to phagosomes (B and D) and corresponding phase contrast images (C and E) in W7-treated (D and E) or -untreated (B and C) macrophages. Triangles indicate EEA1 colocalization with phagosomes. (F) Phagosome colocalization quantitation of EEA1 and Syntaxin 8 by immunofluorescence (mean ± SE; n = 1,145 phagosomes, 35 fields). (G) Immunoblotting analysis of EEA1 and Syntaxin 3 on purified phagosomes from 2 μM KN62-treated and -untreated cells.

**Ca^{2+}/calmodulin and PI3 kinase–dependent association of EEA1 with liposomes and Ca^{2+}-dependent binding of calmodulin to a protein complex containing PI3 kinase hVPS34.** (A) Quantitation (mean ± SE) of EEA1 on phosphatidylserine (PS) and phosphatidylinositol (PI) or PS and PI3P liposomes after incubation with J774 cytosol in the presence or absence of 100 nM PI3 kinase inhibitor wortmannin or 100 μM calmodulin inhibitor W7. (B) Immunoblotting analysis of hVPS34 and p150 on calmodulin agarose beads after incubation with J774 cytosol in the presence of EGTA (lane 1), Ca^{2+} (lanes 2, 3, and 4), W7 (lane 3), and W5 (lane 4).

**Figure 3.** Ca^{2+}/calmodulin and PI3 kinase–dependent association of EEA1 with liposomes and Ca^{2+}-dependent binding of calmodulin to a protein complex containing PI3 kinase hVPS34. (A) Quantitation (mean ± SE) of EEA1 on phosphatidylserine (PS) and phosphatidylinositol (PI) or PS and PI3P liposomes after incubation with J774 cytosol in the presence or absence of 100 nM PI3 kinase inhibitor wortmannin or 100 μM calmodulin inhibitor W7. (B) Immunoblotting analysis of hVPS34 and p150 on calmodulin agarose beads after incubation with J774 cytosol in the presence of EGTA (lane 1), Ca^{2+} (lanes 2, 3, and 4), W7 (lane 3), and W5 (lane 4).

**Figure 2.** Ca^{2+}/calmodulin and CaMKII positively regulate EEA1 recruitment to phagosomes. (A) Immunoblotting analysis and quantitation (mean ± SE) of EEA1 on purified LBC isolated from 25 μM W7-treated or -untreated macrophages. (B–E) Immunofluorescence images of EEA1 recruited to phagosomes (B and D) and corresponding phase contrast images (C and E) in W7-treated (D and E) or -untreated (B and C) macrophages. Triangles indicate EEA1 colocalization with phagosomes. (F) Phagosome colocalization quantitation of EEA1 and Syntaxin 8 by immunofluorescence (mean ± SE; n = 1,145 phagosomes, 35 fields). (G) Immunoblotting analysis of EEA1 and Syntaxin 3 on purified phagosomes from 2 μM KN62-treated and -untreated cells.

**Discussion**

Here, we have reported a new signaling cascade, connecting intracellular Ca^{2+}, calmodulin, and CaMKII with the recruitment of hVPS34 and production of PI3P on phagosomes. This signaling pathway is important for phagosome maturation and is a target for inhibition by *M. tuberculosis*. Based on our results, we conclude that the inhibitory effects of LAM on cytosolic Ca^{2+} increases can account for
the known Ca\textsuperscript{2+} block associated with phagocytosis of \textit{M. tuberculosis} (8). This action of LAM precludes interaction of PI3 kinase hVPS34 with calmodulin necessary for the downstream recruitment of EEA1. Because EEA1, in combination with Syntaxin 6, is necessary for the delivery of lysosomal components from the TGN to the phagosome (6), mycobacterial phagosome maturation arrest is caused by LAM-mediated disruption of Ca\textsuperscript{2+}/calmodulin-dependent regulation of PI3P and EEA1 on phagosomes.

ManLAM has been reported to prevent Ca\textsuperscript{2+} rise in B10R macrophages (24). The inhibition of Ca\textsuperscript{2+} fluxes shown here is restricted to LAM isolated from virulent \textit{M. tuberculosis}. There are several structural differences between LAM from \textit{M. tuberculosis} and nonpathogenic mycobacteria such as \textit{M. smegmatis}. These include acyl chains and the polysaccharides modifying the inositol ring (25). For instance, the polysaccharide portion of \textit{M. tuberculosis} LAM has mannose termini whereas \textit{M. smegmatis} LAM lacks mannose caps but has PI residues (25).

It is worth noting that an early study suggested that LAMP-1 acquisition by phagosome is independent of calcium in macrophages (26). However, more recent reports have demonstrated that cytosolic Ca\textsuperscript{2+} is important for phagosome maturation (27), including acidification (8, 10) and phagosome acquisition of lysosomal markers such as CD63 and Cathepsin D (8). The role of LAM in inhibiting these processes might be attributed to its partitioning into the host cell endomembranes (7), with its strongest action at the point of origination, the mycobacterial phagosome. Because dead mycobacteria do not block Figure 4. Calmodulin positively regulates PI3P on phagosomes. RAW 264.7 macrophages, transfected with the PI3P probe p40PX-EGFP, were imaged live while phagocytosing latex beads using an UltraView confocal microscope. After latex bead internalization and determination of PI3P positivity of the LBC, solvent without (Ctrl) or with 25 μM W7 (+W7) were added to the chamber. Panels: a, d, g, and j, Texas Red–labeled latex beads; b, e, h, and k, GFP probe for PI3P; c, i, and l, merged red and green channel images. Note localization of PI3P GFP probe on LBC after bead internalization (a–c and g–i), continued presence of the PI3P GFP probe on phagosomes 10 min after the addition of solvent alone (d–f), and the disappearance of the PI3P GFP probe when W7 was added (j–l). Arrows depict representative LBC in each experimental set. Examples of three independent experiments with comparable results are shown. Also, see Video 1 (available at http://www.jem.org/cgi/content/full/jem.20030527/DC1), which corresponds to panels g–l.
[Ca\(^{2+}\)]\(_{\text{rise}}\) is it likely that LAM has to be actively shed by live organisms to maintain appropriate concentration and localization. Alternatively, LAM might be extracted from or trapped in a denatured or cross-linked cell envelope during bacterial killing.

PI3P is crucial for phagosome maturation (3, 22). Inhibition of PI3P production, using wortmannin or blocking antibodies against hVPS34, prevents EEA1 recruitment, blocking phagosome maturation (2, 3, 22). This involves inhibition of delivery of hydrodases and H\(^{\text{+}}\)-ATPase proteolipid subunit from the TGN (3, 6), albeit a subset of wortmannin-insensitive markers (such as LAMP, Syntaxin 8, and Syntaxin 13) is not affected (3, 6). The effects on PI3 kinase may also affect the recruitment to phagosomes of other PI3P binding proteins such as p40\(^{\text{phox}}\) subunit of NADPH oxidase (28), which positively regulates superoxide production (29). Thus, Ca\(^{2+}\)-dependent regulation of PI3K may not only promote phagolysosome biogenesis but may also regulate assembly of NADPH oxidase and oxidative burst. Interference with Ca\(^{2+}\)signaling by M. tuberculosis LAM could thus have a dual effect by diminishing the oxidative burst during mycobacterial uptake by macrophages (30) and blocking mycobacterial phagosome maturation (7).

In summary, the data presented here, combined with a number of recent reports (3, 6, 8–10, 15) are consistent with a model in which M. tuberculosis LAM inhibits a cascade consisting of cytosolic Ca\(^{2+}\)transients, calmodulin, PI3 kinase hVPS34, and EEA1. This pathway is necessary for conversion of phagosomes into phagolysosomes, as EEA1 and Syntaxin 6 cooperate in the delivery of lysosomal components to the phagosome (3, 6). Thus, M. tuberculosis LAM acts as a trafficking toxin causing mycobacterial phagosome arrest by interfering with the Ca\(^{2+}\)/calmodulin PI3 kinase cascade. This is the first molecular definition of the mode of action of an M. tuberculosis toxin. Understanding the mechanism of mycobacterial phagosome maturation block will help in designing new antituberculosis therapies.

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