



Susceptibility of *Mycobacterium tuberculosis* Cytochrome *bd* Oxidase Mutants to Compounds Targeting the Terminal Respiratory Oxidase, Cytochrome *c*

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ABSTRACT We deleted subunits I (*cydA*) and II (*cydB*) of the *Mycobacterium tuberculosis* cytochrome *bd* menaquinol oxidase. The resulting $\Delta cydA$ and $\Delta cydAB$ mutants were hypersusceptible to compounds targeting the mycobacterial *bc*₁ menaquinol-cytochrome *c* oxidoreductase and exhibited bioenergetic profiles indistinguishable from strains deficient in the ABC-type transporter, CydDC, predicted to be essential for cytochrome *bd* assembly. These results confirm CydAB and CydDC as potential targets for drugs aimed at inhibiting a terminal respiratory oxidase implicated in pathogenesis.

KEYWORDS TB drug discovery, mycobacterial respiration, electron transport chain, extracellular flux analysis, oxidative phosphorylation

There is resurgent interest in mycobacterial respiration and energy metabolism as potential sources of new targets and improved compounds for tuberculosis (TB) chemotherapy (1–3). This has been fueled primarily by the success of bedaquiline (BDQ), a diarylquinoline that inhibits the mycobacterial ATP synthase (4) and is approved for clinical use against multidrug-resistant (MDR) TB (5). However, additional agents in the TB drug discovery pipeline include Q203, an imidazopyridine that targets the mycobacterial cytochrome *bc*₁ complex (6), as well as the repurposed drug, clofazimine, which acts via a redox cycling mechanism involving reduction by the type II NADH dehydrogenase followed by nonenzymatic oxidation that produces reactive oxygen species (7). Moreover, a number of recent studies have demonstrated the potential to inhibit other components of the mycobacterial electron transport chain (ETC) (1, 2, 8) as well as the opportunities inherent in simultaneously targeting multiple components of mycobacterial oxidative phosphorylation (3, 9).

The rationale is strong: respiration is essential for the survival of replicating and nonreplicating bacilli (10). In addition, while the flexibility inherent in the multiply branched mycobacterial electron transport chain implies redundancy (8), the dependence of *Mycobacterium tuberculosis* on a single lipoquinone, menaquinone, and only two terminal respiratory oxidases—the *aa*₃-type cytochrome *c* oxidase and the cyto-

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chrome *bd* menaquinol oxidase (11)—suggests the potential for targeted disruption of respiratory function for both adjunctive (12) and combination (3) strategies. The *cydAB*-encoded cytochrome *bd* functions as the terminal acceptor in *M. tuberculosis* under microaerophilic conditions (11) and is also able to support aerobic growth during chemical inhibition of the bc_1 complex, QcrCAB; for example, following exposure to imidazopyridines (3, 13).

In *Escherichia coli*, assembly of cytochrome *bd* is dependent on the ABC-type transporter, CydDC, which is also required for the synthesis of other periplasmic cytochromes (14). As a result, *cydAB* and *cydDC* mutants of *E. coli* exhibit overlapping, but distinct, phenotypes, consistent with the genomic separation of the two operons. In contrast, the *cydDC* genes in *M. tuberculosis* are operonic with *cydAB*. At the inception of this study, it was not known whether *M. tuberculosis* CydDC functioned solely in cytochrome *bd* biosynthesis; previous reports exploited a *cydC::aph* mutant (15), in which only the terminal gene of the *cydABDC* locus was eliminated, or a $\Delta cydA::hyg$ mutant (12), which was expected to disrupt full operon function owing to polar effects. There were also two articles that utilized a knockout mutant, the “*cydKO*” strain, reportedly lacking the 3' end of *cydB*, the entire *cydD*, and the 5' end of *cydC* (9, 13); however, a subsequent author correction to reference 13 has noted that the strain actually employed in those papers was the *cydC::aph* mutant (15). It was not clear, therefore, when we initiated the current study whether disruption of the entire locus was phenotypically equivalent to targeted deletion (or, by implication, chemical inhibition) of the individual genes; moreover, no reports at the time had attempted to unlink the effects of disrupted cytochrome *bd* menaquinol oxidase function (*cydAB* inactivation) from deficient ABC transport (*cydDC* inactivation).

In a key study published during the preparation of the manuscript, Berney, Pethe, and colleagues (3) reported that targeted disruption of *cydAB* eliminated oxygen respiration in *M. tuberculosis* bacilli exposed to Q203, killing the cells and rendering the resulting $\Delta cydAB$ mutant strain hypersusceptible to Q203 treatment *in vitro* in both replicating and nonreplicating (tolerant) conditions as well as in a mouse model. In that case, $\Delta cydAB$ mutants were constructed using a phage-mediated unmarking (16) system that leaves an approximately 130-bp “scar” at the deletion site following activity of the $\gamma\delta$ resolvase.

Here, we generated targeted, in-frame deletion mutants of *cydA* and *cydAB* in *M. tuberculosis* H37RvMA (17) using two-step allelic exchange mutagenesis (18) in order to preserve the sequence integrity of the locus. This was confirmed by PCR and whole-genome sequencing (see Table S1 in the supplemental material). In standard microplate-based alamarBlue assays (MABA) (19) using Middlebrook 7H9 liquid growth medium (Difco) supplemented with 10% oleic acid-albumin-dextrose-catalase (OADC), 0.5% glycerol, and 0.05% Tween 80, the MIC₉₀ values recorded for a representative panel of approved anti-TB agents from different antibiotic classes and with diverse mechanisms of action were the same for *cydA* and *cydAB* mutants and identical to those observed for wild-type *M. tuberculosis* H37Rv and the *cydKO* (*cydC::aph*) mutant strain (Table 1). That is, no hypersensitivity phenotype was observed for any of the *cyd* mutants against any of the agents tested. This included BDQ, which was in contrast to some reports (12) but consistent with other recent results (3, 9). All three *cyd* mutants were, however, hypersusceptible to experimental compounds for which resistance maps to *qcrB* (Table 1; see also Fig. S1 in the supplemental material). Moreover, there were no significant differences in MIC values across the *cydA*, *cydAB*, and *cydKO* (*cydC::aph*) strains, suggesting that elimination of either the CydAB oxidase or CydDC transport subunits was sufficient to abrogate cytochrome *bd* function.

To investigate the impact of the different *cyd* alleles on mycobacterial respiratory function, we determined the bioenergetic responses of the *cydKO* (*cydC::aph*), *cydA*, and *cydAB* strains to Q203 treatment. Previously, we showed that Q203 inhibits electron flux through the *M. tuberculosis* cytochrome bc_1 , and this block is alleviated by rerouting electrons through cytochrome *bd* (9). Moreover, to compensate for the decreased proton motive force (PMF) generated by cytochrome *bd* and consequent

TABLE 1 MIC determinations against wild-type *M. tuberculosis* H37Rv and *cyd* mutant strains

Compound	<i>M. tuberculosis</i> strain ^a			
	H37Rv	<i>cydKO</i> (<i>cydC::aph</i>) mutant strain	Δ <i>cydA</i> mutant strain	Δ <i>cydAB</i> mutant strain
Rifampin	0.01	0.01	0.01	0.01
Isoniazid	0.04	0.04	0.04	0.04
Streptomycin	0.9	0.9	0.9	0.9
Ethambutol	0.47	0.47	0.47	0.47
Pretomanid (PA-824)	0.1	0.1	0.1	0.1
Levofloxacin	0.94	0.94	0.94	0.94
BDQ	0.03	0.03–0.06	0.03	0.03–0.06
Q203	0.0097 (>50) ^c	0.0003	0.0012	0.0003
Compound 1 ^b	3.125 (>50) ^c	0.39	0.39	0.39
Compound 2 ^b	0.390 (>25) ^c	0.02	0.0488	0.02

^aAll values are 14-day MABA (19) MIC₉₀s and are reported in micrograms per milliliter.

^bCompound numbers are as per reference 13.

^cThe MIC was determined visually according to the presence/absence of a definite mycobacterial pellet.

drop in ATP production, bacilli increase the total electron flux through the alternative terminal oxidase, with a subsequent increase in oxygen consumption rate (OCR) (9). In contrast, in the *cydKO* mutant strain, Q203 treatment is associated with a rapid decrease in OCR owing to the complete inhibition of terminal oxidase function.

As observed previously (9), exposure of wild-type *M. tuberculosis* H37Rv to Q203 caused a significant increase in the OCR from basal levels (measurement ten [M10]) (Fig. 1A). In contrast, OCR decreased in the *cydKO* (*cydC::aph*) (M10 in Fig. 1B) strain, an effect which was also observed in the *cydA* and *cydAB* strains (M10 in Fig. 1C and

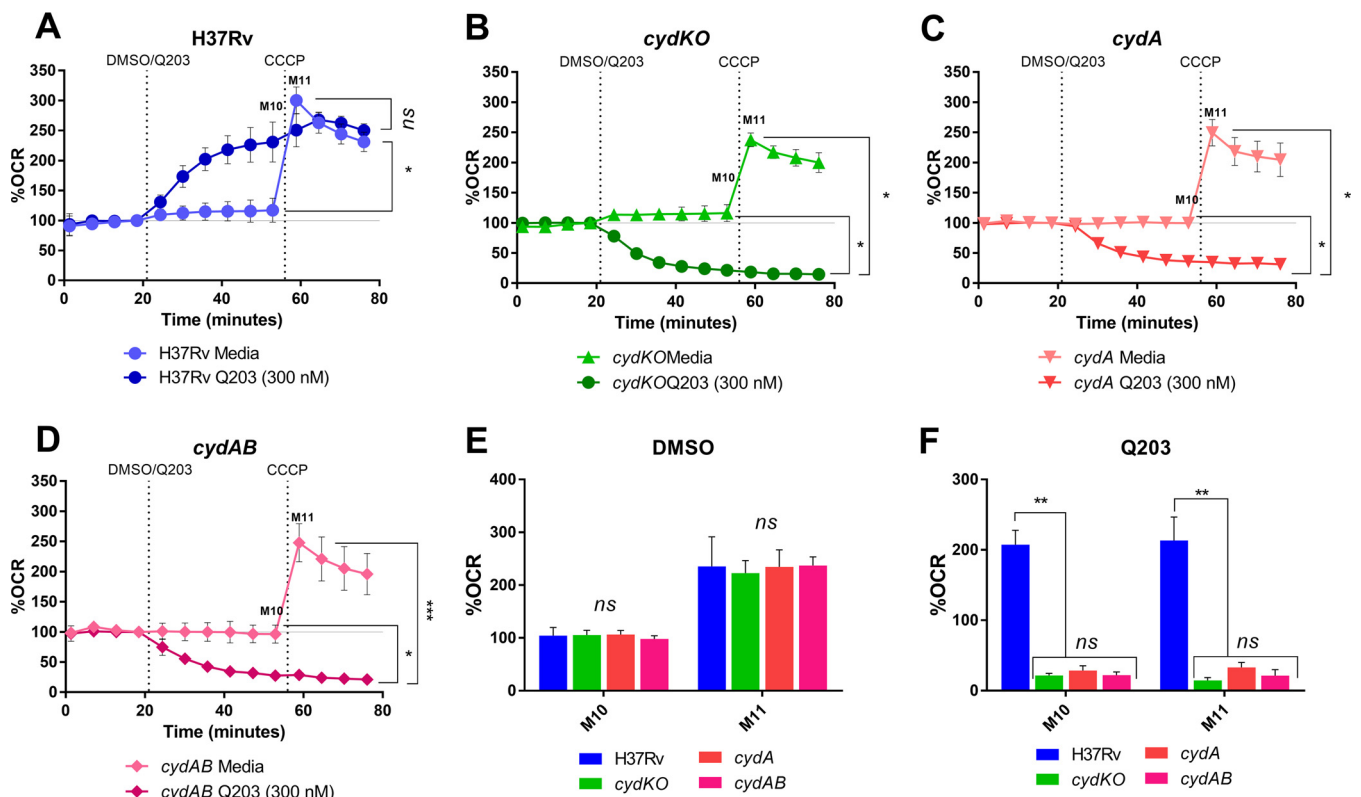


FIG 1 The *cyd* operon mutants are characterized by near-identical bioenergetics profiles. (A to D) The OCR profiles of wild-type *M. tuberculosis* H37RvMA and the *cydKO* (*cydC::aph*), Δ *cydA*, and Δ *cydAB* mutant strains treated with 300 nM Q203 and DMSO (as vehicle control), respectively. All plots are representative of three independent experiments, and the statistical analysis was by analysis of variance (ANOVA) (95% confidence interval) for the three biological replicates. ns, not significant; *, $P < 0.05$; **, $P < 0.005$; ***, $P < 0.0005$ (ANOVA, GraphPad Prism 6.05).

D) and was consistent with the phenotype of the $\Delta cydAB$ mutant described by Berney, Pethe, and colleagues (3). Following addition of the protonophore, carbonyl cyanide *m*-chlorophenylhydrazone (CCCP), there was no increase in OCR in any of the Q203-treated *cyd* mutants (M11 in Fig. 1B to D); this was in contrast to that in wild-type *M. tuberculosis* H37Rv, as well as that in the mock (dimethyl sulfoxide [DMSO])-treated *cyd* mutants (M11 in Fig. 1A to D), and indicated the complete shutdown of electron flux through the ETC in the absence of functional cytochrome *bd*. No significant differences were detected in OCR levels (M10 and M11) of all strains—wild-type strain and *cyd* mutants—treated with DMSO (Fig. 1E). This indicated that, in the absence of Q203 treatment, ETC function of the *cyd* deletion mutants was similar to that of the wild type; basal OCR levels were the same (M10), and all strains exhibited comparable capacity to raise OCR to maintain membrane potential upon uncoupling through CCCP addition (M11). Moreover, the OCR levels of the Q203-treated *cyd* strains were equivalent, and all three mutants exhibited the same inability to elevate OCR levels after CCCP exposure (Fig. 1F).

In combination, our results indicate that disruption of any of the *cyd* operon genes (or any combination thereof) results in a cytochrome *bd* functionally deficient mutant characterized by a common, but distinct, bioenergetic profile that is consistent with the observed hypersusceptibility to compounds inhibiting the cytochrome *c* respiratory oxidase. As such, these observations offer support to recent work which has provided compelling evidence of the potential for pathway-specific combination therapies to cripple metabolic escape mechanisms, thereby enhancing compound cidal activity and eliminating drug-tolerant bacilli (3).

SUPPLEMENTAL MATERIAL

Supplemental material for this article may be found at <https://doi.org/10.1128/AAC.01338-17>.

SUPPLEMENTAL FILE 1, PDF file, 0.3 MB.

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We declare no conflicts of interest.

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