Genomic distribution of the small multidrug resistance protein EmrE over 29 Escherichia coli strains reveals two forms of the protein

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Analysis of the genomes of 29 Escherichia coli strains revealed two different versions of the EmrE protein, a member of the small multidrug resistance family. The versions are different in length and contain 110 residues (EMRE_{110}) and 165 residues (EMRE_{165}). The N-terminal extension found in the longer sequence has the properties of a signal sequence, i.e. contains at the extreme N-terminus a hydrophobic region followed by a predicted cleavage site. Analysis of the genetic context of the genes in the different strains showed that all of the genes encoding EMRE_{165} had the same context, whereas the genes encoding EMRE_{110} were distributed over four different, but similar, contexts. The different genetic contexts corresponded to the branching of the phylogenetic tree of the emrE genes. Membrane topology studies using translational fusions with the two reporter proteins alkaline phosphatase and green fluorescent protein showed the well-described dual topology mode of insertion of EMRE_{110}. In contrast, but in line with the presence of the signal sequence, EMRE_{165} was inserted in a single orientation into the membrane, with the C-terminus in the periplasm. The N-terminal region was removed from the protein after insertion into the membrane. In contrast to cells expressing EMRE_{110}, cells expressing only mature EMRE_{165} were not able to grow on plates containing ethidium bromide. The results suggest that if dimers were formed from EMRE_{165} monomers with the same orientation in the membrane, they would not be active in drug extrusion.

Introduction

Members of the small multidrug resistance (SMR) family are secondary transporters found exclusively in prokaryotes. The transporters extrude toxic compounds such as ethidium bromide (EtBr), methyl viologen and tetraphenyl phosphonium from the cells, and also render the cells resistant to antibiotics such as cephalosporins [1,2], aminoglycosides [3,4], and β-lactams [5–7]. The extrusion process is energized by the electrochemical proton gradient across the membrane [8]. The proteins are the smallest secondary efflux proteins known to date, and consist of 100–140 residues that fold into four tightly packet α-helices [9]. The catalytic unit is a dimer. The best studied protein from the family is EmrE of Escherichia coli, which consists of 110 residues. EmrE is a so-called dual topology protein; that is, it inserts into the membrane in two opposite orientations [10–13]. The presence of both orientations in the membrane allows the formation of

Abbreviations
AP, alkaline phosphatase; BAD, biotin acceptor domain; EtBr, ethidium bromide; GFP, green fluorescent protein; HGT, horizontal gene transfer; LIC, ligase-independent cloning; SMR, small multidrug resistance; TMS, transmembrane segment.
two types of dimer: those in which two monomers of the same orientation interact (parallel), and those in which the subunits in the dimer have opposite orientation (antiparallel). Evidence in favor of the antiparallel dimer \[14–18\], the parallel dimer \[19,20\] or both \[21,22\] has been presented. Thus, the issue is still under debate.

The EmrE used in these studies was taken from \textit{E. coli} strain K-12. Surprisingly, an analysis presented here of 29 strains of \textit{E. coli} for which the complete genome sequence was available showed that 10 strains encoded a longer version of EmrE consisting of 165–170 residues (EmrE\(_{165}\)), rather than the 110 residues of the K-12 variant (EmrE\(_{110}\)). The longer version of EmrE was extended at the N-terminus, and contained an additional hydrophobic segment that was predicted to be part of a signal sequence (SIGNALP) \[23,24\]. Consequently, the long version might be directed in one orientation into the membrane, which, if it was capable of forming dimers, would allow only the formation of the parallel dimers.

This study focuses on the properties of the long version of EmrE in comparison with the short version. Genomic localization of genes encoding EmrE proteins demonstrates that the two versions are found in different loci. The reporter proteins alkaline phosphatase (AP) and green fluorescent protein (GFP) fused to the C-terminus confirmed that EmrE\(_{165}\) inserts into the membrane in a single orientation, and processing of the signal sequence is demonstrated by the loss of the additional hydrophobic segment. Finally, the activity of matured EmrE\(_{165}\) was determined by checking the ability of cells expressing EmrE\(_{165}\) to grow in the presence of EtBr.

### Results

#### Distribution of EmrE over 29 strains of \textit{E. coli}

Analysis of the genome of 29 \textit{E. coli} strains available from the National Center for Biotechnology Information (NCBI) database showed that 18 strains contained a single copy of the \textit{emrE} gene, three strains contained two copies, and eight strains lacked the gene (Table 1). Analysis of the genomic context divided the 24 \textit{emrE} genes into two groups. A group of 10 genes showed a well-defined context. At one side, they were flanked by flagellar region IIIB, containing genes involved in flagellum assembly, and at the other side by a putative kinase inhibitor gene and a regulatory gene (Fig. 1; FLA). The other 14 \textit{emrE} genes were flanked downstream by a gene encoding a phage recombinate and upstream by a gene encoding the \textit{REN} protein.

Differences in the upstream region of the \textit{REN} gene discriminated four different subgroups (Fig. 1; REN\(_1\) to REN\(_4\)). The variable upstream regions contained many genes encoding integrases (REN\(_1\), REN\(_2\), and REN\(_3\)), replication proteins (REN\(_1\) and REN\(_4\)), exonucleases (REN\(_2\)), and IS elements (REN\(_2\)) that may be involved in the insertion/deinsertion of mobile elements, suggesting that the \textit{emrE} gene, together with the two flanking genes, was inserted in these sites at some point in evolution. The two \textit{emrE} genes found in the genome of strain EC4115 are both of the REN type, whereas strains 55989 and SE11 contain both an FLA type and a REN type.

A phylogenetic tree of the \textit{emrE} genes found in the different \textit{E. coli} strains was constructed on the basis of the alignment of the corresponding parts of the DNA (see below). The alignment contained no gaps, and revealed pairwise nucleotide sequence identities of

<table>
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between 90% and 99%, indicating that the tree represents the very recent divergence of the genes in the different strains. The tree revealed two well-separated clusters represented by the FLA and REN types of gene (Fig. 2). With the exception of the gene in strain 55989 (GI: 218694205), the different genomic contexts of the REN types were found as different branches on the tree as well, indicating that the divergence of the genes took place after insertion into the genome. No correlation was found between the phylogenetic tree of the genes encoding EmrE proteins and the whole-genome phylogenetic tree of *E. coli* strains computed with feature frequency profiles [23]. The strains containing the FLA-type EmrE did not group together on one branch of the strain tree, and, similarly, the strains containing the REN type were scattered over the tree. This suggests that the genes encoding the different types of EmrE were spread by horizontal gene transfer (HGT).

The well-studied EmrE from strain K-12 consists of the usual 110 residues found for most of the members of the SMR family. The K-12 protein is of the REN type, and all EmrE proteins of this type from the other strains were annotated in the databases as proteins of the same size. Surprisingly, FLA-type EmrE proteins were annotated as proteins containing 165 or 170 residues. The additional base pairs resulting in the larger proteins were found at the 5′-end of the gene. Inspection of the nucleotide sequence revealed that all FLA-type EmrE proteins had the same upstream sequence, which differed from that of the REN-type EmrE proteins. Annotation differences (165 versus 170) were

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**Fig. 1.** Genetic context of long and short versions of EmrE. See text for explanation.
The widely used membrane topology predictor TMHMM 2.0 [24] predicts the presence of four transmembrane segments (TMSs) in EMRE110, which is in agreement with experimental data [25–27]. The protein is predicted to have no preference for one of the two orientations in the membrane, because of the lack of a positive charge bias over the loops at both sides of the membrane (positive-inside rule) [13]. The prediction is in line with the dual topology character of EMRE110, which was convincingly demonstrated experimentally (Fig. 3B) [10,11,13,28]. In the EMRE165 sequence, TMHMM predicts an additional TMS positioned at the N-terminus. The putative TMS would be connected to the four TMS bundle by a loop of 34 residues. The signal peptide predictor SIGNALP [29,30] predicted the N-terminal TMS to be part of a signal sequence with maximal cleavage site probability between positions 23 and 24. The presence of the signal sequence suggested that the protein would be inserted in the membrane in one specific orientation and, following cleavage of the leader sequence by leader peptidase, would leave the matured protein in the N_outC_out orientation (Fig. 3B).

Membrane topology of EMRE110 and EMRE165

The ORFs encoding EMRE110 and EMRE165 of strains K-12 and 536, respectively, were cloned in pLIC vectors [31], yielding pLIC_EMRE110 and pLIC-C_EMRE165, respectively. The pLIC vectors produce the proteins with a His6-tag at the N-terminus and AP (pLIC1) or GFP (pLIC2) fused to the C-terminus. The two reporters AP and GFP allow for the determination of the cellular location of the C-termini of EMRE110 and EMRE165. GFP is properly folded and fluorescent only when targeted to the cytoplasm, whereas AP is enzymatically active only when transported to the periplasm. High GFP fluorescence and low AP activity indicate that the C-terminus is located in the cytoplasm, whereas high AP activity and low GFP fluorescence indicate a periplasmic C-terminus localization. Significant activity of both reporters indicates dual topology. It is important to stress here that expression of the EMRE165-encoding gene from pLIC plasmids is likely to produce reporter fusions of both EMRE165 and EMRE110, only the former of which contains the N-terminal His6-tag. To produce only EMRE165, the Met at position 56 (start of EMRE110) was mutated to Ala, yielding the vectors pLIC1_EMRE165(M56A) and pLIC2_EMRE165(M56A). The same set of plasmids was constructed by using the pBAD-cLIC vectors that produce the fusion proteins with a His10-tag at the C-terminus of the reporter proteins. In this case, both long and short versions produced from the EMRE165-encoding gene contain the His-tag (see Table 2 for an overview of the constructs).

The normalized activities (see Experimental procedures) of the reporter proteins GFP and AP fused to EMRE110 produced from both pLIC_EMRE110 and
pBADcLIC_EMRE_{110} were similar (Fig. 4A,B), indicating that the short version inserted into the membrane was distributed more or less equally over the two orientations (dual topology), as documented many times before [10,11,13]. The distribution shifted significantly to the orientation with the C-terminus in the periplasm with the EMRE_{165} encoding gene in plasmids pLIC_EMRE_{165} and pBADcLIC_EMRE_{165} (Fig. 4A,B). Importantly, the signals obtained from the reporters are likely to be the sum of the contributions of both long and short EmrE versions. Apparently, the long version contributes significantly to the fraction of molecules with the C-terminus in the periplasm. Within the limits of experimental error, the result was independent of the position of the His-tag at the N-terminus or C-terminus of the fusion proteins (Fig. 4A,B). Also, the levels of expression deduced from the reporter activities were of the same order of magnitude for the different constructs. In contrast, the level of expression dropped significantly for both pLIC_EMRE_{165}(M56A) and pBADcLIC_EMRE_{165} (M56A), when only the long version was produced. Relative to EMRE_{110}, the distribution of the version with the His-tag at the N-terminus was shifted to the orientation with the C-terminus in the periplasm, but a significant fraction had the opposite orientation (Fig. 4A). With the His-tag at the C-terminus, the orientation of EMRE_{165}(M56A) with the C-terminus in the periplasm was dominant (Fig. 4B). Optimization of the expression level of the latter construct by using a range of inducer concentrations resulted in a two-fold increase in expression level. Importantly, the
orientation of the protein in the membrane was unaffected (Fig. 4B).

The EmrE–GFP fusion proteins produced from the pBADcLIC–GFP and pLIC2 vectors were purified from isolated membranes by Ni$^{2+}$–nitrilotriacetic acid affinity chromatography. The yield of the proteins was too low to be visualized by protein staining after SDS/PAGE or western blotting with antibodies raised against GFP or the His-tag. Rather, the proteins were visualized by in-gel GFP fluorescence (Fig. 5). The EMRE$_{110}$ fusion protein expressed from the pBADcLIC–GFP vector and carrying the His$_{10}$-tag at the C-terminus bound strongly to the resin, and was only observed in the elution fractions. The band represents the membrane-bound protein molecules that originally had the C-terminus in the cytoplasm, where GFP matures to its fluorescent state. The same EMRE$_{110}$–GFP fusion was observed with membranes isolated from cells containing EMRE$_{165}$-encoding DNA from which both EMRE$_{110}$ and EMRE$_{165}$ are produced. In contrast, no fluorescent EMRE$_{165}$-GFP fusion protein was observed, suggesting that the GFP moiety was exported to the periplasm during biosynthesis. In agreement with this, no fluorescent band was observed when EMRE$_{165}$ was produced alone [EMRE$_{165}$ (M56A)] (Fig. 5A). Apparently, within the detection limit, all EMRE$_{165}$–GFP fusion proteins insert with the C-terminus in the periplasm, which is in agreement with the orientation assay above (Fig. 4B). The majority of the EMRE$_{110}$–GFP fusion protein carrying the His$_{10}$-tag at the N-terminus produced from the pLIC2 vector was found in the elution fraction, but binding to the resin was clearly weaker, leaving significant fractions in the flowthrough and wash steps (Fig. 5B). As expected, EMRE$_{110}$ produced from EMRE$_{165}$-encoding DNA showed up in the flowthrough because it was translated from an internal ORF without a His-tag. No clear band for EMRE$_{165}$ was observed. In contrast to the protein carrying the C-terminal His-tag, the EMRE$_{165}$ (M56A) fusion protein with the N-terminal His-tag was clearly observed, indicating that some of the molecules were inserted with their C-termini in the cytoplasm, which, again, was in line with the orientation assay above (Fig. 4A). Possibly, the N-terminal His-tag interferes with proper insertion of the protein in the membrane, which is also supported by the breakdown products observed in the flowthrough and elution fractions.

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**Table 2.** Vectors used in this study to express EMRE$_{110}$, EMRE$_{165}$, and EMRE$_{165}$(M56A). All vectors are pBAD24-based, and use the arabinose promoter for induction of expression. N-terminus: tag fused at the N-terminus of EmrE. C-terminus: tag/reporter fused at the C-terminus of EmrE.

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<td>pLIC2</td>
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<td>pBADBAD</td>
<td>His$_{6}$-tag/BAD</td>
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<td>41</td>
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</tbody>
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**Fig. 4.** Membrane orientation of EmrE variants. Normalized AP (nAP) activity is plotted against GFP fluorescence of cells producing EMRE$_{110}$ (gray square), EMRE$_{165}$ (white square) and EMRE$_{165}$(M56A) (black square) with (A) an N-terminal His$_{6}$-tag and a C-terminal reporter, and (B) a C-terminal reporter and His$_{10}$-tag. EMRE$_{165}$(M56A) was induced with 0.04% (black triangle) and 0.1% (white triangle) arabinose.

**Fig. 5.** In-gel fluorescence of GFP fusion proteins isolated from membranes prepared from cells harboring (A) pBADcLIC–GFP vectors encoding the indicated EmrE variants containing a C-terminal His$_{10}$-tag, and (B) pLIC2 vectors encoding the same EmrE variants containing an N-terminal His$_{6}$-tag (Table 2). The EmrE variants were purified by Ni$^{2+}$–nitrilotriacetic acid affinity chromatography, and samples from the flowthrough (FT), wash (W1 and W2) and elution (E1 and E2) steps were analyzed by SDS/PAGE followed by fluorescence imaging of the gel, as detailed in Experimental procedures. ●, EMRE$_{110}$–GFP; ○, EMRE$_{165}$–GFP; □, free GFP.
The results suggest that the long version of EmrE inserts into the membrane in a single orientation, with the C-terminus in the periplasm, which would be in line with the presence of a signal sequence at the N-terminus of the protein (Fig. 3B).

**Maturation of EMRE_{165}**

The genes encoding EMRE_{110} and the EMRE_{165}(M56A) were cloned in the pBADhis vector (Table 2) to study the fate of the putative signal sequence present in EMRE_{165}. The pBADhis vector produces the inserts with an N-terminal His_{6}-tag. Following isolation of cytoplasmic membranes from the cells harboring the plasmids, and purification by Ni^{2+}-nitrilotriacetic acid affinity chromatography from the solubilized membranes, the expression levels were too low to be detected by staining of the gel after SDS/PAGE (not shown). To enhance the sensitivity of the detection, the biotin acceptor domain (BAD) of the oxaloacetate decarboxylase of *Klebsiella pneumoniae* was inserted in between the His_{6}-tag and the EmrE protein (pBADBAD vectors; Table 2). BAD is biotinylated *in vivo*, and can be detected with high sensitivity by western blotting with streptactin. BAD fused to the short version of EmrE produced from pBAD-BAD_{EMRE_{110}} was readily detected in the membrane fraction as a protein with an apparent molecular mass of ~20–22 kDa, which is in line with the masses of EMRE_{110} and the 10-kDa BAD (Fig. 6). In contrast, no BAD was detected in the membrane fraction from cells expressing EMRE_{165}(M56A). Rather, the cytoplasmic fraction of the cells contained a low amount of biotinylated protein with an apparent molecular mass that was slightly more than expected for BAD itself. The results demonstrate that the N-terminal BAD was efficiently removed from the membrane-bound EmrE part.

**Activity of EMRE_{110} and EMRE_{165}**

EmrE makes the cells resistant to toxic compounds. EtBr is a known substrate of EmrE of strain K-12 (EMRE_{110}). The ability of the EmrE variants to confer resistance to *E. coli* SF100 was assayed by spotting 10-fold serial dilutions on LB plates containing 500 μg·mL^{-1} EtBr (Fig. 7). The host *E. coli* SF100 by itself or harboring the pBADhis vector grew well on the plates in the absence of EtBr, whereas growth was completely inhibited in its presence. Plasmid pBADhis_{EMRE_{165}} producing both EMRE_{110} and EMRE_{165} conferred significant resistance to the cells. Plasmid pBADhis_{EMRE_{165}(M56A)} producing only EMRE_{165} did not confer resistance, suggesting that EMRE_{110} was responsible for the resistance in the former case. However, surprisingly, plasmid pBADhis_{EMRE_{110}} producing only EMRE_{110} did not confer resistance. Control experiments showed that cells harboring the three plasmids all showed the same growth on plates without EtBr.

The EmrE proteins produced from the pBADhis vectors carry an N-terminal His_{6}-tag. The three genes were recloned in pBAD24 vectors that produce the proteins without any tags. The untagged EMRE_{110} made the SF100 cells resistant to EtBr (Fig. 7), demonstrating that the N-terminal His_{6}-tag inhibited the activity of the protein. The matured EMRE_{165} did not confer resistance, whereas the mixture of the two
versions did confer resistance, as was observed with the His-tagged versions. The activity of the latter is explained by the fact that EMRE110 produced from pBADhis_EMRE165 does not carry a His6-tag.

The pattern of resistance was the same for the EmrE versions produced from the pLIC1 and pLIC2 vectors when plated on LB plates containing 500 μg·mL⁻¹ EtBr (not shown). Plasmids pLIC1_EMRE165 and pLIC2_EMRE165 conferred resistance to EtBr, demonstrating, in addition, that EMRE110 with the reporters fused at the C-terminus are active proteins. Most importantly, matured EMRE165 inserted into the membrane in one orientation did not confer resistance against EtBr to the cells.

Discussion

Evolutionary distribution of the emrE gene in E. coli

The emrE gene is a member of one of a number of gene families that confer resistance to toxic compounds, to allow the organism to survive in hazardous environments. The presence of these genes is required in particular habitats, and is therefore often strain-specific rather than species-specific. The mechanism by which the genes are propagated in a particular species is believed to be through HGT. The analysis of the distribution of the emrE gene in 29 E. coli strains presented here supports this view, because: (a) different strains contain no, one or two copies of the gene; (b) different genetic contexts of the genes were found; and (c) the phylogenetic tree of the proteins does not correspond to the tree of the strains. Among 29 analyzed strains, eight do not possess the emrE gene. Possibly, these particular strains do not encounter the toxic substrates of EmrE in their environment, or the resistance is conferred by another protein. Strains with two emrE genes may require a higher capacity to remove toxic compounds because of higher concentrations in their habitats. Analysis of the genetic context of all emrE genes revealed two major insertion sites, termed here the FLA and REN sites. The FLA region appears to be more stable than the REN region, which is more variable and contains several genes putatively involved in the process of HGT. The different genetic contexts correlated with the sequence divergence of the emrE genes (Fig. 2) and the properties of the encoded proteins, i.e. the long and short versions, suggesting independent evolution of the FLA and REN types. It is not clear why the sequence divergence of the genes correlates with the insertion sites, but not with the phylogeny of the different strains. Apparently, the region that is horizontally transferred is larger than the emrE gene.

Function of EMRE165

Two types of emrE were found in the genomes of different E. coli strains, encoding proteins of different lengths, i.e. EMRE110 and EMRE165. The ORF encoding the long version contains the ORF encoding the short version, so both EMRE165 and EMRE110 are likely to be produced. EMRE110 is typical of the members of the SMR family. It is a highly hydrophobic, dual topology membrane protein that is active in drug extrusion. In EMRE165, this protein is preceded by a putative signal sequence connected by a 34-residue loop. The properties of EMRE165 were studied separately by inactivating the translation of the shorter gene encoding EMRE110. EMRE165(M56A) is inserted into the membrane in one orientation with the C-terminus in the periplasm, and matures through removal of the N-terminal part, which is in agreement with the signal sequence hypothesis. In addition, matured EMRE165(M56A) was shown to be inactive in conferring resistance to EtBr, which may be related to the single orientation of the protein in the membrane. EmrE-like proteins are believed to be active as dimers, two types of which can be formed when both orientations of the protein are available in the membrane. One type is built from two monomers with the same orientation (parallel dimer), and the other type from monomers with opposite orientations (antiparallel dimer). Recent studies have shown that antiparallel dimers are more stable than parallel dimers [32], but, in spite of many efforts, it is still not entirely clear which dimers are formed and which is the active configuration. EMRE165 inserts into the membrane in a single orientation, and can only form parallel dimers. The lack of activity would support the view that the antiparallel dimer represents the physiological, active dimer complex, but other reasons for the lack of activity, such as the presence of the additional N-terminal region, cannot be excluded. Also, the lack of activity in drug extrusion does not exclude another function for EMRE165.

What might be the function of EMRE165, which by itself, appears to be inactive? Possibly, an ancestor of EmrE was inserted into the membrane in a single orientation, but, from a physiological point of view, there was an evolutionary advantage in the formation of antiparallel dimers, e.g. to broaden the substrate specificity (reviewed by Bay [33]). In order for this to be possible, part of the protein would need to be inserted into the membrane in the opposite orientation. One
way to achieve this was by manipulation of the insertion process by insertion/deletion of positive charges in the loops, resulting in 'dual topology' proteins. Another possible way would be to produce separately proteins with both orientations via a gene duplication followed by divergence of one of the two genes, yielding the opposite orientation. Both mechanisms can be easily identified in the proteins of the SMR family and other families [11,12,34–36]. A gene reminiscent of the EMRE165-encoding gene may represent another solution, yielding two proteins with the opposite orientation, but without requiring a gene duplication event. A single messenger would encode both orientations in two overlapping reading frames. The short ORF would encode the ancestor EmrE that would be forced into the opposite orientation by the signal sequence of six histidines fused at the N-terminus of EMRE110. The long ORF would encode both orientations in the long ORF. Eventually, the solution into the opposite orientation by the signal sequence would encode the ancestor EmrE that would be forced two overlapping reading frames. The short ORF would encode the ancestor EmrE that would be forced into the opposite orientation by the signal sequence encoded in the long ORF. Eventually, the solution faded out in evolution, and EMRE165 might be an evolutionary relic of this mechanism.

Inhibitory properties of the N-terminal His6-tag

EmrE is a multidrug transporter that transports a multitude of organic cations. Glu14 positioned in the middle of the membrane in TMS1 is highly conserved in the SMR family, and is believed to be directly involved in substrate and proton binding. It has been suggested that release of two protons into the cytoplasm from the two Glu14 residues in the binding site at the interface of the dimer of two EmrE subunits would allow binding of the positively charged substrate. Subsequently, conformational changes would expose the substrate to the periplasm, and this would be followed by release of the substrate and re-binding of the protons at the periplasmic side. Reorientation of the binding would return the protein to the original state, with the binding site facing the cytoplasm [14,33,37]. The present study has demonstrated that a sequence of six histidines fused at the N-terminus of EMRE110 (His6-tag) interferes with this mechanism. Cells expressing the His-tagged EMRE110 could not grow on agar plates containing EtBr. His-tagged EMRE165 did not suffer from this inhibition, because of the processing of the protein, which removes the tag, and because of the production of EMRE110 without the tag from the same messenger. Possibly, one or more His residues protonated at the imidazole ring bind to the active site and block the activity. The poor affinity of the His+ substrate may be well compensated for by the high local concentration. Alternatively, the His-tag at the N-terminus might interfere with dimer formation, explaining the inhibition of EMRE110.

Experimental procedures

Strains and growth conditions

E. coli strain SF100 [38] carrying vectors pLIC, pBAD-cLIC, pBAD24 (Invitrogen), pBADhis and pBADBAD (see below) was grown in LB medium supplemented with 50 µg·mL−1 ampicillin at 37 °C under continuous shaking. Overnight cultures were diluted 1 : 10, and grown to an OD600 nm of 0.6, after which expression was induced with 0.004% arabinose unless otherwise indicated, followed by incubation for another 1.5 h.

DNA manipulations

The constructs used in this study are listed in Table 2. The genes encoding EMRE165 and EMRE110 were amplified from E. coli strains 536 and K-12, respectively, by PCR with pfu polymerase (Fermentas, Waltham, MA, USA). Both genes were cloned into pLIC1 and pLIC2 plasmids by ligase-independent cloning (LIC), with primers that contained an overhang sequence compatible with the pLIC cassette, as described previously [13,31]. In order to create single-stranded overhangs, PCR products were treated for 30 min at room temperature with T4 DNA polymerase (Fermentas) in the presence of dCTP. Similarly, plasmids pLIC1 and pLIC2 were treated with T4 DNA polymerase in the presence of dGTP after linearization with SwaI (Fermentas). T4 polymerase was inactivated by incubation at 75 °C for 20 min. The T4 polymerase-treated PCR products and vectors were combined, and, after 5 min of incubation at room temperature, transformed into E. coli SF100. The start codons of EMRE110 were inactivated (M56A mutants) by PCR of the whole plasmids with a forward primer containing the mutation. PCR products were purified, treated with DpnI, and transformed into E. coli SF100. Gene expression from pLIC1 and pLIC2 results in transcriptional fusion of the cloned genes with AP and GFP, respectively. The pLIC1 and pLIC2 vectors encode EmrE variants with an N-terminal His6-tag linked by a Leu to the protein, and, at the C-terminus, the linker sequence QNSGVVP followed by the reporter protein.

Cloning into the LIC vector pBADcLIC–GFP (a kind gift from E. Geertsmma, University of Zurich, Switzerland) was performed as described previously [39]. The primers used in cloning contained an overhang sequence compatible with the cLIC cassette (forward, 5′-ATGGGTGGTGGATTGTGCT-3′; reverse, 5′-TGGGAAGTATAAATTTC-3′). Plasmid pBADcLIC–AP was derived from pBAD-cLIC–GFP. The gene encoding AP was amplified from pLIC1 with a forward primer containing an SvaI restriction site and a reverse primer containing an SpeI restriction site. The GFP gene was restricted from pBADcLIC–GFP with the same enzymes, and replaced with the AP gene encoding PCR product after digestion with SvaI and SpeI.
Insertion of the EmrE-encoding genes was performed as described above for pBADcLIC-GFP. Expression of the genes from pBADcLIC plasmids results in transcriptional fusions with a tobacco etch virus cleavage site, the reporter protein, and a His6-tag.

Cloning into pBAD24 (Invitrogen) and its derivative pBADhis [40] was performed by amplification of the emrE genes with forward primers containing an NcoI site and a reverse primer containing an XhoI site. Plasmids and PCR products were digested with NcoI and XhoI, and ligated with T4 DNA ligase (Fermentas) by incubation at room temperature for 1 h.

Finally, the gene encoding BAD was restricted from pBADCitS [41] with NcoI, and inserted into plasmids pBADhis_EMRE110 and pBADhis_EMRE165 (M56A) containing the different emrE variants. The expressed proteins contained a His6-tag followed by BAD at their N-termini.

**GFP and AP activity of whole cells**

**GFP fluorescence**

Cells from 2 mL of culture were washed once, and resuspended in 50 mM Tris/HCl (pH 8.0), 200 mM NaCl and 15 mM EDTA to a D$_{660}$ nm of 0.2. N-dodecyl β-D-maltoside was added to the suspension to a final concentration of 0.5% (w/v). The fluorescence was measured with an Aminco-Bowman Series 2 Spectrometer at an excitation wavelength of 468 nm and an emission wavelength of 507 nm. For each sample, background fluorescence of cells harboring the vector without insert and reporter was subtracted. Experiments were performed in triplicate.

**AP activity**

Cells from 2 mL of culture were washed once and resuspended in 1 mL of 1 M Tris/HCl (pH 8.0), and the D$_{660}$ nm was measured. Following equilibration of 500 µL of the suspension at 37 °C for 5 min, p-nitrophenyl phosphate (Sigma Aldrich, Zwijndrecht, The Netherlands) was added to a final concentration of 1.4 mg·mL$^{-1}$. The reaction was stopped with 1 mL K$_2$HPO$_4$ when a yellow color developed. AP activity was expressed in Miller units [42]. Measurements were performed in triplicate. GFP fluorescence and AP activities were normalized by the ratio of the averages of the positive PhoA and GFP activities of a set of 27 SMR proteins, as described previously [13,31].

**Resistance assay**

Cells were grown as described above. After induction with 0.004% arabinose, cells were allowed to grow for another hour. After this time, all cultures were diluted to a D$_{660}$ nm of 0.6, and 10-fold serial dilutions were prepared. Five microliters of each dilution in the range of 10$^{-2}$ to 10$^{-7}$ was spotted onto plates containing 500 µg·mL$^{-1}$ EtBr. The plates contained no ampicillin. Plates were incubated overnight at 37 °C.

**Protein purification**

His-tagged proteins were purified by Ni$^{2+}$–nitrilotriacetic acid affinity chromatography with a small-scale purification protocol, as described previously [43]. E. coli SF100 cells from 200-mL cultures were washed twice with 50 mM potassium phosphate (pH 7.0), and resuspended in 2 mL of the same buffer. Cells were broken by sonication (Soniprep 150, MSE Ltd, London, UK) with nine cycles of 15 s on and 45 s off while the suspension was kept on ice. Unbroken cells and debris were removed by low-speed centrifugation (10 min, 7600 g). The cytoplasmic fraction was incubated with Ni$^{2+}$–nitrilotriacetic acid. Membranes were collected by ultracentrifugation with a Beckman TLA 100.4 rotor (25 min, 347 000 g) and washed once with 50 mM potassium phosphate (pH 7.0). Subsequently, the membranes were solubilized for 30 min on ice in 50 mM potassium phosphate (pH 8.0), 400 mM NaCl and 10% glycerol containing 1% Triton X-100. Undissolved material was removed by ultracentrifugation at 80 000 r.p.m. for 25 min. The supernatant was mixed with 100 µL of Ni$^{2+}$–nitrilotriacetic acid resin, and incubated overnight. The column material was pelleted by pulse centrifugation with a table-top centrifuge. The supernatant was discarded. The resin was washed twice with 500 µL of 50 mM potassium phosphate (pH 8.0), 300 mM NaCl and 10% glycerol containing 40 mM imidazole and 0.1% Triton X-100. Bound proteins were eluted with 50 µL of 50 mM potassium phosphate (pH 8.0), 300 mM NaCl and 10% glycerol containing 150 mM imidazole and 0.1% Triton X-100 and, when indicated, with 50 µL of the same buffer containing 300 mM imidazole. Samples from the different purification steps were run on a 15% SDS/PAGE gel, after which GFP-tagged proteins were visualized by fluorescence imaging of the gel with a Fuji LAS-4000 imager. BAD-tagged proteins were detected by western blotting. The proteins were transferred to a poly(vinylidene difluoride) membrane with the semidry transfer technique. The membrane was incubated overnight at 4 °C with NaCl/P$_7$, with 0.1% Tween-20 supplemented with 0.2% I-block (Sigma Aldrich), and this was followed by three washes for 10 min each with NaCl/P$_7$ containing 0.1% I-block, incubation for 1.5 h with Streptactin (IBA, Göttingen, Germany), and finally three washes for 10 min each. The chemiluminescence signal was obtained with CDP-Star (Roche), and visualized with a Fujif LAS-4000 imager.

**References**

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