Prevalence of Fst-like toxin–antitoxin systems

Toxin–antitoxin (TA) systems are widespread in Gram-negative bacteria, and all systems identified to date encode a toxic protein and an unstable antitoxin, which may be in the form of either an antisense RNA (type I) or a second protein (type II). The enterococcal plasmid pAD1-encoded TA system (par), encoding the Fst toxin, was the first type I TA system identified in Gram-positive bacteria (Weaver et al., 1996). In a recent issue of Microbiology, Weaver et al. (2009) identified an additional eight pAD1-like TA systems. Individual Fst-like genes were identified on the chromosomes of Enterococcus faecalis, Lactobacillus casei and Staphylococcus saprophyticus strains, plasmids from E. faecalis, Lactococcus curvatus and Staphylococcus aureus, and a phage from Lactobacillus gasseri. It was also hypothesized that the small size of Fst-like toxins may cause the failure of other members of the family to be recognized and annotated. We have now addressed this issue through iterative tblastn searching of the translated NCBI nucleotide sequence database (http://blast.ncbi.nlm.nih.gov/Blast.cgi).

Fst-like toxins were found to be prevalent in a diversity of Gram-positive bacteria. More than 200 additional toxins were detected in the database, and sequence similarity between previously identified Fst peptides and new family members in pairwise alignments was shown to be statistically significant using PRSS (E<0.02; Pearson, 1996). All are 27 to 35 residues in length and are predicted to contain a hydrophobic transmembrane domain. New Fst family members were found to be encoded chromosomally by Staphylococcus aureus, Staphylococcus epidermidis, Lactobacillus helveticus, Lactobacillus gasseri, Lactobacillus johnsonii, Lactobacillus brevis, Streptococcus pneumoniae, Streptococcus equi, Streptococcus suis, Streptococcus thermophilus, Streptococcus mutans and Listeria monocytogenes. Additional Fst-like toxins were also found on plasmids from Enterococcus faecalis, Enterococcus faecium, Staph. aureus, Staph. epidermidis, Staphylococcus warneri, Lactobacillus fermentum, Lactobacillus paracasei, Lactococcus lactis, Macroccocus caseolyticus and Carnobacterium divergens.

Analysis of the DNA sequence encompassing representatives of the newly identified Fst coding sequences from the various species revealed the presence of characteristic features shown to be important for function of the prototype pAD1 TA system (Greenfield & Weaver, 2000; Greenfield et al., 2000). Specifically, in addition to expression sequences for the toxin, they each possess sequences necessary for expression of an antisense RNA antitoxin, including a potential promoter closely resembling the ρ70 consensus and a bidirectional terminator, converging towards the end of the toxin gene (Fig. 1). Thus, the resulting toxin mRNA and antitoxin possess a complementary thermodynamically stable stem–loop structure derived from the terminator; the loop residues have recently been shown to be important for interactions between the transcripts that result in the inhibition of pAD1 Fst toxin expression (Greenfield et al., 2001). Likewise, the directly repeated sequences DRA and DRB are readily identifiable. These tandemly arranged repeats overlap the toxin start codons, and are repeated downstream of the bidirectional terminators within each antitoxin gene, so as to provide a region of complementarity between the single-stranded 5’-tail of the antitoxin and the translation initiation region of Fst mRNA. Other intramolecular helices in the Fst mRNA have recently been shown to be important in the prototype pAD1 system: a 5’ stem–loop structure that sequesters the Fst ribosome-binding site (comprising RBS and anti-RBS sequences), causing translational inhibition (Shokeen et al., 2008); and an upstream helix formed between complementary sequences at each end of the transcript (5’ UH and 3’ UH) that contributes to the stability of the toxin mRNA in vivo (Shokeen et al., 2009). The presence of sequences corresponding to all of these features in association with the newly identified toxin-coding sequences (Fig. 1) suggests a conserved mechanism of RNA–RNA interaction and control of toxin expression. It is therefore likely that most, if not all, of the Fst-like peptides detected are encoded by functional TA systems. Although the features above are well conserved, the nucleotide sequences of individual systems are quite divergent, even between multiple systems co-existing in the same strain, suggesting that cognate TA components might exhibit specificity.

Fst-like TA systems are particularly prevalent in Staphylococcus species, although this may partly reflect the abundance of sequence information available for this genus. All 15 available completely sequenced Staph. aureus chromosomes contain at least two distinct systems that are conserved between strains, with some possessing more; MRSA252 has four systems but two are carried by an integrated plasmid. Staph. epidermidis RP62A contains five systems in its chromosome, several of which may have resulted from plasmid integration, whereas Staph. epidermidis ATCC 12228 was found...
to carry three chromosomal systems and two plasmid-encoded systems. Fst-like TA systems are commonplace but not ubiquitous on theta-replicating staphylococcal multiresistance and conjugative plasmids, with several, such as VRSAp and pN315, containing two; none were detected on small rolling-circle plasmids. Additionally, the staphylococcal pathogenicity island SaPIbov2, which is involved in biofilm formation (Ubeda et al., 2003), was found to carry a TA system. Likewise, at least one fst-like toxin gene was found in each of the available E. faecalis chromosome sequences and on most enterococcal plasmids. New Fst-like systems were also detected in some of the available E. faecium, Enterococcus casseliflavus and Enterococcus gallinarum genome sequences, but these are all unclosed and our analyses suggest that the contigs might be plasmid derived; however, the possibility that they represent chromosomally integrated plasmids cannot be excluded.

Weaver et al. (2009) noted an association between the previously identified chromosomally encoded Fst-like systems and genes involved in carbon metabolism. The newly identified Fst-like TA systems were commonly associated with recognizable mobile genetic elements, or remnants thereof, indicating for toxin-mediated repression of toxin translation, are shown with lower-case letters requiring of the toxin mRNA and antitoxin RNA that can hybridize using standard RNA–RNA pairing rules.
chromosomally. However, one of the conserved systems on the *Staph. aureus* chromosome is located between genes that encode a putative ABC transporter and glycerate kinase, whereas the system in *L. monocytogenes* is downstream of a gene encoding a glycosyl hydrolase. The common carriage of Fst-like TA systems on resistance plasmids in particular is potentially significant in terms of the maintenance of antimicrobial resistance in important Gram-positive pathogens.

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**Prevalence of Fst-like toxin–antitoxin systems – author’s response**

The work of Kwong, Jensen and Firth (above) dramatically expands the pAD1 *par*-like family of RNA-regulated toxin–antitoxin (TA) systems described in our recent study (Weaver et al., 2009). While the primary sequences of these systems are highly diverse, important interacting and regulatory structures are clearly conserved. These results would appear to contradict an earlier report indicating that, while several proteic TA systems are widespread among enterococci, *par*-like sequences are rare (Moritz & Hergenrother, 2007). However, given the sequence diversity of the *par*-like systems identified, it is not surprising that the PCR-based screening approach used by Moritz & Hergenrother (2007) failed to amplify any of the *par*-like loci. This information should be considered in future surveys designed to determine the distribution of other type I TA systems.

Our work and that described above should also be viewed in the larger context of RNA-regulated, probably membrane-localized, small peptide toxins, which were originally reviewed by Fozo et al. (2008). While the number of Gram-positive representatives in their sample was limited, it is now clear that such peptides are widespread in Gram-positive bacteria and are likely to play roles at least as important as their counterparts in Gram-negative bacteria. Finally, while most of the *par*-like loci appear to be associated with mobile elements, the association of some of the chromosomally located loci with genes involved in basic carbon metabolism is intriguing. Since the function of many chromosomally encoded TA systems has been elusive and controversial, it would be worth determining if regulation of these elements is integrated with basic cellular metabolism.

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