SUBSTRATE BINDING AND ACTIVE SITE RESIDUES IN RNases E AND G:  
THE ROLE OF THE 5'-SENSOR 
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Running Head: Role of the 5'-sensor in RNase E / G  
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The paralogous endoribonucleases, RNase E and RNase G, play major roles in  
intracellular RNA metabolism in Escherichia coli and related organisms. To  
assay the relative importance of the principal RNA binding sites identified by  
crystallographic analysis, we introduced mutations into the 5'-sensor, the S1 domain and the Mg\(^{2+}/\)Mn\(^{2+}\) binding sites. The effect of such mutations has been measured by assays of activity on several substrates as well as by an assay of RNA binding. RNase E R169Q and the equivalent mutation in RNase G (R171Q) exhibit the strongest reductions in both activity (k\(_{\text{cat}}\) falls ~40 to 100-fold) and RNA binding consistent with a key role for the 5'-sensor. Our analysis also supports a model in which the binding of substrate results in an increase in catalytic efficiency. Although the phosphate sensor plays a key role in vitro, it is unexpectedly dispensable in vivo. A strain expressing only RNase E R169Q as the sole source of RNase E activity is viable, exhibits a modest reduction in doubling time and colony size, and accumulates immature 5S rRNA. Our results point to the importance of alternative RNA binding sites in RNase E and to alternative pathways of RNA recognition.

The RNase E/G family of bacterial endoribonucleases is widely distributed among bacteria (1). Both RNase E and RNase G are expressed in Escherichia coli. RNase E was first characterized as an essential processing enzyme required for the maturation of 5S rRNA (2, 3). It is now known also to be involved in processing the 5'-spacer region of 16S rRNA (4), most tRNA precursors (5, 6), tmRNA (7), and in the metabolism of many small regulatory RNAs (8, 9). It is also responsible for catalyzing the initial cleavage in the degradation of most mRNAs (10, 11). Furthermore, RNase E is part of a larger complex, the RNA degradosome (12-14). In contrast, RNase G appears to play a more limited role in RNA metabolism. It is responsible for the formation of the mature 5'-terminus of 16S rRNA (4, 15) and also participates in the degradation of a limited set of mRNAs (16, 17). It is not essential, however. Although both enzymes prefer single-stranded substrates, neither displays stringent sequence specificity (18-20). However, both enzymes are 5'-end-dependent; i.e., their activity is stimulated, both in vivo and in vitro by a 5'-monophosphorylated terminus on their substrates (21-26). To explain this observation, it was postulated that a 5'-phosphate binding pocket existed on the surface of these enzymes (24). This idea has
been substantially verified by the crystal structure of the catalytic domain of RNase E in complex with a substrate analog (27). These authors showed that RNase E contains a 5’-sensor domain that can interact specifically with a 5’-monophosphorylated substrate via contacts with G124, V128, R169 and T170 (27).

Several investigations have identified potential RNA binding surfaces on RNase E in addition to the 5’-sensor, including an arginine-rich region (28-30) and the S1 domain (31-32). In addition, the active (catalytic) site itself must contribute to substrate binding. The arginine-rich region, however, lies outside the minimal N-terminal domain of RNase E that is sufficient for enzymatic activity (28-30). Several residues in the S1 domain could contribute to RNA binding, but only three, F57, F67 and K112 provide obvious contacts to the substrate (27). Thus, it is not clear to what extent the 5’-sensor contributes to substrate binding. Indeed, it has been suggested that interaction of RNase E or G with a 5’-monophosphorylated substrate increases these enzymes’ $V_{\text{max}}$, effectively providing activation of these enzymes (25).

### EXPERIMENTAL PROCEDURES

**Strains** - E. coli K12 strain SK9714 (thyA715, λ-, rph-1, srlD300::Tn10, recA56, rneΔ1018::bla/pSBK1 [Cm$^R$, rne$^+$]) and plasmid pQLK26 (Km$^R$, rne$^+$) (33) were obtained from Dr. Sidney Kushner, University of Georgia. The host strain for mutagenesis was E. coli DH5α (obtained from Invitrogen). The host for enzyme over-expression was E. coli BL21(DE3) originally obtained from Novagen.

The plasmid pQLK26 was modified by replacing its ~6 kbp insert containing rne with a shortened 3,881 bp fragment amplified from pQLK26 to form pSG-Rne (see Supplementary Fig. 1, step 1 and Supplementary Table 1). The replacement insert contains 600 nt upstream of the rne start codon, the entire coding sequence, and 101 nt downstream from the rne stop codon. All three rne promoters and its transcriptional terminator are included within the 3.8 kbp insert. The empty vector lacks this insert and only contains the backbone from pQLK26 with a single SalI site (this is equivalent to pWSK129 in ref. 33). To facilitate the construction of mutations in pSG-Rne, the 3.8 kbp insert was further subcloned into pUC19 (see Supplementary Fig. 1, step 2). Appropriate fragments containing a mutation of interest were reassembled in pWSK129 to generate a full-length, mutant rne construct (see Supplementary Fig. 1, step 4).
Plasmid displacement from strain SK9714 was measured as follows. Approximately 10^9 competent SK9714 in 0.06 mL were transformed with derivatives of pSG-Rne, allowed to recover in 1.0 mL LB medium, then diluted 200-fold in LB containing thymidine, kanamycin, tetracycline and carbenicillin (20 mg/L each) and allowed to grow to saturation. The saturated culture was diluted 1000-fold into fresh medium also containing selective antibiotics and grown to saturation at 37°. Portions of this culture were spread on LB agar plates containing thymidine, kanamycin, tetracycline and carbenicillin (20 mg/L each). Colonies were picked onto fresh plates containing thymidine, tetracycline, carbenicillin and either kanamycin or chloramphenicol. Plasmid displacement was measured as the fraction of kanamycin-resistant colonies that had lost resistance to 20 mg/mL chloramphenicol.

**Construction of rne or rng mutants and purification of mutant enzymes** – Plasmid pSG-Rne1-529 was constructed in the pET24b (Novagen) backbone between the NdeI and XhoI sites using appropriate PCR primers (See Supplementary Materials) to amplify DNA corresponding to amino acid residues 1-529 from *E. coli* DNA. The resultant construct will encode a C-terminal hexahistidine tag. Additional mutants were made as described below with the primers listed in Supplementary Materials.

Plasmid pDB1, based on pET24b, encodes RNase G with six additional N-terminal Histidine residues (34), and was the basis for all further constructions involving RNase G. Mutagenesis was performed using the Stratagene "Quik-Change®" kit. Oligonucleotides used for mutagenesis are listed in Supplementary Table 3. Putative mutant plasmids were checked for the desired change by DNA sequence analysis.

His6-RNase E (1-529), His6-RNase G and derived mutants were purified as described (34). In brief, cell pellets from 1 L induced cultures grown to saturation at 20° were harvested and lysed in a French Pressure cell (Amino). A cleared lysate was passed through a column packed with Talon resin (Clontech). Fractions eluted with >50 mM imidazole were pooled, supplemented with 6 mM 2-mercaptoethanol and subjected to further chromatography on a column of Source Q (Pharmacia). Fractions containing the desired RNase were pooled, made 1 mM in DTT and quantitated prior to further characterization.

**RNase Assays** - Three RNA substrates were used in assays of activity. The first was Ribo-8 (5’-ACAGUAUUUdG), a derivative of BR10 (20) containing a 3’-deoxy G residue. The other substrates were BR14-FD (25; see Fig. 2A below) and BR13-3’-fluorescein (26). Assays using Ribo-8 contained 50 nM 5’-32P-Ribo-8 and RNase G or its mutants in 25 mM Tris-HCl, pH 7.8, 5 mM MgCl2, 30 mM KCl, 1 mM dithiothreitol, and 5% glycerol. Incubations were initiated by addition of enzyme (8 nM for wild type; see the text). Samples were removed at timed intervals, denatured in buffered 90% formamide and boiled for 45 sec. Products were separated by electrophoresis on a 15% polyacrylamide gel (29:1 acrylamide:bis acrylamide) containing 8 M urea and detected by phosphorimaging.

The fluorescent substrates, 5’-P-BR14-FD (25) and 5’-P-BR13F (26), were synthesized by the University Core DNA Services at the University of Calgary. Assays were performed at 30° in a buffer containing...
25 mM Tris-HCl pH 7.6, 10 mM MgCl₂, 30 mM NaCl, 1 mM DTT, and 5% (vol/vol) glycerol. For BR14FD, fluorescence at 517 nm was monitored on a Cary Eclipse Fluorescence Spectrophotometer using excitation at 495 nm. Initial rates were determined by monitoring the increase of fluorescence over the first 5 min following addition of enzyme (i.e., in the linear range). Measurements of initial rates for a given substrate concentration were repeated at least three times and the average was determined. For assays with BR13F, portions of the assay were withdrawn, quenched in 3 volumes of buffered 90% formamide and treated as for BR13 above, except that wet gels were scanned for fluorescence using a Typhoon phosphorimager. Kinetic constants were extracted from the data using an Eadie-Hofstee Plot.

RNA Binding Assays - We adapted the double filter assay of Wong and Lohman (35) to measure the binding of 5'-³²P-Ribo-8 to RNase G. Briefly, incubations containing 20 nM RNA oligonucleotide and from 100 nM to 4 mM RNase G were assembled on ice in FAB buffer (20 mM PIPES, 50 mM NaCl, 0.5 mM EDTA, 0.5 mM DTT, 20 μg/mL acetylated BSA (New England Biolabs), pH 6.5). Samples were applied to individual wells in a Bio-Rad 96 well Dot-Blot apparatus containing a BioRad nitrocellulose membrane over an Amersham Biosciences Hybond-NX nylon membrane, both previously washed with 1x FAB at room temperature. The samples were incubated for 5 min at ambient temperature before being drawn through the membranes with a gentle vacuum and washed with 100 mL 1x FAB. Membranes were allowed to dry under suction for 5 min and were then exposed to a phosphor storage screen.

Northern Blotting – Total RNA was extracted from exponential cultures grown in LB medium supplemented with 50 μg/ml thymidine and appropriate antibiotics. Samples (3 μg) were dissolved in 8 μL of buffered 80% formamide, separated in a 5% polyacrylamide gel containing 8 M urea in Tris-borate-EDTA buffer, and electrophoretically transferred to Hybond NX. Hybridization was performed at 35.5 ºC as described (42) using a 5'-³²P-labelled oligonucleotide complementary to 5S RNA (5'-CGTTTCACCTCTGAGTTCGGC).

RESULTS

Identification and mutation of conserved residues in RNase G – Our goal was the clarification of the role of different potential RNA binding domains in RNase E on this enzyme’s activity. However, to avoid some of the complexities of RNase E, including its association with other proteins (12-14) and membranes (36) as well as potential RNA binding sites outside the catalytic domain (28, 29), we initially used RNase G as a surrogate. This enzyme displays 5'-end-dependence (22-23), like RNase E (21), and can be assayed against the same substrates (25). We postulated that residues playing important functions in catalysis and substrate binding would be highly conserved in both RNase E and RNase G. To this end, we constructed an alignment of the members of the RNase E and RNase G family similar to published alignments (1, 27). In particular, we identified E298, D304, E326, D347 and D350 in RNase G (E297, D303, E325, D346 and D349, respectively, in RNase E) as conserved acidic residues that could play a role in metal ion chelation. Likewise, R171 and R338 (R169 and R337, respectively, in RNase E) are highly conserved basic residues that could interact with backbone phosphates. Each of
these residues was mutated independently to Ala or Gln and the resultant mutant proteins expressed, purified and characterized. Figure 1a summarizes the mutations used in this study and indicates their location in the presumed domain structure of RNase G. A typical purification of a mutant enzyme, RNase G R171Q, is shown in the Supplementary material. The enzyme was substantially pure after immobilized metal ion chromatography and was essentially homogeneous after ion exchange chromatography (see Supplementary Fig. 2B). In several cases, mutant proteins were further characterized by mass spectrometry. Interestingly, for RNase G D347A and D350A, the observed masses of 56,420 and 56,432, respectively, correspond to the expected loss of mass associated with a change from Asp to Ala, but with the retention of the N-formyl group at the N-terminus (expected mass, 56,433).

We also examined several physical properties of some of the mutant enzymes. The mid-point unfolding temperature (Tm) was determined for several mutants using circular dichroism (34). Generally, the mutants tested displayed a Tm equal to that of His6-RNase G (50.3°C; 34). RNase G D350A, however, displayed a somewhat lower Tm (approx 47°C). Nonetheless, this mutant enzyme cosedimented with His6-RNase G implying that it was still capable of forming dimers (data not shown).

Effects of mutation on enzyme activity - Many of the mutant enzymes were initially assayed on a 519 nt substrate which mimics the RNase III-processed pre-16S rRNA (34). Although this assay is rather insensitive, several mutants, including RNase G R171Q, D304A and D347A exhibited detectable losses in activity (>50%; data not shown). More informative data were obtained by assaying each of the mutant enzymes against 5'-32P-Ribo-8 (Table 1). While wild type RNase G could be assayed at limiting enzyme concentrations, most of the mutants had to be assayed in enzyme excess. Nonetheless, RNase G R171Q (5'-sensor domain) and D304A (active site) were virtually inactive. Modest levels of activity could be observed with RNase G F67A, K115A (both in the S1 domain), R171H and R338Q, especially at high enzyme concentrations. The remaining mutants, including RNase G V131I, E298A, E326A, D347A and D350A retained significant levels of activity against this substrate (Table 1). Although E298 and E326 are conserved, they appear not to be required for activity under the conditions tested and were not characterized further. As a control for the validity of the assay, in particular for its sensitivity to the status of the substrate’s 5'-end, we repeated several assays with 5'-hydroxyl, 3'-32P-Cp-BR10 as a substrate to determine the fraction of activity that was 5'-end-independent. His6-RNase G displayed only ≤6% as much activity on this 5'-OH substrate as on 5'-32P-Ribo-8 (data not shown). Moreover, the mutants tested, including R171Q and R338Q, were virtually inactive against this 5'-OH substrate (data not shown).

In order to obtain kinetic parameters, we assayed many of the mutant enzymes against BR14FD, a fluorescent oligoribonucleotide substrate developed by Jiang and Belasco (25). Representative time courses and Eadie-Hofstee plots are shown in Figure 2 while the kinetic data are summarized in Table 1. In general, the results obtained with this assay are qualitatively similar to the data obtained with Ribo-8. The fluorescence assay is, however, far more sensitive and can be
conducted at limiting enzyme concentrations. WT (His6) RNase G exhibited a $K_m$ of 70 nM and a $k_{cat}$ of 1.4 min$^{-1}$ (Fig. 2c, d; Table 1). These values are similar to those reported by Jiang and Belasco: 230 nM and 2.1 min$^{-1}$ (25). They also compare favourably to 120 nM and 3.0 min$^{-1}$, respectively, reported by Jourdan and McDowall (26) using a somewhat different fluorescence assay. To verify the 5'-end dependence of RNase G under these conditions (22, 23, 25), wild type RNase G was assayed against 5'-OH-BR14. With this substrate, the $K_m$ increased to 570 nM and the $k_{cat}$ fell to 0.03 min$^{-1}$. This result differs from that reported by Jiang and Belasco (25) who found that the state of phosphorylation of BR14 did not affect $K_m$ but only $k_{cat}$. In this regard, our results more closely agree with those of Jourdan and McDowall (26).

The use of fluorescent substrates permitted an objective comparison of the mutants. The most striking of these is RNase G R171Q for which the $k_{cat}$ drops by almost 100-fold while, the $K_m$ increases about 14-fold (Fig. 2d; Table 1). This finding points to the key role in the recognition of some substrates that is played by the phosphate binding pocket in RNase G (see the Discussion). Interestingly, mutations in three residues in the S1 domain which line the RNA binding channel, F57, F67 and K115 (27), also affect both kinetic parameters, but not as severely. The $K_m$ increases 3 to 7 fold while the catalytic efficiency, $k_{cat}$, falls 30 to 140 fold. Among the putative metal ion chelating residues, mutations in either D304 or D347 affect both $K_m$ and $k_{cat}$, with D304A being the more severe mutation. In contrast, D350A exerts only a modest effect on $K_m$ and little effect on $k_{cat}$ (see Table 1). The strong effects of mutations on D304 and D347 agree with the findings of Callaghan et al (27) for the N-terminal domain of RNase E (see below).

**RNA binding by mutant RNase G enzymes** -
We employed a double filter assay (35) to determine the relative affinities of His6-RNase G and its derivatives for 5'-$^{32}$P-Ribo-8 (see Experimental Procedures). The main challenge was avoidance of contamination by Mg$^{2+}$ ions and the resultant destruction of the ligand by cleavage. Typical binding isotherms are shown in Fig. 3 and the data are summarized in Table 1. Wild type RNase G displayed an apparent $K_d$ of 190 nM. This value is close to the $K_d$ of 162 nM reported by Jourdan and McDowall (26) who used fluorescence anisotropy to assess RNA binding to a 2'-O methyl substrate. In contrast, R171Q exhibited very little binding to this RNA ligand at the protein concentrations tested (Fig. 3c and Table 1). The F57A, F67A and K115A mutations in the S1 domain also resulted in lowered RNA binding with apparent $K_d$ values of 900-1200 nM, respectively, or 5-fold more than wild type. Interestingly, mutations in the metal binding site, including D304A and D347A, resulted in partial loss of binding to Ribo-8 and elevated $K_d$ values. Nonetheless, the data show that the most severe effect on RNA binding, a >25-fold increase in $K_d$, is exerted by R171Q. In support of this finding, we tested the binding of 3'-fluorescein-labelled BR13, with or without a 5'-monophosphate, to wild type RNase G. Binding of 5'-OH-BR13F was much weaker than that of BR13-5'-monophosphate and did not reach 50% at the highest protein concentration tested.

**Effect of selected mutations on RNase E** –
To test the implied assumption that the effect of mutations in RNase G could be extrapolated to RNase E, we reconstructed some of the most severe alleles of RNase G in...
a derivative of RNase E spanning residues 1-529 (i.e., the catalytic domain used for crystallographic analysis; ref 27). Mutant proteins were expressed and purified as described for RNase G (see Experimental Procedures), then assayed on BR14FD. These data are summarized in Table 2. Several salient observations emerge by comparison to the data in Table 1. First, RNase E is more active than RNase G (i.e., lower K_m and higher k_cat). This differs from the findings of Jiang and Belasco (25) and may reflect the fact the RNase E construct used by these authors was shorter than the one employed here. Second, mutations in the S1 domain of RNase E (F57A and F67A) exert modest increases in K_m (4-10 fold) and decreases in k_cat (6-12 fold). The corresponding mutations in RNase G, however, resulted in 30-100 fold reductions in k_cat (Table 1). Third, the R169Q mutation in RNase E (5’-sensor domain) increases the K_m 10-fold and decreases the k_cat almost 40-fold. The change in K_cat, in particular, is less severe than observed in the corresponding mutation in RNase G (i.e., R171Q). As a control, we tested the 5’-end-dependence of RNase E 1-529. Dephosphorylating the substrate led to a 36-fold increase in K_m and a 32-fold decrease in k_cat consistent with the effects of the R169Q mutation (see Table 2). Finally, the mutation D303A reduced k_cat by 1000-fold, essentially eliminating activity as did D304A in RNase G (Table 1). We were unable to measure the affinity of RNase E 1-529 or any of its derived mutants for Ribo-8 by the double filter method as binding was too weak and did not reach saturation.

Effect of mutations in RNA binding residues of RNase E in vivo - Since RNase G is not essential in E. coli under normal laboratory conditions we instead determined the phenotype of mutations in the corresponding residues in RNase E since the latter enzyme is essential for viability (10; 33). Mutations were constructed in the rne gene carried on pSG-Rne, a derivative of pQLK26 (Km_R), a low copy plasmid capable of complementing rneΔ1018::bla, an otherwise lethal deletion of the chromosomal rne gene (33). Each such construct was tested for its ability to displace a wild type plasmid, pSBK1 (rne+, Cm_R), from strain SK9714 which requires a functional rne gene supplied in trans for survival. Data for such experiments are shown in Table 3. The mutants tested fall into two clear classes. The first fails to displace pSBK1 and includes F67A, D303A, D346A and R337E. F67 interacts with the RNA substrate in the S1 domain close to the catalytic site while D303 and D346 are believed to chelate an essential Mg^{2+} ion and participate in catalysis (27). Our data support this view and demonstrate that these residues are essential for RNase E. The deleterious effect of R337E is most likely due to the charge reversal caused by this substitution because R337Q displays almost no phenotype (Table 3). The second class of mutants was able to displace pSBK1 at significant frequencies (Table 3). These mutants, including F57A, R169Q and T170A, affect residues involved in contacting RNA in the S1 domain (F57) or phosphate-binding pocket (27). Although R169Q was able to displace pSBK1 at a significant frequency, the resultant colonies were noticeably smaller (Fig. 4). Transformants of SK9714 containing pSG-Rne-R169Q grew with a doubling time of 32.3 minutes in rich medium. In contrast, SK9714 containing pSG-Rne (WT) grew significantly more quickly under the same conditions with a doubling time of 24.5 min. Strains transformed with pSG-Rne T170A which showed no phenotype also grew well, with a doubling time of 27 min.
We further characterized the three mutants able to displace WT pSG-Rne by examining the accumulation of 5S RNA. For comparison, we also included the well known temperature-sensitive rne-1 allele. Fig. 5 shows that precursors to 5S RNA accumulate at non-permissive temperature in the rne-1 strain, SK5665 (compare lane 2 to lane 1), as expected. A strain containing pSG-Rne R169Q as its only source of RNase E exhibits a pattern of precursor accumulation that is qualitatively identical to that of the rne-1 allele (compare lane 5 to lane 2). In contrast, a strain carrying the T170A allele contains almost no precursors at this exposure (compare lane 6 to lanes 2 and 5) although they are detectable with longer exposures. Interestingly, the F57A allele (lane 4) also accumulates some precursors but to a lesser extent than either rne-1 or R169Q. Processing of the hisR transcript (tRNA$^{His}$) from the same strains was also tested. Unlike the case above, it was normal in R169Q and T170A, but defective in rne-1 as expected (6) (data not shown).

**DISCUSSION**

This investigation was initiated with the goal of using conserved residues identified by bioinformatic means or subsequently, the crystal structure of RNase E (27), to clarify the contribution of potential RNA binding surfaces to the activity of RNases E and G. A major focus was the interaction with the 5'-phosphate of substrates and its mechanism of stimulation of the activity of RNase E and G. The 5'-end-dependence of RNase E (21) is a signature property of RNase E and RNase G (22, 23). Interestingly, the unrelated RNase J1 of *B. subtilis* also exhibits a preference of 5'-phosphates (37). At least two mechanisms have been invoked to explain why 5'-monophosphorylated RNAs are preferred by RNases E and G. Jiang and Belasco (25) have presented data that suggest that binding of a monophosphorylated oligonucleotide to RNase E or RNase G stimulates $V_{max}$ up to 30-fold with little effect on $K_m$. These authors did not measure RNA binding independently of catalysis. In contrast, Jourdan and McDowall (26) reported that the stimulatory effect of a 5'-monophosphate on RNase G is exerted primarily through enhanced substrate binding resulting in a 100-fold improvement in $K_m$. Our data, using the same substrate as Jiang and Belasco, support the view that the primary effect of a 5'-monophosphorylated substrate is enhanced binding. Neutralization of the positive charge on a key residue in the phosphate binding pocket, R171, resulted in a ~14-fold drop in $K_m$ and a 100-fold decrease in $k_{cat}$ by RNase G. Furthermore, measurement of substrate binding in the absence of catalysis showed that the same mutation caused a 25-fold or greater loss in affinity for substrate. Quantitatively, the loss of affinity for RNA by R171Q is greater than by F57A, F67A or K115A, residues in the S1 domain which line the RNA binding channel. The corresponding residues are known to affect the activity of RNase E as assessed by loss of feedback regulation (31). Nonetheless, our data show that binding of a monophosphorylated substrate to RNase E or RNase G also activates the enzyme as proposed (27, 38). Koslover *et al.* have shown that binding of a substrate via its 5'-monophosphate residue triggers a significant conformational change in RNase E involving both the 5'-sensor and S1 domains (38). In this regard, interactions between substrate and enzyme remote from the catalytic site are known to contribute to the efficiency of catalysis (39). The large decreases in $k_{cat}$ exhibited by RNase E R169Q and by G R171Q are, in this view, obvious consequences of weak substrate binding.
Based on previous data (31), we anticipated that RNase E F57A might be unable to displace pSBK1 from strain SK9714. Nonetheless, displacement was very efficient. Apparently the reduced activity of RNase E F57A is still sufficient to support growth and results in only modest impairment of 5S rRNA processing. We presume that requirements for autoregulation (31) differ subtly from those for viability.

The physiological effects of mutations in residues in the phosphate binding pocket of RNase E have not previously been reported. To our surprise, both R169Q and T170A are viable, although the former leads to a slow growth phenotype, small colonies and significant reduction in the rate of 5S RNA processing. Conversely, mutations D303A and D346A are inviable, consistent with their proposed role in coordinating a hydrated Mg\(^{2+}\) ion that serves as the source of a base in phosphodiester bond cleavage (26, 27). The modest effect of R169Q on RNase E in vivo stands in stark contrast to its effects on both RNase E and RNase G in vitro (26). This dichotomy suggests that the role of the phosphate sensor is more subtle than initially envisaged. We believe that at least two factors should be considered in explaining this outcome. First it is noteworthy that the most pronounced effects of either monophosphorylation or mutations in the phosphate sensor are detected with oligonucleotides such as BR10 and its derivatives or relatively short substrates (e.g., the 9S RNA precursor to 5S RNA [246 residues]) (21, 22, 23, 26). Such short substrates may make relatively few contacts with RNase E and thus rely on the phosphate sensor and the S1 domain for binding. Second, at least one additional RNA binding surface is known in full length RNase E, notably the “arginine-rich region” between residues 610 and 632 (28, 29, 30). A comparable region is not found in RNase G. The arginine-rich region may be able to compensate, in part, for deficiencies in 5'-end recognition in R169Q. In this regard, a strain carrying ΔrppH and thus unable to remove the terminal pyrophosphate from RNAs is viable although the half lives of many mRNAs are elevated in this strain (40). We infer, therefore, that internal entry (41, 42) may play a greater role in the action of RNase E, particularly on longer RNAs, than hitherto appreciated. The availability of the viable R169Q mutation will greatly facilitate elucidating the physiological role of the 5'-sensor and investigating possible alternative pathways of substrate recognition.

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REFERENCES


Figure Legends

FIGURE 1. A) Schematic map of RNase G. This linear map of RNase G shows the domains inferred from alignment against RNase E. The boundaries are given by the residue numbers below the linear map and correspond to those in RNase E (27). The positions of mutations in RNase G created in this work are noted below the map.

B) Structure of the N-terminus of RNase E. The ribbon diagram was provided by Dr. Ben Luisi and shows the N-terminal region of two monomers of RNase E (27). The positions of substrates (in green) prior to cleavage and the positions of some of the mutations created in this study, are indicated using space filling atoms. Domains are similarly coloured in both A and B.

FIGURE 2. Fluorescence assay of RNase G. Panel A shows a schematic cartoon of RNA 1, a 108 nt regulatory RNA that is a model substrate for RNase E. The major cleavage site is denoted by the vertical arrow. BR14FD, a synthetic fluorescent substrate for RNase E or G is based on the 5'-end of RNA 1 (25). Panel B. Time course showing the increase in fluorescence as BR14FD is cleaved under conditions described in Experimental Procedures. Panel C. Eadie-Hofstee plot of initial rates as a function of concentration of BR14FD. The data for RNase G R171Q are compressed in this graph. Panel D. Expansion of the data in panel C to show the Eadie-Hofstee plot for RNase G R171Q.

FIGURE 3. Double filter assay of RNA binding by RNase G. The assay of Wong and Lohman (35) was adapted for RNase G as described in Experimental Procedures. A typical set of data is shown. The left hand column in each panel contained no added protein. Protein concentrations ranged from 125 nM to 2000 nM from left to right. Panel A shows the nitrocellulose filter (retaining RNA-protein complexes) while panel B shows the nylon filter with free RNA. The RNase G preparations assayed for binding are listed in the right margin. Panel C shows the fraction of RNA bound as a function of protein concentration for WT RNase G (●) and RNase G R171Q (▲).

FIGURE 4. Colony Size of SK9714 transformed with different plasmids. Samples of cultures of SK9714 (33) transformed with plasmids of interest (see Table 2) were streaked on plates containing LB, thymidine, carbenicillin and kanamycin.

FIGURE 5. Effect of RNase E mutations on stable RNA processing. Total RNA from the following strains was subjected to Northern blotting as described in Experimental Procedures using a probe complementary to 5S rRNA and its precursors: lane 1, MG1693 (WT); lane 2, SK5665 (rne-1); lane 3, SK9714/pSG-Rne [WT]); lane 4, SK9714/pSG-Rne F57A; lane 5, SK9714/pSG-Rne R169Q; lane 6, SK9714/pSG-Rne T170A. The position of mature 5S RNA is shown by the arrow in the left margin.
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<td>V131I</td>
<td>50</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>R171Q</td>
<td>≤1</td>
<td>≥1000 e</td>
<td>0.015 e</td>
</tr>
<tr>
<td>R171H</td>
<td>≤10</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>E298A</td>
<td>100</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>D304A</td>
<td>≤2</td>
<td>330</td>
<td>0.014</td>
</tr>
<tr>
<td>E326A</td>
<td>100</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>R338Q</td>
<td>15</td>
<td>210</td>
<td>0.011</td>
</tr>
<tr>
<td>D347A</td>
<td>40</td>
<td>300</td>
<td>0.046</td>
</tr>
<tr>
<td>D350A</td>
<td>8</td>
<td>230</td>
<td>0.80</td>
</tr>
</tbody>
</table>

a. Except as noted in footnote (e) below, kinetic constants were estimated from Eadie-Hofstee plots of data generated from assays using 5'-P-BR14FD as substrate (see Experimental Procedures). Each enzyme was assayed in triplicate and initial rates for each concentration of substrate were averaged. The averaged values were then used to obtain slopes and intercepts.

b. Binding data, usually in triplicate, using <sup>32</sup>P-Ribo-8 as ligand were obtained from the double filter method (see Experimental Procedures) and are reported as apparent K<sub>d</sub> values.

c. Activities were measured with 5'-<sup>32</sup>P-Ribo-8 and are reported as apparent initial rates of formation of 5 nt product expressed as a percentage of the rate measured for His6-RNase G. Most of the mutants were assayed in enzyme excess in order to obtain measurable rates while wild type was assayed in substrate excess. Values are the average of duplicates.

d. nd, not determined.

e. Since BR14FD could not be used at concentrations > 800 nM, we employed an in gel assay with 5'-P-BR13F containing a 3’-fluorescein modification to obtain kinetic parameters for R171Q (26; see Experimental Procedures).
Table 2. Relative activities of RNase E point mutants

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>$K_m$ (nM)</th>
<th>$k_{cat}$ (min$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>33</td>
<td>11</td>
</tr>
<tr>
<td>WT $^c$</td>
<td>5100</td>
<td>0.95</td>
</tr>
<tr>
<td>F57A</td>
<td>120</td>
<td>1.9</td>
</tr>
<tr>
<td>F67A</td>
<td>320</td>
<td>1.1</td>
</tr>
<tr>
<td>R169Q</td>
<td>350</td>
<td>0.28</td>
</tr>
<tr>
<td>D303A</td>
<td>38</td>
<td>0.008</td>
</tr>
<tr>
<td>D346A</td>
<td>77</td>
<td>0.007</td>
</tr>
</tbody>
</table>

a. Except where noted, kinetic constants were estimated from Eadie-Hofstee plots of data generated with 5’-P-BR14FD as substrate (see Experimental Procedures). Rates for each substrate concentration were determined at least in triplicate, then averaged prior to plotting.
b. In all cases, the enzyme includes residues 1-529 of RNase E
c. Data on this line were obtained with 5’-OH-BR14FD as substrate (see Experimental Procedures).
Table 3. Complementation of a lethal *rne* deletion by *rne* mutants

<table>
<thead>
<tr>
<th>Mutation</th>
<th>Plasmid</th>
<th>Percent Displaced</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>pSG-Rne</td>
<td>76 ± 4.1</td>
</tr>
<tr>
<td>F57A</td>
<td>pSG-Rne F57A</td>
<td>93 ± 1.0</td>
</tr>
<tr>
<td>F67A</td>
<td>pSG-Rne F67A</td>
<td>0</td>
</tr>
<tr>
<td>R169Q</td>
<td>pSG-Rne R169Q</td>
<td>47 ± 5.0</td>
</tr>
<tr>
<td>T170A</td>
<td>pSG-Rne T170A</td>
<td>89 ± 2.3</td>
</tr>
<tr>
<td>D303A</td>
<td>pSG-Rne D303A</td>
<td>0</td>
</tr>
<tr>
<td>R337E</td>
<td>pSG-Rne R337E</td>
<td>0</td>
</tr>
<tr>
<td>R337Q</td>
<td>pSG-Rne R337Q</td>
<td>92 ± 1.2</td>
</tr>
<tr>
<td>D346A</td>
<td>pSG-Rne D346A</td>
<td>0</td>
</tr>
</tbody>
</table>

a. All complementing plasmids were constructed in the backbone from pWSK129 (see Experimental Procedures and Supplementary Fig. 1).

b. The fraction displaced is recorded as the fraction of colonies that have acquired resistance to kanamycin via the mutant plasmid with concomitant loss of resistance to chloramphenicol conferred by pSBK1 after >20 doublings (see Experimental Procedures).

c. Colonies that were resistant to kanamycin but sensitive to chloramphenicol were noticeably smaller than those that retained pSBK1 (see also Fig. 4).
Figure 2

A

RNA I

5' A C A G U A U U U

3'

RNase G

Fluor

RNase G

Dab

P-BR14-FD

5' PO₄-A mA mA cT mA cT G U A U U cT G-3'

B

Fluorescence (A.U.)

Time (min)

0 10 20 30 40 50

RNase G WT

R171Q

C

\[
\frac{v}{[S]/[E]} \text{ (min}^{-1}\text{mM}^{-1})
\]

D

\[
\frac{v}{[S]/[E]} \text{ (min}^{-1}\text{mM}^{-1})
\]
Figure 3

A

wild-type

R171Q

B

wild-type

R171Q

C

Fraction of RNA Bound

RNase G (nM)
Substrate binding and active site residues in RNases E and G: the role of the 5'-sensor
Stephen M. Garrey, Michaela Blech, Jenna L. Riffell, Janet S. Hankins, Leigh M. Stickney,
Melinda Diver, Ying-Han Roger Hsu, Vitharani Kumanithy and George A. Mackie

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