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Identification of Novel sRNAs in Mycobacterial Species

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Abstract

Bacterial small RNAs (sRNAs) are short transcripts that typically do not encode proteins and often act as regulators of gene expression through a variety of mechanisms. Regulatory sRNAs have been identified in many species, including Mycobacterium tuberculosis, the causative agent of tuberculosis. Here, we use a computational algorithm to predict sRNA candidates in the mycobacterial species M. smegmatis and M. bovis BCG and confirmed the expression of many sRNAs using Northern blotting. Thus, we have identified 17 and 23 novel sRNAs in M. smegmatis and M. bovis BCG, respectively. We have also applied a high-throughput technique (Deep-RACE) to map the 5’ and 3’ ends of many of these sRNAs and identified potential regulators of sRNAs by analysis of existing ChiP-seq datasets. The sRNAs identified in this work likely contribute to the unique biology of mycobacteria.

Introduction

The genus Mycobacterium contains many clinically relevant pathogens, including Mycobacterium tuberculosis and Mycobacterium leprae, the etiologic agents of tuberculosis (TB) and leprosy, respectively. M. tuberculosis alone was responsible for 8.7 million incident cases and 1.4 million deaths globally in 2011 [1]. The treatment of TB has become increasingly difficult due to its high drug resistance and adaptability; hence, the development of new and more effective treatments for TB is imperative.

Bacterial “small RNAs” (sRNAs) are small (50–400 nt), typically untranslated transcripts. Many sRNAs play important roles in gene regulation in response to environmental changes [2]. sRNAs can originate from their own independent genes or through the processing of larger transcripts [3]. To exert their function, sRNAs typically base-pair with target messenger RNAs (mRNAs), resulting in altered transcription, mRNA stability, or translation [4]. sRNAs are key regulators of pathogenesis in many bacterial species [5]. Recently, RNA-seq has been widely applied to identify novel sRNA candidates in many bacterial species [6–10], including M. tuberculosis [11]. sRNAs have also been identified/predicted in M. tuberculosis using other experimental approaches [12–14] and computational analysis of RNA sequence data [13,15,16]. In total, 63 sRNAs have been experimentally validated in M. tuberculosis. sRNAs have also been identified in other mycobacterial species: 34 and 15 sRNAs have been experimentally validated in Mycobacterium bovis BCG and Mycobacterium smegmatis, respectively [13].

In a previous study, we used computational predictions from the SIPHT (sRNA Identification Protocol using High-throughput Technologies) [17] algorithm to identify 144 sRNA candidates in M. bovis BCG. We selected 34 conserved sRNA candidates which we experimentally confirmed by Northern blot [13]. In the current study, we expanded our search to include all the remaining SIPHT predictions for M. bovis BCG as well as all SIPHT predictions for M. smegmatis (these were not explored in the previous study). By combining SIPHT predictions with large-scale Northern blot validation, we have identified 23 and 17 novel sRNAs in M. bovis BCG and M. smegmatis, respectively. Thus, we have substantially increased the number of experimentally validated sRNAs in mycobacterial species. We also analyzed existing ChiP-seq datasets to identify possible regulators of sRNA expression, and used Deep-RACE, a technique that combines high throughput RNA-seq with Rapid Amplification of cDNA Ends (RACE) [18], to identify sRNA 5’ and 3’ ends. Lastly, it is worth noting that this work is one of the first efforts to better coordinate genome annotation; all sRNA candidates identified in this study have been renamed with a new nomenclature [19].

Materials and Methods

Strains and Plasmids

M. bovis BCG (Pasteur strain, Trudeau Institute), and M. tuberculosis H37Rv were grown in mycobedium (as previously reported, [13]). M. bovis BCG and M. tuberculosis cultures were grown for 7 days, with shaking, to late-log phase. Cultures of M. smegmatis MC2155 were grown for 7 days, with shaking, to late-log phase. Cultures of M. bovis BCG and M. smegmatis were grown for 18 hours with shaking (late-log phase).
Phylogenetic Selection of Computationally Predicted sRNA Candidates

Small RNA candidates of *M. smegmatis* were predicted using the SIPHT program with the same parameters as described previously [17,20]. SIPHT identifies potential sRNA candidates based on the presence of intergenic sequence conservation upstream of putative Rho-independent terminators. SIPHT has been widely applied in sRNA studies [21–23], and its reliability has been tested and compared with other algorithms [24].

RNA Isolation and Northern Blot Analysis

RNA was isolated as previously reported [13]. Northern blot analysis was performed as previously reported [13]; probes were designed according to SIPHT predicted sequences and tested in *M. bovis* BCG, *M. smegmatis* and *M. tuberculosis* [13]. All the oligonucleotides that were used in this study are listed in Table S1.

ChIP-seq Analysis

We analyzed existing ChIP-seq datasets for 55 *M. tuberculosis* transcription factors extracted from a previous study [25]. ChIP-seq peak positions were compared to the 5' end positions of *M. bovis* BCG and *M. tuberculosis* sRNAs from the current study and two previous studies [12,15]. For *M. bovis* BCG sRNAs, we first identified the equivalent region of the *M. tuberculosis* H37Rv genome. Possible sRNA regulators were selected if the ChIP-seq peak was located within 100 bp upstream and 20 bp downstream of an sRNA 5' end.

Deep 5' and 3' RACE

Deep 5' RACE and Deep 3' RACE were performed as previously described [18] with the following exceptions. Deep 5' RACE libraries and Deep 3' RACE libraries were pooled and sequenced together using an Ion Torrent 316 chip (Wadsworth Center Applied Genomic Technologies Core Facility). For Deep 5' RACE, sequence reads were identified by the presence of the expected adapter sequence at the read 5' end. Adapter sequences were removed and reads of >40 nt were mapped to the reference genomes using BWA [26]. For Deep 3' RACE, sequence reads were identified by the presence of the expected adapter sequence.

Figure 1. Schematic for sRNA identification. This schematic shows the combination of computational approaches and Northern blotting analysis used to identify the reported novel sRNAs in *M. bovis* BCG and *M. smegmatis*. doi:10.1371/journal.pone.0079411.g001

Figure 2. Northern blotting confirmation of sRNA candidates in *M. smegmatis*. Selected images of Northern blotting analysis for validated *M. smegmatis* sRNAs; the remaining images are included in Figure S1. Lane 1 and 2 indicate total RNA samples extracted from *M. smegmatis* and *M. bovis* BCG, respectively. We used Phi-X174/Hae III Marker for the size prediction. The probes we used for this analysis are listed in Table S1. doi:10.1371/journal.pone.0079411.g002
Adapter sequences were removed. The oligo-dT stretch was removed by identifying the first consecutive pair of bases not including a “T” and removing all sequence upstream of this. Sequences of 40 nt were mapped to the reference genomes using BWA [26]. For both Deep 5′RACE and Deep 3′RACE, 5′ and 3′ ends were identified as the position with the most sequence reads, and with a minimum of 5 reads. Sequences of all primers used for Deep RACE are listed in Table S2.

Results and Discussion

Prediction of sRNAs in silico using SIPHT

Using SIPHT, we identified 93 candidate sRNAs in *M. smegmatis* (refseq: NC_008596) (Table S3) and 144 candidate sRNAs in *M. bovis* BCG (refseq: NC_008769) (Table S4). Tables S3 and S4 include a detailed description of the predicted coordinates, orientations, sizes and neighboring upstream and downstream genes. Northern probes were designed according to SIPHT prediction. Figure 1 summarizes the overall approach that was employed in this work for sRNA identification and confirmation.

### Table 1. sRNAs confirmed by Northern blotting analysis in *M. smegmatis*.

| Intergenic sRNAs | 5′ end* | 3′ end* | Homology confirmed by Northern analysis in: | New nomenclature | Length Confirm by Northern blotting analysis(nt) |
|------------------|---------|---------|-------------------------------------------|------------------|---------------------------------------------|
| Sm19             | 5029661 | 5029530 | ncMSMEG14931Ac                            | 100–118          |
| Sm32/33          | 417709  | 417796  | ncMSMEG10373A                             | 44               |
| Sm35             | 1458488 | 1458562 | ncMSMEG113863A                            | 118              |
| Sm46             | 5864890 | 5864989 | ncMSMEG15796A                             | 82               |
| Sm49             | 1086797 | 1087035 | ncMSMEG131061A                            | 48–66            |
| Sm64             | 2523008 | 2522888 | ncMSMEG12439Ac                            | 100–118          |
| Sm76             | 3690377 | 3690280 | ncMSMEG13628Ac                            | 100–118          |
| Sm82             | 4392939/4392970 | 4393039 | ncMSMEG14302A                            | 66/82–100        |

| Total overlapping sense sRNAs | 5′ end* | 3′ end* | Homology confirmed by Northern analysis in: | New nomenclature | Length Confirm by Northern blotting analysis(nt) |
|-------------------------------|---------|---------|-------------------------------------------|------------------|---------------------------------------------|
| Sm38             | 2236980 | 2237466 | ncMSMEG2161A                             | 48–66/66–82      |
| Sm41             | 3815700/3815647 | 3815581 | ncMSMEG349Ac                             | 48–66/100–118    |
| Sm90             | 6845964 | 6846035 | ncMSMEG6699A                             | 48–66            |
| Sm93             | 858482 | 858588  | ncMSMEG7074A                             | 66–82/100–118    |

| Total overlapping antisense sRNAs | 5′ end* | 3′ end* | Homology confirmed by Northern analysis in: | New nomenclature | Length Confirm by Northern blotting analysis(nt) |
|-----------------------------------|---------|---------|-------------------------------------------|------------------|---------------------------------------------|
| Sm42               | 4290417/4290487 | 4290537 | ncMSMEG4206A                             | 48–66/100–118    |
| Sm67               | 2600405/2600425 | 2600485 | ncMSMEG5214A                             | 48–66/66–82      |
| Sm68               | 2600389 | 2600701 | ncMSMEG5214B                            | 82–100           |
| Sm74               | 3111233 | 3111268 | ncMSMEG3037A                             | 66–82            |

| Partial overlapping antisense sRNAs | 5′ end* | 3′ end* | Homology confirmed by Northern analysis in: | New nomenclature | Length Confirm by Northern blotting analysis(nt) |
|-------------------------------------|---------|---------|-------------------------------------------|------------------|---------------------------------------------|
| Sm11                | 2835860 | 2835964/2835999 | ncMSMEG12771A                             | 100–118/140–151  |

| Not categorized sRNAs | 5′ end* | 3′ end* | Homology confirmed by Northern analysis in: | New nomenclature | Length Confirm by Northern blotting analysis(nt) |
|-----------------------|---------|---------|-------------------------------------------|------------------|---------------------------------------------|
| Sm47                  | 6242319 | 6242668 | ncMSMEG16173A                             | 311               |

*The coordinates in bold were determined by 5′ or 3′ Deep-RACE. Where only one end was determined by Deep RACE, the other end was estimated based on the size determined by Northern blot. Where neither end was determined by Deep RACE, SIPHT-predicted coordinates are listed (underlined text).

Experimentally demonstrated in previous study [27].

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17 Novel sRNAs Identified in Mycobacterium Smegmatis

All 93 *M. smegmatis* sRNA candidates were tested by Northern blot using oligonucleotides in both orientations; expression was confirmed for 18 sRNA (listed in Table 1; see blot pictures in Figure 2 and Figure S1). One of them (Sm32/33) was identified in recent work as IGR-1 with similar size, coordinates and same orientation [27]. Thus, 17 *M. smegmatis* sRNAs identified here have not been experimentally demonstrated in any previous studies. In our previous study [13], we reported homologs of 6 *M. smegmatis* sRNA candidates (Sm32/Sm33, Sm35, Sm46, Sm47, and Sm74) in *M. bovis* BCG (Mpr13/Mcr14, Mpr20, Mpr3, Mpr4, and Mpr5, respectively). These were confirmed directly in *M. smegmatis* by Northern blotting in current study and listed in the 17 novel confirmed sRNAs. A homologue of Sm76 was previously identified in *M. tuberculosis* by RNA-seq [15] and microarray analysis [14] but not otherwise experimentally confirmed. All of the validated sRNAs were in the same orientation to that predicted by SIPHT. This suggests that the sequence specificity of SIPHT for this prediction is higher than in our previous work, in which 9 out of 37 of the validated sRNAs were in the opposite orientation to the prediction [13]. All confirmed sRNAs were assigned gene names according to a recently-proposed nomenclature [19].
Given the practical convenience of testing RNA from both species simultaneously to search for novel sRNA candidates, we used the designed probes for sRNA detection in *M. smegmatis* to also probe expression of these candidates in *M. bovis* BCG and *M. tuberculosis*. Although our focus was to validate *M. smegmatis* predictions, we fortuitously discovered homologues of 9 candidates in *M. bovis* BCG and 4 candidates in *M. tuberculosis* (Table 1, Figure S2). Since these probes were not specifically designed for the other two species, lack of detection could be due to either the absence of sRNA expression or to non-optimization of the probe sequence that was used for hybridization to the targeted region in the *M. bovis* BCG and *M. tuberculosis* genome. Also, differences in culture medium might contribute to the low number of expressed homologous sRNAs of *M. smegmatis* in *M. tuberculosis* as expression of these sRNAs could be specific to different conditions in *M. tuberculosis*. Given our focus in sRNA identification, specific conditions that could lead to differences in sRNA expression will be explored in future work.

23 Novel sRNAs Identified in Mycobacterium Bovis BCG

Twenty-one of the sRNA candidates for *M. bovis* BCG (Bo12, Bo15, Bo41, Bo52, Bo58, Bo67, Bo68, Bo75, Bo80, Bo85, Bo99, Bo100, Bo111, Bo113, Bo115, Bo117, Bo122, Bo125, Bo126, Bo137, and Bo139) were previously identified, under the nomenclature Mpr 1–21, respectively [13]. Forty-six other candidates were also tested previously but showed no signal; therefore, only the remaining 77 candidates were tested using Northern blotting analysis in this study, and we confirmed expression of 23 new sRNA candidates (Figure 3 and Figure S3). For some sRNAs we identified multiple 5' and 3' ends. Multiple 5' ends could be due to multiple transcription start sites or RNA processing. Multiple 3' ends could be due to RNA processing or may indicate imprecise Rho-dependent termination of transcription.

Deep-RACE Identifies sRNA 5' and 3' Ends

We used Deep-RACE, a previously described approach that combines conventional RACE and deep sequencing to identify 5' and 3' ends of selected RNAs [18,28]. In total, we identified 5' ends for 9 sRNAs and 3' ends for 21 sRNAs. Examples are shown in Figure 4. For some sRNAs we identified multiple 5'/3' ends. Multiple 5' ends could be due to multiple transcription start sites or RNA processing. Multiple 3' ends could be due to RNA processing or may indicate imprecise Rho-dependent termination of transcription.

Size Comparisons between Experimental and Prediction Analysis

As noted in our earlier study [13], the predicted size of the candidate sRNAs correlates only weakly with experimental observations. Only about 17% of the confirmed sRNAs were within 10% of their predicted sizes. Additionally, in many cases, multiple bands were detected by Northern analysis, suggesting the presence of multiple start sites, multiple termination sites, and/or sRNA processing. This is consistent with the Deep RACE data (Figure 4; Figure S4). Deep RACE identified both 5' and 3' ends for seven sRNAs. In these cases, the sizes determined by Deep RACE are similar to those confirmed by Northern blotting.

Location of sRNAs with Respect to Genes

To investigate the potential roles of the novel sRNAs, we mapped them all to the latest annotated genome (National Center for Biotechnology Information, NCBI). Although we aimed to find intergenic sRNAs, half of the candidates we identified in this study overlap partially or entirely protein-coding genes in either the
sense or antisense orientation (Table 1, Table 2). We categorized sRNAs into different classes according to their position relative to adjacent coding regions. Where possible, we used 5’/3’ end information from Deep-RACE data. For sRNAs that have only one end mapped by Deep-RACE, the other end was estimated according to the length confirmed by Northern blotting analysis (Figure 4). For sRNAs that have neither end mapped by Deep-RACE, the farthest possible ends were estimated according to Northern blotting analysis and the sRNAs would be categorized as “not determined” if multiple class options exist.

Nine sRNAs in *M. smegmatis* (Sm19, Sm32/33, Sm35, Sm46, Sm49, Sm64, Sm76, Sm82) and twelve sRNAs in *M. bovis* BCG (Bo35, Bo48, Bo53, Bo60, Bo71, Bo73, Bo78, Bo86, Bo101, Bo105, Bo118, Bo132) were mapped completely to intergenic regions. Four sRNAs in *M. smegmatis* (Sm42, Sm67, Sm68, Sm74). One sRNA in *M. smegmatis* (Sm11) and five in *M. bovis* BCG (Bo32, Bo47, Bo81, Bo96, Bo130) overlap partially with adjacent genes in the antisense orientation, and four sRNAs in *M. bovis* BCG (Bo27, Bo46, Bo82, Bo87) overlap partially with adjacent genes in the sense orientation. One sRNA in *M. smegmatis* (Sm47) and two in *M. bovis* BCG (Bo13, Bo29) were not classified.

The location of sRNAs relative to protein-coding genes also gives clues as to their function. Regulatory sRNAs that are completely intergenic typically function by base-pairing with distally-encoded mRNAs; however, some of the sRNAs are close to the 5’ end or 3’ end of adjacent genes, suggesting possible alternative regulatory roles. sRNAs antisense to ORFs or UTRs can regulate expression of the overlapping gene [29]. sRNAs located within UTRs or ORFs in the sense orientation may be degradation products or mRNAs or could be important cis-acting regulatory elements such as riboswitches.

| Table 2. sRNAs confirmed by Northern blotting analysis in *M. Bovis* BCG. |
|---------------------------------------------------------------|
| **Homology confirmed by Northern analysis in:** | **M. smegmatis** | **M. tuberculosis** | **New nomenclature** | **Length Confirm by Northern blotting analysis(nt)** |
|---------------------------------------------------------------|
| **Intergenic sRNAs** | | | | |
| Bo35 | 576179 | 576067/576104 | ncBCG10493Ac | 48–66/82–100 |
| Bo48 | 3028936 | 3028876 | ncBCG12782Ac | 48–66 |
| Bo53 | 1044606 | 1044706/1044720/1044727 | ncBCG10960A | 82–100/100–118 |
| Bo60 | 1247638 | 1247538 | ncBCG11150Ac | 66/100 |
| Bo71 | 1588853 | 1588693 | ncBCG11448Ac | 66 |
| Bo73 | 1647817 | 1647853 | ncBCG11504A | 66–82 |
| Bo78 | 207337 | 207179 | ncBCG10186Ac | 66/100 |
| Bo86 | 2325795 | 2325960 | ncBCG12107A | 66–82 |
| Bo101 | 2919337 | 2919227 | ncBCG2654Ac | 48–66 |
| Bo118 | 3765977 | 3765917 | ncBCG13438Ac | 48–66 |
| Bo132 | 4260533 | 4260610 | ncBCG13885A | 66–82 |
| Bo105 | 3073445 | 3073514 | ncBCG12831A | 66–82 |
| **Partial overlapping sense sRNAs** | | | | |
| Bo27 | 2157804 | 2157704 | ncBCG10194Ac | 82–100 |
| Bo46 | 2603016 | 2602916 | ncBCG12368Ac | 100 |
| Bo82 | 2235286 | 2235196 | ncBCG12024Ac | 82–100 |
| Bo87 | 2351000/2351046 | 2350915/2350874 | ncBCG12128Ac | 48–66/66–82/82 |
| **Partial overlapping antisense sRNAs** | | | | |
| Bo32 | 817571 | 817483 | ncBCG10734Ac | 66–82/82 |
| Bo47 | 2705925/2705838 | 2705735 | ncBCG12462Ac | 82–100 |
| Bo81 | 218700 | 2187796 | ncBCG10195A | 66/100 |
| Bo96 | 2686849 | 2686909/2686989 | ncBCG12441A | 66–82/118–142 |
| Bo130 | 413416 | 413288 | ncBCG0352Ac | 66–82/118–142 |
| **Not categorized sRNAs** | | | | |
| Bo13 | 3126934 | 3127070 | ncBCG12882A | 48–66/82–100 |
| Bo29 | 1770012 | 1769806 | ncBCG11603Ac | 66–82 |

*The coordinates in bold were determined by 5’ or 3’ Deep-RACE. Where only one end was determined by Deep RACE, the other end was estimated based on the size determined by Northern blot. Where neither end was determined by Deep RACE, SIPHT-predicted coordinates are listed (underlined text). doi:10.1371/journal.pone.0079411.t002
sRNAs can be transcribed independently or generated by processing of mRNA UTRs. Several features of the sRNAs identified in this work are consistent with the sRNAs being independently transcribed from their own promoters. First, the Northern blots showed no evidence of larger bands that could correspond to pre-processed mRNAs. Second, 13 sRNAs (Sm35, Sm42, Sm67, Sm68, Sm74, Bo13, Bo32, Bo60, Bo71, Bo73, Bo81, Bo118, Bo130) are oriented away from the surrounding genes. Third, 5 sRNAs (Sm64, Sm82, Bo47, Bo105, Bo132) are located <200 bp from the nearest gene start/stop. Nineteen sRNAs are close to (<200 bp) upstream or downstream of coding regions (Sm11, Sm19, Sm32/33, Sm46, Sm47, Sm49, Sm76, Bo27, Bo29, Bo55, Bo46, Bo48, Bo53, Bo78, Bo82, Bo66, Bo87, Bo96, Bo101) and four (Sm38, Sm41, Sm90, Sm93) overlap coding regions in

Figure 4. Identification of sRNA 5' and 3' ends by Deep RACE. Blue lines show the number of 5' RACE reads mapped to respective genome, while red lines show the number of 3' RACE reads. The coordinates with the highest number of mapped reads (the peak) indicate the likely 5' and 3' ends of sRNAs and are labeled in the figure. The orange arrow under the chart shows where the Northern probes base-paired and the blue arrows are the adjacent annotated coding regions. Results for other sRNAs can be found in Figure 5A.

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Figure 5. ChIP-seq peaks associated with predicted sRNA homologues in *M. tuberculosis*. ChIP-seq peaks that are unambiguously associated with sRNA 5' ends. Raw ChIP-seq data from www.tbdb.org are shown for two transcription factors, (A) Rv2887, and (B) Rv3249c. Data are shown for genomic regions surrounding (A) sRNA Bo132 (this work), and (B) sRNA B55 [12]. The green and blue graphs indicate the relative number of sequence reads mapping to the plus and minus strands, respectively. The yellow graphs indicate the sum of plus and minus strand reads. Annotated genes are shown as gray arrows. sRNAs are shown as red triangles.

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the sense orientation. It is formally possible that these sRNAs are generated by mRNA processing or premature termination, although the Northern blot analysis argues against this. Regardless, sRNAs processed from mRNAs could still have important regulatory functions [3,30,31]. Indeed, a recent study identified 3’ UTRs as an abundant source of regulatory sRNAs in Salmonella enterica [32]. Alternatively, sRNAs generated by processing of mRNAs could indicate cis-acting regulatory elements such as riboswitches.

Likely Regulators of sRNAs Identified by Analysis of ChIP-seq

The regulation of sRNAs can provide important clues as to their biological functions. However, very little is currently known about regulation of mycobacterial sRNAs. The genome-wide binding profiles of many M. tuberculosis transcription factors have recently been determined using ChIP-seq and these data are publicly available [25]. Although we identified sRNAs in M. bovis BCG, it is highly likely that these sRNAs are conserved in M. tuberculosis genomes [33]. Hence, we searched existing ChIP-seq datasets of M. tuberculosis for transcription factors that bind close to sRNA 5’ ends, including sRNAs identified in earlier studies [12]. We identified 10 ChIP-seq peaks (indicative of a transcription factor binding site) located between 100 bp upstream and 20 bp downstream of sRNA 5’ ends (Table S5). Thus, we have identified likely examples of sRNA regulation. In some cases, the ChIP-seq peak is also close to the start of an annotated protein-coding gene. Hence, the transcription factor may regulate the protein-coding gene rather than the sRNA. Nevertheless, in four cases, the ChIP-seq peak was unambiguously associated with an sRNA 5’ end. The two examples with highest ChIP-seq signal are shown in Figure 5. For each of these examples, the transcription factor is otherwise uncharacterized.

Conclusion

In summary, we have identified 17 novel sRNAs in M. smegmatis and 23 novel sRNAs in M. bovis BCG, verified 5’ and 3’ ends, and list these sRNAs according to a recently-proposed annotation nomenclature. Our analysis of sRNA position relative to protein-coding genes suggests various potential roles for these sRNAs in gene regulation. Although the specific biological function of these, and all other known mycobacterial sRNAs, is not understood, we speculate that some of these sRNAs contribute to the biology of pathogenic mycobacterial species. Future studies will focus on the functional characterization of these novel sRNAs.

Supporting Information

Figure S1 Northern blotting analysis for M. smegmatis sRNAs. (PDF)

Figure S2 Northern blotting analysis of sRNA candidates in M. tuberculosis with M. smegmatis and M. bovis BCG probes. (PDF)

Figure S3 Northern blotting analysis for M. bovis BCG sRNAs. (PDF)

Figure S4 Deep-RACE mapped reads of all sRNAs and adjacent gene annotations. (PDF)

Table S1 The oligonucleotide sequence of all probes used for Northern Blotting analysis in this study. (PDF)

Table S2 The oligonucleotide sequence of all primers used for Deep-RACE PCR. (PDF)

Table S3 All 93 sRNA sequences predicted by SIPHT in M. smegmatis. (PDF)

Table S4 All 144 sRNA sequences predicted by SIPHT in M. bovis BCG. This list excludes predicted tRNAs. (PDF)

Table S5 All transcription factor ChIP-seq peaks located within 100 bp upstream and 20 bp downstream of sRNA 5’ ends. (PDF)

Acknowledgments

We would like to thank Marquis Martin for his assistance with data analysis, Marlene Belfort for supporting our initial studies (please see funding statement), Todd Gray for helpful discussions and for generously providing materials for this study, Matt Stanger for his assistance with figures, Jeannie DiChiara and Damien Schaar for sample preparation. We thank the Wadsworth Center Applied Genomic Technologies Core Facility for Ion Torrent sequencing.

Author Contributions

Conceived and designed the experiments: KAM JTW LMC. Performed the experiments: CHT CB LMC. Analyzed the data: CHT CB JTW LMC. Contributed reagents/materials/analysis tools: JL KAM JTW LMC. Wrote the paper: CHT JTW LMC.

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Supporting Information

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Author Contributions

Conceived and designed the experiments: KAM JTW LMC. Performed the experiments: CHT CB LMC. Analyzed the data: CHT CB JTW LMC. Contributed reagents/materials/analysis tools: JL KAM JTW LMC. Wrote the paper: CHT JTW LMC.

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