Mycobacterial Esx-3 Requires Multiple Components for Iron Acquisition

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(Article begins on next page)
Mycobacterial Esx-3 Requires Multiple Components for Iron Acquisition

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ABSTRACT The type VII secretion systems are conserved across mycobacterial species and in many Gram-positive bacteria. While the well-characterized Esx-1 pathway is required for the virulence of pathogenic mycobacteria and conjugation in the model organism Mycobacterium smegmatis, Esx-3 contributes to mycobactin-mediated iron acquisition in these bacteria. Here we show that several Esx-3 components are individually required for function under low-iron conditions but that at least one, the membrane-bound protease MycP3, of M. smegmatis, is partially expendable. All of the esx-3 mutants tested, including the ΔmycP3ms mutant, failed to export the native Esx-3 substrates EsxHms and EsxGms, to quantifiable levels, as determined by targeted mass spectrometry. Although we were able to restore low-iron growth to the esx-3 mutants by genetic complementation, we found a wide range of complementation levels for protein export. Indeed, minute quantities of extracellular EsxHms and EsxGms were sufficient for iron acquisition under our experimental conditions. The apparent separation of Esx-3 function in iron acquisition from robust EsxGms and EsxHms secretion in the ΔmycP3ms mutant and in some of the complemented esx-3 mutants compels reexamination of the structure-function relationships for type VII secretion systems.

IMPORTANCE Mycobacteria have several paralogous type VII secretion systems, Esx-1 through Esx-5. Whereas Esx-1 is required for pathogenic mycobacteria to grow within an infected host, Esx-3 is essential for growth in vitro. We and others have shown that Esx-3 is required for siderophore-mediated iron acquisition. In this work, we identify individual Esx-3 components that contribute to this process. As in the Esx-1 system, most mutations that abolish Esx-3 protein export also disrupt its function. Unexpectedly, however, ultrasensitive quantitation of Esx-3 secretion by multiple-reaction-monitoring mass spectrometry (MRM-MS) revealed that very low levels of export were sufficient for iron acquisition under similar conditions. Although protein export clearly contributes to type VII function, the relationship is not absolute.

One of the many strategies evolved by Mycobacterium tuberculosis to prevent clearance by the host is protein export via Esx-1 (1–3), a specialized secretion system that is also required for conjugation in M. smegmatis (4, 5). There are four paralogous esx loci in the M. tuberculosis genome (6–8), but the functions of these Esx systems are just beginning to be revealed (9–19, 55).

Whereas Esx-1 is essential for the in vivo growth of pathogenic mycobacteria, there is strong evidence that Esx-3 is essential for in vitro growth (12, 13, 19, 20). Building on observations that esx-3 expression responds to iron and zinc availability (21, 22), we and others have demonstrated that Esx-3 is required for mycobacterial growth in low iron (12, 13, 19). Mycobacteria acquire iron by at least two siderophore pathways—exochelin, present in fast-growing species, such as M. smegmatis, and mycobactin, present in nearly all species (23–25)—in addition to a porin-based, low-affinity iron transport system (26) and the heme uptake system (27, 28). Epistasis experiments using M. smegmatis strains with deficiencies in Esx-3 and in the production of exochelin or mycobactin show that Esx-3 functions in iron acquisition via the mycobactin pathway (13). Moreover, addition of purified, iron-bound mycobactin does not rescue the low-iron growth defect, suggesting that Esx-3 is required for optimal utilization of the siderophores (13).

The organizations and contents of the esx-1 and esx-3 loci are similar (8). Both encode small, secreted proteins; Esx-1 contains EsxB (Cfp-10) and EsxA (Esat-6), and Esx-3 contains the paralogous EsxG and EsxH proteins (Fig. 1). We use the systematic nomenclature proposed by Bitter et al. (29). Genes that flank esxB/A and esxG/H include those encoding EccC3 (a putative FtsK/ SpoIIE ATPase that is paralogous to EccCa/EccCb, where the “a” and “b” suffixes indicate the parts of the split gene and the subscript number refers to the esx-1 gene cluster), EspG3 (a putative soluble protein of unknown function that is paralogous to EspG2, EccD3 (paralogous to the hypothesized secretion channel...
Multiple studies on the Esx-1 system support a model in which the FtsK/SpoIIIE ATPase EccCa1/EccCb1 provides energy to propel EsxB and EsxA across the cytoplasmic membrane via a translocation pore composed of EccD1 (30–32). It is not yet clear how type VII substrate proteins cross the cell envelope. Esx-1 may simply export these proteins across the cell envelope into the extracellular space. Alternatively, it may act only across the cytoplasmic membrane and require a mechanism for driving substrates across the remainder of the thick mycobacterial cell wall. Such a structure may be composed of yet-unidentified components or of EsxA, EsxB, and possibly other unlinked Esx-1 substrates (33, 34).

EspG1, EccCa1/EccCb1, EccD1, and MycP1 are required for both EsxB and EsxA export and Esx-1 function in most mycobacterial species tested (3, 5, 35–41), prompting early speculation that EsxB and EsxA are the effector proteins of the secretion system. However, there have since been reports of several Esx-1 mutations that abolish function without affecting EsxB and EsxA export (4, 35, 42, 43), as well as two genetic perturbations that prevent \textit{M. tuberculosis} EsxB (EsxB\textsubscript{mt}) and EsxA\textsubscript{mt} secretion but do not alter \textit{M. tuberculosis} virulence (44). These studies suggest that the relationship between protein export and Esx function may be more complicated than previously assumed.

\section*{RESULTS}

\textbf{Esx-3 components are required for low-iron growth.} We have previously shown that Esx-3 is required for mycobacterial growth in low-iron medium via the mycobactin pathway (13). The secretion system is essential for growth in \textit{M. tuberculosis} (12, 13, 20), however, complicating efforts to test the contributions of individual Esx-3 components to the function of the entire system. The model organism \textit{M. smegmatis} can grow without functional Esx-3 in normal growth medium. We therefore constructed unmarked, in-frame deletions of \textit{esx-3} genes in \textit{M. smegmatis} (see Fig. S1 in the supplemental material). Because \textit{M. smegmatis} has partially redundant siderophore-based iron acquisition mechanisms, i.e.,...
the mycobactin and exochelin pathways (24), we combined each esx-3 deletion with an insertional mutation in fxbA, which encodes a formyl transferase required for exochelin synthesis. Previously, we found that the fxbA ΔeccC3ms mutant grows significantly more slowly than the fxbA strain in low-iron medium (13). Although the fxbA ΔesxGHms fxbA ΔespG3ms, and fxbA ΔeccD3ms mutants display similar low-iron growth deficiencies, the fxbA ΔmycP3ms strain has a less pronounced defect (Fig. 2 and 3). These strains are rescued by the presence of iron (Fig. S2) and upon reintroduction of the corresponding esx-3 gene (13) (Fig. 2).

Thus, M. smegmatis growth in low iron requires the Esx-3 components EccC3ms, EsxGms/EsxHms, EspG3ms, and EccD3ms, with a more minor contribution from MycP3ms.

**Esx-3 components contribute to optimal mycobactin utilization.** Previously, we constructed an M. smegmatis strain that contains insertions in both fxbA, described above, and mbtD, which encodes a polypeptide synthase required for mycobactin synthesis (13). This mutant, which lacks both means of high-affinity iron uptake, does not grow in iron-depleted medium but can be rescued by the addition of purified, iron-bound mycobactin or carboxymycobactin (13). However, the siderophores fail to rescue the fxbA Δesx-3 mutant, suggesting that Esx-3 is required for optimal utilization of iron bound to mycobactins (13). In the absence of the exochelin pathway, deletion of the esx-3 gene eccC3ms, esxGHms, espG3ms, or eccD3ms impairs iron-bound mycobactin utilization in M. smegmatis to an extent similar to that after removal of the entire Esx-3 system, whereas deletion of mycP3ms has a more modest effect (Fig. 3). We conclude that the Esx-3 components EccC3ms, EsxGms/EsxHms, EspG3ms, and EccD3ms, are critical to the function of the M. smegmatis Esx-3 system in mycobactin-mediated iron acquisition.

**Secretion of EsxHms and EsxGms requires Esx-3 components.** Secretion of EsxB and EsxA is generally linked to Esx-1 function; that is, most mutations that abolish export of these proteins also inhibit virulence (M. tuberculosis and M. marinum) or conjugation (M. smegmatis) (3–5, 35–40). Our work on the Esx-3 system demonstrates that EccC3ms, EsxGms/EsxHms, EspG3ms, and EccD3ms are required for function in mycobactin-mediated iron acquisition and that MycP3ms plays a more limited role (Fig. 2 and 3). Previously, we showed that export of heterologously expressed, myc-tagged EsxH depends on iron levels and on the presence of an intact Esx-3 locus (13). To test whether the loss of individual Esx-3
components similarly influences protein export, we monitored the abundance of representative EspG
ms and EspH
ms peptides in culture filtrates and selected whole-cell extracts by targeted, quantitative mass spectrometry (MS). Assays for peptides from each of these proteins were constructed using stable-isotope dilution MS (SID-MS) and multiple-reaction-monitoring MS (MRM-MS) (45, 46). For these experiments, we grew strains with intact exochelin production in medium with a level of iron chelation that induces EspH secretion (13) but does not produce differences in growth. Deletion of the esx-3 gene eccC
ms, esxGH
ms, espG
ms, or eccD
ms results in supernatant levels of EspH
ms and EspG
ms that are below the limit of quantitation (LOQ) across two biological replicates (Fig. 4 and S3 to S5 in the supplemental material). Interestingly, although the mycP
ms mutation causes a much smaller decrease in iron concentration than the other mutations (Fig. 2), there is a comparable decrease in supernatant peptides in three of the four data sets to levels below the LOQ (Fig. 4 and S3 to S5).

We find most of the detectable EspH
ms and EspG
ms in the supernatant fraction of wild-type M. smegmatis (Fig. 4 and S5). To test whether the observed lack of secretion by the esx-3 mutants reflects a general decrease in protein expression, we also compared the whole-cell extracts of the wild type, ΔespG
ms mutant, and complemented ΔespG
ms strain. The amounts of EspH
ms and EspG
ms were similar across the samples (Fig. S5), suggesting that the observed change in supernatant abundance accurately reports an export defect. The general lack of protein accumulation in the whole-cell extract, furthermore, implies that the cell tightly regulates the abundance of what we hypothesize is a small, cytoplasmic pool of EspH
ms and EspG
ms.

These data were consistent with our previous findings that Esx-3 is required for the export of EspH
ms-myc (13). Unlike native EspG
ms and EspH
ms, however, the tagged protein accumulates in the bacterial cytoplasm to robust levels (13). Therefore, we confirmed the mass spectrometry findings by constructing a new plasmid that constitutively expresses espG
ms and FLAG-tagged espH
ms and comparable amounts of EspH
ms-FLAG in cell-associated and supernatant fractions of wild-type and esx-3 mutant M. smegmatis strains. In agreement with the MRM-MS results, we were consistently unable to detect EspH
ms-FLAG from the supernatants of the ΔeccC
ms, ΔespG
ms, ΔeccD
ms, and ΔmycP
ms mutants or from any of the whole-cell extracts (Fig. 5).

**DISCUSSION**

We found that EccC
ms, EspG
ms, and EccD
ms are core Esx-3 components that are required for both mycobactin-mediated iron uptake and EspG
ms and EspH
ms export. The M. tuberculosis homologs EccC
ms, EspG
ms, and EccD
ms are all predicted to be necessary for in vitro growth (20, 47, 48). The Ess-1 paralogs EccCa, EccCb, EspG1, and EccD1 are required for virulence in pathogenic mycobacteria and conjugation in M. smegmatis and, with the exception of EspG1mt (35, 42), for EssB and EssA export (3–5, 35–40).

We have also identified a potential accessory Esx-3 component, MycP3, that is necessary for EspG and EspH export (Fig. 4 and 5) but not absolutely required for mycobactin-mediated iron acquisition (Fig. 2 and 3). The first observation is not unexpected, as mutants that lack MycP1 fail to secrete EspB and EssA (36, 41). The data on the contribution of MycP to Ess function are less clear; although MycP1mt is required for DNA transfer in M. smegmatis to the same or greater extent as other Ess-1 components (4, 36), mycP1mt disruption in M. tuberculosis results in a delayed phenotype in mice compared to the phenotypes resulting from transposon insertions in other ess-1 genes (49). More recent work corroborates an in vivo growth defect from loss of MycP1mt (41), but the lack of a direct comparison to other ess-1 mutant strains precluded analysis of the relative defect. Like the other esx-3 genes, mycP1mt is essential for M. tuberculosis growth in vitro (47). Given that MycP1 and MycP3 likely have different substrate specificities.

**FIG 3** Loss of Esx-3 components is not rescued by exogenous mycobactin. Growth of fxbA, fxbA mbtD, and fxbA esx-3 mutants in unsupplemented, low-iron medium or in low-iron medium containing 20 μg/ml mycobactin S at 48 h. The experiment was performed at least three times in triplicate. Representative data are shown and are expressed as percentages of the fxbA mutant’s growth in low-iron medium. Error bars indicate the standard errors of the proportions.

1 - fxbA
2 - fxbA mbtD
3 - fxbA ΔeccC
ms
4 - fxbA ΔespG
ms
5 - fxbA ΔespG
ms
6 - fxbA ΔespD
ms
7 - fxbA ΔmycP
ms
8 - fxbA Δesx-3
ms
FIG 4  EsxGms (A) and EsxHms (B) abundances in wild-type and exs-3 mutant supernatants. Protein concentrations for EsxGms and EsxHms were approximated, respectively, by measuring the concentration of the FVEVSAK peptide alone and by summing the individual concentrations above the LOD of three of the methionine forms of AMATTHEQNTMAMSAR peptides (Fig. S4). Dotted lines show the LOQ (Fig. S4). The experiments were performed in technical replicate across two biological replicates. The protein abundance data from one of the biological replicates are shown here in graphical and table format, and the data from the other replicate are reported in the Fig. S5 table. comp, complemented; ND, none detected.

**TABLE 1**

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<tr>
<th>Sample</th>
<th>EsxGms: FVEVSAK</th>
<th>EsxHms: AMATTHEQNTMAMSAR</th>
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<tr>
<td></td>
<td>Concentration</td>
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</tr>
<tr>
<td></td>
<td>fmol/µg</td>
<td>pg/µg</td>
</tr>
<tr>
<td>ΔesxGHms</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>ΔeccC3ms</td>
<td>0.071 +/- 0.002</td>
<td>0.706 +/- 0.019</td>
</tr>
<tr>
<td>ΔespG3ms</td>
<td>0.084 +/- 0.002</td>
<td>0.835 +/- 0.019</td>
</tr>
<tr>
<td>ΔeccD3ms</td>
<td>0.071 +/- 0.001</td>
<td>0.706 +/- 0.009</td>
</tr>
<tr>
<td>ΔmycP3ms</td>
<td>0.062 +/- 0.001</td>
<td>0.616 +/- 0.009</td>
</tr>
<tr>
<td>comp ΔesxGHms</td>
<td>6.16 +/- 0.12</td>
<td>61.21 +/- 1.23</td>
</tr>
<tr>
<td>comp ΔeccC3ms</td>
<td>0.899 +/- 0.015</td>
<td>8.94 +/- 0.15</td>
</tr>
<tr>
<td>comp ΔespG3ms</td>
<td>8.527 +/- 0.223</td>
<td>84.76 +/- 2.22</td>
</tr>
<tr>
<td>comp ΔeccD3ms</td>
<td>0.085 +/- 0.002</td>
<td>0.845 +/- 0.019</td>
</tr>
<tr>
<td>comp ΔmycP3ms</td>
<td>0.145 +/- 0.005</td>
<td>1.44 +/- 0.05</td>
</tr>
<tr>
<td>wildtype</td>
<td>38.96 +/- 0.70</td>
<td>387.24 +/- 6.99</td>
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FIG 5  Export of epitope-tagged EsxHms in the presence or absence of Exs-3 components. Anti-FLAG immunoblotting of whole-cell lysates (wcl) and culture supernatants (sup) from wild-type and exs-3 M. smegmatis containing pSYMP-exsGHms-FLAG in low-iron medium. All strains contain either the empty pJEB402 vector or pJEB402 containing the complementing gene. The antibody against the intracellular protein RNAP is a loading and lysis control. The experiment was performed twice with similar results.
(41, 50, 51), it may be that the relative importance of MycP as an Esx component varies according to the secretion apparatus with which it associates.

Despite our attempts to avoid polar effects by constructing in-frame, unmarked, full gene deletions, it is possible that the mutations altered the expression of downstream genes. However, this does not appear to be the case for at least the ΔmycP<sub>sm</sub> mutant, as neither mycP<sub>sm</sub> alone nor mycP<sub>sm</sub> alongside the downstream eccEs<sub>sm</sub> restored EsxH<sub>mt</sub>-FLAG export (not shown). Transcription of the esx-3 locus varies according to iron and zinc availability (13, 21, 22). It is possible that expression of the complementing genes from a heterologous, constitutive promoter altered the stoichiometry of Esx-3 components, which in turn resulted in suboptimal protein secretion.

We attempted to measure secreted proteins using native antibodies and Western blotting. However, the antisera that we were able to obtain had low affinity and poor specificity, making quantitation difficult. Given the tendency of secretion systems to be refractory to reporter fusions (52), we turned to MRM-MS to measure bacterial protein export. This label-free method is highly specific and sensitive and is likely to have broad applicability to bacterial protein secretion studies (53).

Precise quantitation of secretion by MRM-MS revealed a surprising dynamic range in the levels of EsxG and EsxH export that support iron acquisition. We were able to restore esx-3 mutant growth to wild-type levels by adding iron to the growth medium (Fig. S2) or by complementing the deleted genes (Fig. 2). However, the same genetic constructs varied widely in their abilities to restore EsxG<sub>mt</sub> and EsxH<sub>mt</sub> export (Fig. 4 and 5). Only a fraction of secreted wild-type EsxG<sub>mt</sub> and EsxH<sub>mt</sub> levels appeared necessary for complementation; we observed robust low-iron growth (Fig. 2) concomitant with protein export that spanned 3 orders of magnitude, from <1% to approximately 40% of wild-type levels (Fig. 4). We recently found that the essential drug targets dihydrofolate reductase and d-alanine racemase are present in excess (54). It is possible that wild-type <i>M. smegmatis</i> exports EsxG<sub>mt</sub> and EsxH<sub>mt</sub> at levels much greater than those needed to support low-iron growth. This raises the possibility that the locus has multiple functions, each with different secretion requirements.

Indeed, there is growing appreciation that the relationship between Esx protein export and function is more complex than initially assumed. There are now numerous reports of Esx-1 mutants that attenuate pathogenic mycobacteria without impacting virulence but had no effect on EsxG and EsxH secretion, we think that this is unlikely given that the ΔmycP<sub>sm</sub>-FLAG export (not shown). Transcription of the esx-3 locus varies according to iron and zinc availability (13, 21, 22). It is possible that expression of the complementing genes from a heterologous, constitutive promoter altered the stoichiometry of Esx-3 components, which in turn resulted in suboptimal protein secretion.

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Indeed, there is growing appreciation that the relationship between Esx protein export and function is more complex than initially assumed. There are now numerous reports of Esx-1 mutants that attenuate pathogenic mycobacteria without impacting virulence. For example, complementation of the natural esx-1 mutant <i>M. microti</i> (Fig. 1) with a panel of cosmids containing intact or mutant versions of the <i>M. tuberculosis</i> esx-1 region revealed that espE<sub>mt</sub> and espG<sub>mt</sub> are required for virulence but not EspB<sub>mt</sub> and EsxA<sub>mt</sub> export (35). Deletion of these genes from <i>M. tuberculosis</i> also resulted in attenuation without impacting the secretion of EsxB<sub>mt</sub> and EsxA<sub>mt</sub> (42). In a different example, disruption of disulfide bond formation in the Esx-1 substrate EspA<sub>mt</sub> attenuated <i>M. tuberculosis</i> virulence but had no effect on EspB<sub>mt</sub> or EsxA<sub>mt</sub> secretion (43). Finally, transposon insertions in espI<sub>mt</sub>, espK<sub>mt</sub>, and espB<sub>mt</sub> impaired conjugation but not EspB<sub>mt</sub> export (44). In aggregate, these studies show that secretion of EspB and EspA is not sufficient for Esx-1 function in virulence.

Recently, Chen and coworkers isolated two point mutations of EspA<sub>mt</sub> that block EsxB<sub>mt</sub> and EsxA<sub>mt</sub> export in vitro but do not attenuate <i>M. tuberculosis</i> (44). Although they did not rule out a role for the host environment in permitting secretion in vivo, these data suggest that export of these proteins, at least in large amounts, may not be strictly required for virulence. Similarly, we found a mutation that inhibits Esx protein secretion but permits partial function: loss of mycP<sub>sm</sub> blocked the export of native EsxG<sub>mt</sub> and EsxH<sub>mt</sub> and FLAG-tagged EsxH<sub>mt</sub> (Fig. 4 and 5), yet the fxbA ΔmycP<sub>sm</sub> mutant retained some ability to grow in low iron (Fig. 2). We also found that very low quantities of EsxG<sub>mt</sub> and EsxH<sub>mt</sub> secretion were sufficient to reinstate low-iron growth to some of our complemented esx-3 mutants (Fig. 2 and 4). Importantly, dissection of the esx-3 system in the model organism <i>M. smegmatis</i> allowed us to compare the two phenotypes, EsxG and EsxH export and mycobactin-mediated iron acquisition, under similar in vitro conditions.

Why are not protein secretion and iron utilization completely congruent in our mutant strains? This is especially puzzling given that the genome of <i>M. smegmatis</i>, unlike <i>M. tuberculosis</i>, does not encode the closely related paralogs EsxR and EsxS, which might otherwise be hypothesized to substitute for EsxG and EsxH function (8). One reason may be the existence of multiple Esx substrates, each with its own requirements for export and contributions to function. The roles of EspG and EspB are particularly informative in this regard. Inactivation of the paralogous espG<sub>mt</sub>, espG<sub>mt</sub>, or, as we show in Fig. 4, espG<sub>mt</sub> gene generally prevents the export of Esx substrate proteins (11, 17, 37, 42). However, in <i>M. tuberculosis</i>, loss of EspG<sub>mt</sub> did not produce an obvious phenotype (55), while EspG<sub>mt</sub> was required for full virulence but not EspB<sub>mt</sub> or EsxA<sub>mt</sub> secretion (35, 42). Interestingly, EspG<sub>mt</sub> and EspG<sub>mt</sub> have been shown to interact specifically with cognate Pro-Glu (PE)/Pro-Pro-Glu (PPE) proteins (56, 57) and have been proposed to serve as chaperones for Esx secretion of these substrates (57). These data suggest that the PE/PPE proteins have export requirements and functional contributions distinct from those of other type VII substrates. Similarly, the secretion and activity of the Esx-1 substrate EspB appear to be independent of EsxA (58, 59) and EspB (60).

Our data are consistent with at least three general models. It is conceivable that loss of Esx-3 function produces global changes in cell wall structure such that protein localization is affected by changes both in secretion and in the compartment into which translocation occurs. We note that while esx-3 mutants do not have altered sensitivities to SDS, vancomycin, rifampin (Fig. S5), ampicillin, or kanamycin (19), at least when iron is not limiting, we are unable to rule out this model. A second possibility is that Esx-3 secretes a protein or proteins necessary for iron acquisition and that this protein requires the core components EccC<sub>mt</sub>, EccD<sub>mt</sub>, and EspG<sub>mt</sub> but not EsxG, EsxH, or MycP<sub>mt</sub> for export. Although it is possible that Esx-3 function in iron acquisition does not require any EsxG and EsxH secretion, we think that this is unlikely given that the fxbA ΔesxG<sub>mt</sub>H<sub>mt</sub> strain has a complementable growth phenotype in low iron. A third model is that both EsxG and EsxH are substrates and structural components of or chaperones for the Esx-3 machinery. In this scenario, EsxG and EsxH are exported across the cytoplasmic membrane via EccD<sub>mt</sub> into the periplasm, where they are poised to deliver yet-unidentified effectors of ferrimycobactin uptake across the remainder of the cell wall (Fig. 6). If EsxG and EsxH indeed act within or across the mycobacterial envelope, some of the protein detected in the supernatants of broth-grown mycobacteria may represent sloughing of protein associated with the cell wall (33, 34).

While type VII secretion systems have important functions...
both in vitro and in vivo, their molecular mechanisms remain unclear. Clearly, protein export contributes to but does not entirely account for type VII function. More complete models for type VII structure-function relationships will require better characterization of secreted components and assays for protein-protein interactions that occur between Esx components in the cytosol or membrane (55, 61).

MATERIALS AND METHODS

Bacterial strains and growth conditions. M. smegmatis was cultured in chelated Sauton’s medium containing 60 ml glycerol, 0.5 g KH₂PO₄, 2.2 g citric acid monohydrate, 4 g asparagine, and 0.05% Tween 80 per liter. After adjusting the pH to 7.4, the medium was stirred for 1 to 2 days at room temperature with 10 g Chelex 100 resin (Sigma). The medium was filtered, and 1 g MgSO₄·7H₂O was added as a sterile solution. For iron starvation experiments, bacteria were first inoculated from frozen stocks into 7H9 medium, subcultured once in chelated Sauton’s medium, and then diluted 1:1,000 in chelated Sauton’s medium without antibiotics containing either 100 μM 2,2′-dipyridyl or 12.5 μM FeCl₃. For mycobactin complementation experiments, bacteria were directly diluted 1:1,000 from a 7H9 starter culture into chelated Sauton’s medium with or without ferri-mycobactin S.

Strain construction. To create the M. smegmatis esx-3 gene deletions, 1-kb regions flanking eccC₃ms, espG₃ms, eccD₃ms, mycP₃ms, and esxGH₃ms were amplified from M. smegmatis genomic DNA, stitched together by PCR, and cloned into the suicide vector pJM1. The pJM1 vector contains a hygromycin-chloramphenicol resistance cassette and the counterselectable marker sacB. M. smegmatis transformants were screened by PCR using primers specific to the flanks as well as to regions within the putative deletion. Candidates were confirmed by PCR using multiple primers outside the flanks. To construct fxbA insertional mutants, the esx-3 deletion strains were transformed with the pSES-fxbA suicide vector (13) and screened by standard methods. The absence of exochelin production was confirmed for candidate mutants by patching them to chrome azurol (CAS) agar.

Complementing constructs for each mutant were constructed by am-
plifying the regions from genomic \textit{M. smegmatis} DNA and cloning them under the MOP promoter in the integrative pJE8402 plasmid (38). The construct containing \textit{esxG}m and \textit{esxH}m C-terminally tagged with FLAG was generated by amplifying the region from genomic \textit{M. smegmatis} DNA and cloning it under the control of the \textit{hsps60} promoter of pSPY6 (62).

\textbf{SID, MRM-MS. (i) Labeled-peptide internal standards.} Figure S3 shows the amino acid sequences of the proteins \textit{EsxG}m and \textit{EsxH}m and the peptides that were selected for quantitative analysis of these proteins by multiple-reaction-monitoring mass spectrometry (MRM-MS). A peptide from each of the proteins was selected based on their detection in the discovery data by high electrospray MS signal responses and because they have unique sequences as determined by a search of the nonredundant \textit{M. tuberculosis} protein database (NCBI nr). Four different versions of the peptide AMATTHEQNTMAMSAR for the \textit{EsxH}m protein were selected, all of which were observed in the discovery data.

(ii) Peptide synthesis. Five signature peptides from the two proteins, \textit{EsxG}m (FVEYSAK) and \textit{EsxH}m (AMATTHEQNTMAMSAR), with four forms of differing oxidized methionine status, were synthesized with a single, uniformly labeled $^{13}$C-labeled or $^{13}$C$_2$-labeled form at their C termini by New England Peptide (Gardner, MA). Unlabeled $^{12}$C-labeled forms of each peptide were also synthesized by New England Peptide. Synthetic peptides were purified to $\geq 99\%$ purity and analyzed by amino acid analysis (New England Peptide). Calculations of concentrations were based upon amino acid analysis.

(iii) MRM-MS assay configuration. The limits of detection and quantification (LOD and LOQ, respectively) for the signature peptides used to obtain quantitative measurements in each of the 22 samples (5 mutants, 5 complemented mutants and 1 wild-type strain in each of two biological process replicates) are shown in Fig. S4. A 12-point response curve was generated by spiking light peptide versions of the 5 analyte peptides over a range of 0 to 50 fmol/1 $\mu$g of digested supernatant protein and a fixed amount of heavy, internal-standard peptide (1 fmol/$\mu$g) of the superantigen protein mix from the \textit{Delta} \textit{esxGH}m sample. This supernatant of the \textit{Delta} \textit{esxGH}m sample was used as the background matrix for response curve generation, as it does not express the proteins of interest. Each concentration point was analyzed by liquid chromatography (LC)–MRM-MS on a Waters Xevo TQ mass spectrometer (Milford, MA) in three technical replicates. The LOD was determined by the Linnet statistical method, and the lower LOQ was calculated as three times the LOD. The blank sample consists of the \textit{Delta} \textit{esxGH}m sample with only the isotopically labeled (heavy) peptides spiked in.

(iv) Nano-LC–MRM-MS. Tryptic peptides were prepared from culture supernatants from each of the 22 samples (5 mutants, 5 complemented mutants and 1 wild-type strain in each of two biological process replicates) and were used as the background matrix for response curve generation. Each concentration point was analyzed by liquid chromatography (LC)–MRM-MS on a Waters Xevo TQ mass spectrometer (Milford, MA) in three technical replicates. The LOD was determined by the Linnet statistical method, and the lower LOQ was calculated as three times the LOD. The blank sample consists of only the isotopically labeled (heavy) peptides spiked in.

(v) MRM-MS data analysis. Data analysis was performed using the Skyline Software Module (https://skyline.gs.washington.edu/). The relative ratios of the three transitions selected and optimized for the final MRM assay were predefined in the absence of the target proteins (i.e., in buffer) for each peptide using the $^{13}$C-labeled internal standards. The most abundant transition for each pair was used for quantification unless interference in this channel was observed. The $^{12}$C/$^{13}$C peak area ratios were used to calculate concentrations of the target peptides in each sample by the following equation: measured concentration $= \text{peak area ratio } \times (1 \text{ fmol/}$\mu$g internal standard).

\textbf{Sample preparation for MRM-MS analysis.} Strains were inoculated from frozen stocks in \textit{7H}9 medium with appropriate antibiotics and grown with shaking for 48 h. The cells were then washed twice in chelated Sauton’s medium, normalized by their optical densities at 600 nm (OD$_{600}$), and inoculated 1:50 into chelated Sauton’s medium. Cultures were grown for 48 h to log phase, and 8 OD units were harvested. Bacteria in the pellets were lysed by bead beating, and the lysates were stored at $-80^\circ$C. Protein from the supernatant was precipitated by the trichloroacetic acid (TCA) method and dissolved in urea-ammonium-bicarbonate buffer (8 M urea, 50 mM ammonium bicarbonate). Protein concentration was measured by the Bradford assay of diluted samples.

One hundred micromolars of protein was reduced by 20 mM dithiothreitol (DTT) and alkylated using 50 mM iodoacetamide. Prior to being digested with trypsin, samples were diluted to a urea concentration of 0.6 M by the addition of 50 mM ammonium bicarbonate. Tryptsin (Promega Gold) digestion was carried out at an enzyme-to-substrate ratio of 1:50. The peptides were desalted using Sep-Pak cartridges (Sep-Pak C$_{18}$ 1-cc [50-mg] Vac cartridges; Waters) as described by the manufacturer. In the final step, samples were eluted in 80% acetonitrile and 0.1% formic acid and evaporated to complete dryness in a vacuum centrifuge.

\textbf{Immunoblotting.} Strains were inoculated from frozen stocks into \textit{7H}9 medium and grown to saturation. They were then diluted 1:500 in chelated Sauton’s medium, grown to saturation, and diluted 1:100 in chelated Sauton’s medium. Proteins from cell pellets and supernatants of cultures grown for 12 h in this fashion were run on 10 to 20% Tris-Tricine gels (Invitrogen) and revealed using an anti-FLAG antibody. An antibody to RNA polymerase (RNAP; Neoclone W0023), an intracellular protein, served as a loading and lysis control.

\section*{SUPPLEMENTAL MATERIAL}

Supplemental material for this article may be found at http://mbio.asm.org/lookup/suppl/doi:10.1128/mBio.01073-14/-/DCSupplemental.

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\section*{REFERENCES}


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