Riboswitches for Intracellular Study of Genes Involved in Francisella Pathogenesis

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ABSTRACT The study of many important intracellular bacterial pathogens requires an understanding of how specific virulence factors contribute to pathogenesis during the infection of host cells. This requires tools to dissect gene function, but unfortunately, there is a lack of such tools for research on many difficult-to-study, or understudied, intracellular pathogens. Riboswitches are RNA-based genetic control elements that directly modulate gene expression upon ligand binding. Here we report the application of theophylline-sensitive synthetic riboswitches to induce protein expression in the intracellular pathogen Francisella. We show that this system can be used to activate the bacterial expression of the reporter β-galactosidase during growth in rich medium. Furthermore, we applied this system to control the expression of green fluorescent protein during intracellular infection by the addition of theophylline directly to infected macrophages. Importantly, we could control the expression of a novel endogenous protein required for growth under nutrient-limiting conditions and replication in macrophages, FTN_0818. Riboswitch-mediated control of FTN_0818 rescued the growth of an FTN_0818 mutant in minimal medium and during macrophage infection. This is the first demonstration of the use of a synthetic riboswitch to control an endogenous gene required for a virulence trait in an intracellular bacterium. Since this system can be adapted to diverse bacteria, the ability to use riboswitches to regulate intracellular bacterial gene expression will likely facilitate the in-depth study of the virulence mechanisms of numerous difficult-to-study intracellular pathogens such as Ehrlichia chaffeensis, Anaplasma phagocytophilum, and Orientia tsutsugamushi, as well as future emerging pathogens.

IMPORTANCE Determining how specific bacterial genes contribute to virulence during the infection of host cells is critical to understanding how pathogens cause disease. This can be especially challenging with many difficult-to-study intracellular pathogens. Riboswitches are RNA-based genetic control elements that can be used to help dissect gene function, especially since they can be used in a broad range of bacteria. We demonstrate the utility of riboswitches, and for the first time show that riboswitches can be used to functionally control a bacterial gene that is critical to the ability of a pathogen to cause disease, during intracellular infection. Since this system can be adapted to diverse bacteria, riboswitches will likely facilitate the in-depth study of the virulence mechanisms of numerous difficult-to-study intracellular pathogens, as well as future emerging pathogens.
been used as a ligand for synthetic riboswitches. A number of theophylline-sensitive synthetic riboswitches have been reported as robust, broad-host-range genetic control elements (4, 8, 9). We thus anticipated that these riboswitches would be useful tools for studying the mechanisms of virulence in the Gram-negative bacterium F. tularensis.

F. tularensis is an intracellular bacterial pathogen that is the causative agent of the zoonotic disease tularemia, which is characterized by flu-like symptoms and exhibits a mortality rate of 30% (10) to 60% for the pneumonic form of the disease (11). Francisella novicida is closely related to F. tularensis, although it is rarely pathogenic to immunocompetent humans. F. novicida causes a tularemia-like disease in mice (12), possesses a genome that is 98% genetically identical to that of F. tularensis (13, 14), and has many virulence genes in common with F. tularensis. Additionally, F. novicida, like F. tularensis, exhibits the important virulence trait of replicating within host cells such as macrophages (12, 15). It is therefore often used as a model system to study F. tularensis biology.

Relatively little is known about the virulence factors required for Francisella pathogenesis, and the lack of genetic tools to modulate protein expression has hampered the investigation of protein functions (16). Many attempts to employ pre-existing tools from other organisms in Francisella have not been fruitful (17). We therefore set out to determine if riboswitches could be used to induce protein expression in Francisella and whether this system could be employed to modulate the expression of endogenous proteins during intracellular infection.

In this study, we show the efficacy of theophylline-sensitive synthetic riboswitches in inducing protein expression in F. novicida and highly virulent F. tularensis by using riboswitch-controlled β-galactosidase as a reporter. We also employed this system to control green fluorescent protein (GFP) expression during F. novicida infection of macrophages. We adapted this system to regulate the expression of an endogenous novel protein, FTN_0818, and showed that such control could functionally rescue the growth defect of an FTN_0818 mutant in minimal medium. Furthermore, riboswitch-mediated induction of FTN_0818 during macrophage infection restored the ability of the mutant strain to replicate intracellularly. This is the first demonstration that a synthetic riboswitch can be used to efficiently control an endogenous virulence factor and rescue a virulence trait in an intracellular pathogen. We anticipate that synthetic riboswitches will prove useful in numerous applications of gene expression control to study the biology of intracellular bacteria.

RESULTS

We tested a panel of eight theophylline-sensitive synthetic riboswitches that regulate gene expression in a variety of bacteria (4, 8, 9). To determine if any of these riboswitches were functional in F. novicida, each was coupled to a β-galactosidase reporter driven by a strong Francisella promoter (Pgro, the groEL promoter [18]) and cloned into the Francisella-E. coli shuttle vector pFNLTP6 (19). All reporter constructs exhibited at least a 5-fold increase in β-galactosidase activity in the presence of theophylline (see Fig. S1 in the supplemental material). Riboswitch E (E-Rs-βgal), which was rationally designed with the consensus ribosome binding site (4), exhibited a large dynamic range in F. novicida that was calculated by subtracting expression in the absence of theophylline from expression in the presence of theophylline (Fig. 1). Riboswitch F (F-Rs-βgal), selected from a library of randomized sequences (8), exhibited the lowest basal expression levels in the absence of theophylline (Fig. 1). Strains E-Rs-βgal and F-Rs-βgal were selected for further study because they exhibited the highest absolute level of gene expression in the presence of theophylline and the lowest background expression in the absence of theophylline, respectively. Each of these strains demonstrated ligand-dependent induction of β-galactosidase activity in a dose-dependent manner, even with as little as 0.1 mM theophylline (Fig. 2). These data demonstrate that riboswitches can be used effectively to modulate protein expression in F. novicida.

After verifying that the riboswitches function in F. novicida, we tested the feasibility of using them to control a reporter (GFP) during the bacterial infection of macrophages. We knew from previous work that strong expression levels would be required to detect fluorescence. We therefore chose riboswitch E, which induced the highest expression of β-galactosidase (Fig. 1), to drive GFP expression (strain E-Rs-GFP). As controls, we used strains constitutively expressing GFP under the control of the Pgro promoter (GFP-pos) or promoterless GFP. We did not detect GFP expression in macrophages infected with strain GFP-neg or E-Rs-

![FIG 1 Riboswitch-mediated control of β-galactosidase in F. novicida. Strains encoding riboswitch E (E-Rs-βgal) or F (F-Rs-βgal) upstream of lacZ were grown in the presence (○) or absence (●) of 1 mM theophylline to an OD600 between 0.7 and 0.8. β-galactosidase activity was measured in Miller units in the presence (left axis), and the activation ratio (green bar, right axis) was calculated by dividing the number of Miller units in the presence of theophylline by the number of Miller units in the absence of theophylline. The standard deviations of triplicate samples lie within the symbols. The data are representative of three independent experiments performed in triplicate.](mbio.asm.org/files/00253-12.FIG.1.png)
In the absence of theophylline (Fig. 3A and C), GFP expression was observed in macrophages infected with GFP-pos (Fig. 3B). Importantly, the E-Rs-GFP strain expressed GFP in the presence of 1 mM theophylline (Fig. 3D). These data demonstrate the ability of a theophylline-sensitive riboswitch to regulate the expression of a bacterial reporter during the infection of host cells.

Having demonstrated the ability to control exogenous reporter proteins (β-galactosidase and GFP) with riboswitches in F. novicida, we set out to determine if this system could be used to control an endogenous protein. FTN_0818 is a novel protein involved in biotin metabolism that is required for F. novicida replication in minimal medium (32) and within macrophages (20). We engineered a strain in which FTN_0818 is under the control of riboswitch E (E-Rs-FTN_0818) and tested its ability to grow in Chamberlain’s minimal medium. As expected, wild-type bacteria grew well while the ΔFTN_0818 mutant strain exhibited a growth defect. Even in the absence of theophylline, E-Rs-FTN_0818 replicated with wild-type kinetics (see Fig. S2 in the supplemental material), likely because of the increased background expression associated with the use of riboswitch E (Fig. 1; see Fig. S1). It should be noted that the presence of theophylline mildly slowed the growth of both the wild-type and E-Rs-FTN_0818 strains, a phenotype observed in some types of bacteria. To reduce the basal expression of FTN_0818, we placed it under the control of riboswitch F (F-Rs-FTN_0818), which exhibited much lower basal expression in the β-galactosidase assays (Fig. 1). Indeed, in the absence of theophylline, the growth rate of strain F-Rs-FTN_0818 was nearly identical to that of the ΔFTN_0818 mutant strain (Fig. 4). In contrast, in the presence of 1 mM theophylline, the
The growth of F-Rs-FTN_0818 was rescued to a level similar to that of the wild type (Fig. 4). These data demonstrate that a theophylline-dependent synthetic riboswitch can be used to control the expression of an endogenous bacterial protein and functionally control bacterial growth.

The ultimate goal of this work was to modulate endogenous protein expression in the context of an intracellular infection to control and study virulence traits. To test the efficacy of this approach, we performed macrophage infections to determine whether theophylline-induced expression of FTN_0818 could rescue the intracellular growth defect of the ΔFTN_0818 mutant strain. Wild-type bacteria exhibited robust intracellular replication in the absence or presence of theophylline, demonstrating that this compound did not adversely affect this strain (Fig. 5). In contrast, the ΔFTN_0818 mutant strain was unable to replicate to significant levels. Similarly, strain F-Rs-FTN_0818 did not replicate to high levels in the presence or absence of theophylline, suggesting that the expression level of FTN_0818 induced by this riboswitch was insufficient to promote intracellular bacterial replication (Fig. 5). In contrast, the E-Rs-FTN_0818 strain exhibited very low level replication in the absence of theophylline but robust replication similar to that of the wild-type strain in the presence of 2 mM theophylline (Fig. 5). To our knowledge, these data are the first demonstration of the use of synthetic riboswitches to control the expression of a native bacterial virulence factor during the infection of host cells.

To test whether theophylline-dependent synthetic riboswitches function in highly virulent species of *Francisella*, we tested E-Rs-βgal in *F. tularensis* strain SchuS4. As depicted in Fig. 6, riboswitch E induced β-galactosidase expression in a dose-dependent manner in *F. tularensis* to levels similar to those in *F. novicida*. This clearly demonstrates the utility of a theophylline-dependent synthetic riboswitch in inducing protein expression in a highly virulent *Francisella* strain, and taken together, these data highlight the utility of this system in controlling protein expression in intracellular pathogens.

**DISCUSSION**

In this study, we demonstrated the ability to induce protein expression in intracellular bacteria by using a synthetic riboswitch. Our synthetic riboswitches are induced by theophylline, a nonendogenous small molecule, and offer an orthogonal system for protein expression that minimizes interactions with natural biochem-

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**FIG 4** Theophylline-dependent rescue of bacterial replication. Growth rates are represented by cell density measured as OD_600 every hour for 18 h. The wild-type (WT) and ΔFTN_0818 and F-Rs-FTN_0818 mutant strains were grown overnight (~18 h) in TSB. Cultures were washed and then diluted in Chamberlain’s minimal medium to an OD_600 of 0.03 in the presence or absence of 1 mM theophylline. The standard deviations of triplicate samples lie within the areas of the symbols.

**FIG 5** Riboswitch-mediated control of FTN_0818 facilitates intracellular replication. RAW264.7 murine macrophages were infected with the indicated *F. novicida* strains at an MOI of 20:1 in the presence of 0, 1, or 2 mM theophylline. Macrophages were lysed at 30 min and 24 h postinfection and plated to enumerate the intracellular CFU. Fold replication was calculated by dividing the number of CFU at 24 h postinfection by the number of CFU at 30 min. Bars represent the average fold replication of the strains, and error bars depict the standard deviations. The data are representative of four independent experiments. Asterisks indicate a significant difference in fold replication from that of the ΔFTN_0818 mutant strain in the presence of the indicated concentration of theophylline (***, P < 0.0005). WT, wild type.

**FIG 6** Riboswitch E controlling β-galactosidase activity in *F. novicida* and *F. tularensis*. F. novicida strain E-Rs-βgal and *F. tularensis* strain E-Rs-βgal were subcultured and grown to exponential phase (OD_600 of ~0.7 to 0.8) in medium containing 0, 0.5, 1, or 2 mM theophylline. β-galactosidase activity was measured in Miller units. The data are representative of two independent experiments performed in triplicate.
A possible explanation for the difficulty of transporting genetic material when adapting genetic tools from other organisms to Francisella, a highly useful organism in studying the virulence strategies of numerous intracellular bacteria and should therefore be easily applied, and highly useful, in studying the virulence strategies of numerous intracellular pathogens.

The riboswitch system overcomes problems encountered when adapting genetic tools from other organisms to Francisella. A possible explanation for the difficulty of transporting genetic tools from other organisms may lie partly in the unique α subunits of the RNA polymerase (RNAP) of Francisella. The α subunit serves as the initiator of RNAP assembly and binds to a supplementary promoter element (the UP element) upstream of the −35 recognition site (23). In most bacteria, the RNAP holoenzyme contains a dimer of identical α subunits (24). However, in the Francisella genus, the α subunits are encoded by two distinct genes, yielding two unique variants of the RNAP α subunit (25). Given the fundamental role of the α subunit in transcriptional regulation (26), the inefficient transcription of foreign promoters in Francisella may be attributed to the differences in RNAP.

Riboswitches offer a solution to this problem, since they are readily integrated into protocols and can be applied to a diverse set of intracellular bacteria and can be applied to a diverse set of difficult-to-study pathogens such as Ehrlichia chaffeensis, Anaplasma phagocytophilum, and Orientia tsutsugamushi, as well as future emerging pathogens.

### MATERIALS AND METHODS

#### Bacterial strains and conditions.

The bacterial strains used in this study are listed in Table 1. Plasmid manipulations were performed by using E. coli MDS42 (Scarb Genomics, Madison, WI) transformed via electroporation. All experiments were performed with F. novicida strain U112 (15) (a gift from Denise Monack, Stanford University, Stanford, CA) or related strains and F. tularensis strain SchuS4. F. novicida overnight cultures were grown on a rolling drum at 37°C in tryptic soy broth (TSB; Difco/BD, Sparks, MD) supplemented with 0.2% l-cysteine (Sigma-Aldrich, St. Louis, MO). Growth assays were performed with Chamberlain’s minimal medium as previously described (29). For plating on solid medium, modified Mueller-Hinton (mMH; Difco/BD) plates supplemented with 0.025% ferric pyrophosphate (Sigma-Aldrich), 0.1% glucose, and 0.1% l-cysteine were used. When appropriate, kanamycin (Kan; Fisher Scientific, Fair Lawn, NJ) was added to the medium at a concentration of 30 µg ml⁻¹.

### Table 1 Bacterial strains and plasmids used in this study

<table>
<thead>
<tr>
<th>Strain or plasmid</th>
<th>Description</th>
<th>Source</th>
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<tr>
<td>U112</td>
<td>Wild-type F. novicida</td>
<td>D. Monack</td>
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<tr>
<td>ΔFTN_0818 mutant</td>
<td>U112 with FTN_0818 removed by allelic exchange</td>
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</tr>
<tr>
<td>SchuS4</td>
<td>Wild-type F. tularensis</td>
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<td>E-Rs-FTN_0818</td>
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<td>This study</td>
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<tr>
<td>GFP-pos</td>
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<td>Francisella-E. coli shuttle vector with promoter deleted</td>
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<tr>
<td>pCKR47</td>
<td>pFNLTP6 derivative with riboswitch E controlling lacZ</td>
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**Notes:** U112, the wild-type strain of Francisella novicida; ΔFTN_0818, a variant of U112 with a deletion of FTN_0818; SchuS4, the wild-type strain of Francisella tularensis; βgal, a β-galactosidase reporter plasmid; lacZ, a lacZ reporter plasmid; GFP, a green fluorescent protein reporter plasmid; gm, a reporter plasmid for the measurement of gene expression; D. Monack, Stanford University, Stanford, CA; E-Rs, Ehrlichia chaffeensis; F-Rs, Francisella tularensis; βgal, a β-galactosidase reporter plasmid; lacZ, a lacZ reporter plasmid; GFP, a green fluorescent protein reporter plasmid; gm, a reporter plasmid for the measurement of gene expression; D. Monack, Stanford University, Stanford, CA.
Cloning and mutagenesis. The plasmids used in this study are listed in Table 1. Synthetic oligonucleotide primers were purchased from Integrated DNA Technologies (Coralville, IA). DNA polymerase and restriction enzymes were purchased from New England Biolabs (Ipswich, MA). Previously published theophylline synthetic riboswitches (4, 8, 9) were adapted to F. novicida through the integration of a Francisellapromoter. Riboswitch–controlled lacZgene constructs under the control of the strong promoter $P_{\text{rpoE}}$ were cloned into an E. coli-F. novicida shuttle vector, pFNLT6P-gro-gfp, by using the PacI and BamHI restriction sites (19) (a gift from Thomas C. Zahrt, Medical College of Wisconsin, Milwaukee, WI). Riboswitches were amplified from previously reported plasmids (4, 8, 9) and assembled by PCR downstream of the Francisellapromoter $P_{\text{rpoE}}$ and upstream of lacZflanked by PacI and BamHI sites. After restriction enzyme digestion and ligation, constructs were transformed into E. coli MDS42. Plasmids were then extracted by using a Plasmid Midi-Prep kit (Qiagen, Germantown, MD). F. novicida U112 or F. tularensis SchuS4 was transformed as previously described (30).

Microarray purification and screening were performed as described above for lacZ. Sequences were verified by DNA sequencing (MWG Operon, Huntsville, AL). Riboswitch–mediated complement constructs of $\Delta F T N_{0818}$ to be integrated into the F. novicida genome were generated by overlap PCR assembly of $P_{\text{gltA}}$–driven riboswitch E or F (see sequences in Table S1 in the supplemental material) upstream of $\Delta F T N_{0818}$, followed by a Kan resistance cassette and flanked by sequences homologous to a region of the genome known to accept genomic additions without disrupting normal cell function (nucleotides 818016 to 818037 and 818649 to 818670). Transformation of plasmid DNA or allelic exchanges of linear DNA was performed as previously described (30).

Briefly, a 1-ml aliquot of an overnight culture was added to 50 ml of TSB supplemented with 0.2% cysteine and grown at 37°C with shaking for 2 to 4 h until the optical density at 600 nm (OD600) was ~0.8 to 1.0. Cells were then harvested by centrifugation, and the cell pellet was resuspended in 5 ml of room temperature transformation buffer (17). Plasmid or linear DNA (1 μg) was added to 200-μl aliquots of resuspended cells and incubated at 37°C on a rolling drum for 20 min. One milliliter of TSB plus 0.2% cysteine was added, followed by another 2 h of incubation at 37°C on a rotary wheel. Cultures were then concentrated to 200 μl by centrifugation at 5,000 × g and plated on selective mMH medium.

Bacterial growth curves. To measure bacterial growth, mutant, wild-type, and riboswitch strains (Table 1) incubated overnight in TSB plus 0.2% cysteine were centrifuged at 15,294 × g for 2 min at room temperature. Cell pellets were resuspended in Chamberlain’s minimal medium (29) and then subcultured in minimal medium with or without theophylline to an OD600 of ~0.8 to 1.0. Cells were then harvested by centrifugation, and the cell pellet was resuspended in 5 ml of room temperature transformation buffer (17). Plasmid or linear DNA (~1 μg) was added to 200-μl aliquots of resuspended cells and incubated at 37°C on a rolling drum for 20 min. One milliliter of TSB plus 0.2% cysteine was added, followed by another 2 h of incubation at 37°C on a rotary wheel. Cultures were then concentrated to 200 μl by centrifugation at 5,000 × g and plated on selective mMH medium.

β-Galactosidase assay. β-Galactosidase assays were performed as previously described (31), with the following modifications. Strains were cultured overnight at 37°C with shaking. Cells were then diluted (culture/medium) 1:30 (0 mM theophylline) or 1:25 (1 mM theophylline) into TSB containing Kan (30 μg/ml) and 0 or 1 mM theophylline to an OD600 of ~0.7 to 0.8. Theophylline and o-nitrophenyl-β-d-galactopyranoside were purchased from Sigma–Aldrich. Dose-response assays were performed as described above with the addition of various concentrations of theophylline and dilutions of 1:30 (0 and 0.25 mM theophylline), 1:27 (0.5 mM theophylline), and 1:21 (2 mM theophylline). These volumes were used to compensate for small decreases in the growth rate with increasing concentrations of theophylline.

Macrophage infections. For infection, RAW264.7 murine macrophages (ATCC, Manassas, VA) were seeded into the wells of a chambered cover glass (CultureWell; Invitrogen, Carlsbad, CA) at 1 × 106 cells per well and incubated overnight in Dulbecco’s modified Eagle medium (high glucose, 1-glutamine; DMEM; Lonza, Walkersville, MD) supplemented with 10% heat-inactivated fetal calf serum (FCS; HyClone, Logan, UT) at 37°C with 5% CO2. The medium was then removed, and the macrophages were infected with overnight cultures of various GFP-expressing strains (Table 1) that were diluted in DMEM–10% FCS to achieve a multiplicity of infection (MOI) of 50 CFU of bacteria per macrophage. The plates were centrifuged for 15 min at 233 × g at room temperature and then incubated for 30 min. The macrophages were then washed twice with DMEM and returned to incubation overnight (18 to 24 h). Next, macrophages were rinsed twice with sterile phosphate-buffered saline (PBS) and fixed by incubation in 4% paraformaldehyde (PFA) in PBS for 20 min at room temperature. The cells were again rinsed twice with PBS to wash away the PFA. To measure bacterial replication, RAW264.7 macrophages were infected as described above, with the following differences. Macrophages were seeded into the wells of 24-well tissue culture plates at 7.5 × 105 cells/well and infected at an MOI of 20 CFU per macrophage in DMEM–10% FCS containing 100 μg/ml gentamicin (Teknova, Hollister, CA) with or without 1 mM theophylline. Macrophages were then lysed with 1% saponin (Alfa Aesar, Heysham, Lancs, United Kingdom) in PBS without calcium or magnesium (Lonza, Walkersville, MD) at 30 min or 24 h. To quantitatively measure the bacterial load within macrophages at each time point, serial dilutions of the macrophage lysates were plated onto modified mMH agar plates and incubated overnight at 37°C. Finally, the n-fold replication of each strain was calculated (CFU at 24 h/CFU at 30 min).

Microscopy. Fluorescence microscopy was performed with an Eclipse Ti microscope coupled with the Nikon Elements software package (Nikon). Image capture was performed with an Evolve EM charge-coupled device (Photometrics) by using a CFI Apo 100× (numerical aperture of 1.49) objective (Nikon) with an Intensilight epifluorescence source (Nikon). Data acquisition utilized the Nikon Perfect Focus System, which allows the capture of multipoint Z-stack data without loss of focus. Z-stack images in 10 fields of view were taken for each construct by using the fluorescein isothiocyanate (FITC) and 4,6-diamidino-2-phenylindole (DAPI) chroma filter cubes to detect GFP and macrophage nuclei, respectively. Z-stacks probed a 5-μm section of the macrophages at 0.4 μm per slice. The FITC exposure time was 300 ms, while the DAPI exposure time was 50 ms. Images of the negative control were used as a reference to eliminate background fluorescence. Settings from the negative control were propagated to all images to allow accurate comparison. False color was applied to aid in analysis.

Statistics. Macrophage replication data were analyzed for significance by using the unpaired Student t test with two degrees of freedom.

SUPPLEMENTAL MATERIAL

Supplemental material for this article may be found at http://mbio.asm.org/lookup/suppl/doi:10.1128/mBio.00253-12/-/DCSupplemental.

Figure S1, TIF file, 5.5 MB.
Figure S2, TIF file, 3.8 MB.
Table S1, DOC file, 0.1 MB.

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ADDENDUM

During review of this manuscript, LoVullo et al. (Appl Environ Microbiol. 78:6883–6889, 2012) described a Tet-based inducible system for use in Francisella.

REFERENCES

Riboswitches To Control Intracellular Gene Expression