

Nonsense-Mediated mRNA Decay in Yeast Does Not Require PAB1 or a Poly(A) Tail

Stacie Meaux,¹ Ambro van Hoof,^{1,3,*} and Kristian E. Baker^{2,3,*}

¹Department of Microbiology and Molecular Genetics, University of Texas Health Science Center-Houston, Houston, TX 77030, USA

²Center for RNA Molecular Biology, Case Western Reserve University, Cleveland, OH 44106, USA

³These authors contributed equally to this work.

*Correspondence: ambro.van.hoof@uth.tmc.edu (A.v.H.), kristian.baker@case.edu (K.E.B.)

DOI 10.1016/j.molcel.2007.10.031

SUMMARY

Eukaryotic mRNAs harboring premature translation termination codons are recognized and rapidly degraded by the nonsense-mediated mRNA decay (NMD) pathway. The mechanism for discriminating between mRNAs that terminate translation prematurely and those subject to termination at natural stop codons remains unclear. Studies in multiple organisms indicate that proximity of the termination codon to the 3' poly(A) tail and the poly(A) RNA-binding protein, PAB1, constitute the critical determinant in NMD substrate recognition. We demonstrate that mRNA in yeast lacking a poly(A) tail can be destabilized by introduction of a premature termination codon and, importantly, that this mRNA is a substrate of the NMD machinery. We further show that, in cells lacking Pab1p, mRNA substrate recognition and destabilization by NMD are intact. These results establish that neither the poly(A) tail nor PAB1 is required in yeast for discrimination of nonsense codon-containing mRNA from normal by NMD.

INTRODUCTION

Nonsense-mediated mRNA decay (NMD) is a conserved quality control mechanism in eukaryotic cells that recognizes and eliminates mRNA encoding premature translational termination signals in their protein coding region (Baker and Parker, 2004; Maquat, 2004). The rapid degradation of mRNA lacking a complete open reading frame (ORF) protects cells from accumulation of truncated polypeptides that can confer deleterious dominant-negative or gain-of-function phenotypes (Pulak and Anderson, 1993). Mutations in components of the NMD machinery lead to mental retardation in humans or embryonic lethality in mice, underscoring the functional importance of NMD (Medghalchi et al., 2001; Tarpey et al., 2007). Furthermore, NMD is a potent modulator of phenotypic outcome for many human genetic diseases (Frischmeyer and Dietz, 1999; Kuzmiak and Maquat, 2006).

NMD substrates encompass not only mRNAs harboring premature termination codons (PTCs) introduced by mutation but also a significant population of the yeast, *Drosophila*, and human

transcriptomes (He et al., 2003; Lelivelt and Culbertson, 1999; Mendell et al., 2004; Rehwinkel et al., 2005). Many endogenous mRNA targets that undergo NMD contain PTCs as a consequence of inefficient pre-mRNA splicing (He et al., 1993), upstream ORFs (Oliveira and McCarthy, 1995), or use of out-of-frame AUG start codons (Welch and Jacobson, 1999). Interestingly, mRNAs terminating translation at a natural stop codon but harboring an extension of their 3'UTR are also substrates for NMD (Muhlrad and Parker, 1999; Pulak and Anderson, 1993). For all NMD substrates, therefore, translation termination occurs in an inappropriate context, and NMD appears to result from an alteration in the spatial relationship between the termination codon and other features of the mRNA (Baker and Parker, 2004).

Translation termination is considered aberrant as a consequence of its occurrence upstream of a second signal consisting of mRNA sequence elements and associated protein markers. In one model, prematurely terminating ribosomes fail to displace a downstream mRNA-protein complex (mRNP) able to trigger decay of the mRNA by recruiting proteins required for NMD (Maquat, 2004). Ribosomes that elongate through the entire ORF and terminate at a natural stop codon, in contrast, displace the downstream mRNP to prevent NMD. Proteins deposited at exon-exon junctions (exon junction complexes, EJC) during pre-mRNA splicing serve to mark upstream stop codons as premature in mammalian cells (Zhang et al., 1998a, 1998b). Although recognition of mRNAs harboring PTCs is highly dependent upon a downstream exon-exon junction in vertebrates, exceptions have been described, demonstrating that a downstream EJC is not universally required for mammalian NMD (Buhler et al., 2006; Wang et al., 2002; Weil and Beemon, 2006).

In yeast, flies, worms, and plants, PTC definition can occur independently of a downstream exon boundary, and EJC protein components are either predominantly absent or not required for NMD (Culbertson and Leeds, 2003; Gatfield et al., 2003; Longman et al., 2007; Muhlrad and Parker, 1994; van Hoof and Green, 1996). Therefore, other determinants must present the downstream signal required for NMD substrate recognition. Yeast mRNAs are proposed to harbor downstream sequence elements (DSEs), within their coding regions, which bind protein factors (e.g., Hrp1). In a nonsense mRNA these factors trigger NMD, while in a normal mRNA they are removed during translation elongation (Gonzalez et al., 2000; Peltz et al., 1993). The few characterized DSEs, however, share loose sequence consensus, making it difficult to estimate their ubiquity within ORFs and

their importance in NMD. Moreover, analogous elements have not been identified in other organisms (Behm-Ansmant et al., 2007; Maquat, 2004).

An alternative paradigm for recognition of nonsense-containing mRNAs is the “faux UTR” model, which posits that translation termination at a PTC is intrinsically aberrant because it occurs upstream of elements unable to function as an authentic 3'UTR (Amrani et al., 2004, 2006). Ribosomes at a normal stop codon, in contrast, terminate proximal to the 3'UTR and engage in interactions necessary for efficient termination and stabilization of the mRNA. According to this model, an appropriate mRNP context includes the mRNA poly(A) tail and poly(A)-binding protein, PAB1. Importantly, tethering of PAB1 downstream and proximal to a PTC stabilizes NMD substrates in both yeast and *Drosophila* (Amrani et al., 2004; Behm-Ansmant et al., 2007). In addition, targeting of mRNAs with extended 3'UTRs by NMD is consistent with PAB1 and the poly(A) tail providing important positional information for substrate recognition by NMD.

We evaluated the requirement for an mRNA poly(A) tail and PAB1 in recognition of NMD substrates. We show that introduction of a PTC into a yeast mRNA lacking a poly(A) tail can result in destabilization of the mRNA and that rapid decay of the mRNA requires the NMD factor Upf1p, confirming it as a bona fide NMD substrate. Further, we reveal that, in the absence of Pab1p, mRNAs harboring a PTC are recognized and destabilized in an Upf1p-dependent manner. Our findings clearly demonstrate that, in yeast, neither an mRNA poly(A) tail nor Pab1p is required for NMD. These findings illustrate that the proximity of the terminating ribosome to PAB1 either plays no role in substrate discrimination by NMD or is just one of several redundant features that distinguish a termination event as premature.

RESULTS

Unadenylated GFP-RZ mRNA Is Targeted for Degradation by the Cytoplasmic Exosome

To evaluate the relevance of the poly(A) tail in NMD in yeast, we utilized a reporter gene containing the GFP ORF followed immediately by a hammerhead ribozyme (*GAL1-GFP-RZ*; Figure 1A; Dower et al., 2004). Inclusion of the ribozyme sequence results in RNA cleavage. The resulting mRNA has a six nucleotide 3'UTR and lacks a poly(A) tail (see the Supplemental Data available online).

Meaux and van Hoof (2006) reported that unadenylated mRNAs are rapidly degraded by the cytoplasmic exosome. To evaluate if *GFP-RZ* mRNA is also a substrate for the exosome, transcript stability was determined in wild-type cells and a strain lacking cytoplasmic exosome activity (*ski7Δ*). This analysis revealed that *GFP-RZ* mRNA was unstable in wild-type cells decaying with a half-life of approximately 2 min (Figure 1B; Figure S1). In contrast, *GFP-RZ* mRNA was stable in *ski7Δ* cells, with a half-life of 8 min (Figure 1C). Unadenylated *GFP-RZ* mRNA is therefore present in the cytoplasm, where it is degraded by the cytoplasmic exosome.

Nonsense Codon-Containing Unadenylated mRNA Is Targeted for Rapid Degradation

It has been shown that *GFP-RZ* mRNA levels are low and not further decreased by the introduction of a PTC (Baker and Parker,

2006; Dower et al., 2004). Our above results indicate that, in wild-type cells, *GFP-RZ* mRNA is indeed unstable and that further destabilization of the mRNA by the presence of a PTC might have escaped detection. We therefore reasoned that destabilization of an unadenylated mRNA by NMD might be observed when the contribution of the cytoplasmic exosome to the decay of the mRNA is removed.

We measured decay rates of *GFP(PTC)-RZ* mRNA containing a PTC at codon 67 (Baker and Parker, 2006) in wild-type and *ski7Δ* cells. In contrast to the stabilization of *GFP-RZ* mRNA in *ski7Δ* cells, *GFP(PTC)-RZ* mRNA was unstable in both wild-type and *ski7Δ* strains (Figures 1E and 1F). Importantly, in *ski7Δ* cells, *GFP(PTC)-RZ* mRNA stability was reduced compared to *GFP-RZ* mRNA (2 min versus 8 min; Figures 1C and 1F), indicating that normal and premature translation termination events are distinguishable in the absence of a poly(A) tail.

Unadenylated mRNAs Harboring a PTC Are Targets for NMD

One explanation for *GFP(PTC)-RZ* mRNA instability in *ski7Δ* cells is that it is degraded by the NMD pathway while *GFP-RZ* mRNA is not. We therefore tested if rapid degradation of *GFP(PTC)-RZ* mRNA required the NMD machinery. Specifically, we measured decay of *GFP(PTC)-RZ* mRNA in a mutant yeast strain lacking both Ski7p and an essential component of the NMD machinery, Upf1p (Leeds et al., 1991).

Analysis of *GFP(PTC)-RZ* RNA revealed significant stabilization of the mRNA in *ski7Δupf1Δ* cells (half-life, 6.4 min; Figure 1G). In contrast, turnover of *GFP-RZ* mRNA was essentially unaffected by deletion of *UPF1* (Figures 1C and 1D). Thus, mRNA destabilization caused by the introduction of a PTC observed in *ski7Δ* cells was reversed by inactivation of the NMD pathway. The presence of an mRNA poly(A) tail is therefore not required for distinguishing a normal stop codon from a PTC by the NMD surveillance machinery.

The experiments described above utilize the well-characterized *GFP-RZ* reporter to evaluate decay of unadenylated mRNA (Baker and Parker, 2006; Dower et al., 2004). To ensure our results were not restricted to this heterologous reporter, we analyzed yeast *HIS3* harboring a hammerhead ribozyme 55 nt downstream of the natural stop codon. As shown in Figure 2, *HIS3-RZ* mRNA in *ski7Δ* cells was destabilized by introduction of a PTC (compare Figures 2C and 2F; Figure S1), and rapid turnover of the PTC-containing mRNA required a functional NMD pathway (compare Figures 2F and 2G). Thus, targeting of an unadenylated nonsense mRNA to NMD is not limited to the *GFP* reporter and also can occur for yeast mRNA lacking a poly(A) tail. While detection of the destabilization of unadenylated mRNA by a PTC required that cytoplasmic exosome activity be eliminated, these results demonstrate that the NMD machinery is capable of substrate recognition independent of a poly(A) tail.

Pab1p Is Not Required for Destabilization of PTC-Containing mRNA

Our findings with unadenylated mRNAs indicate that an mRNA poly(A) tail is not required for NMD in yeast. An association between PAB1 and an mRNA may, however, occur independently of the poly(A) tail. Indeed, interactions between PAB1, eIF4G,

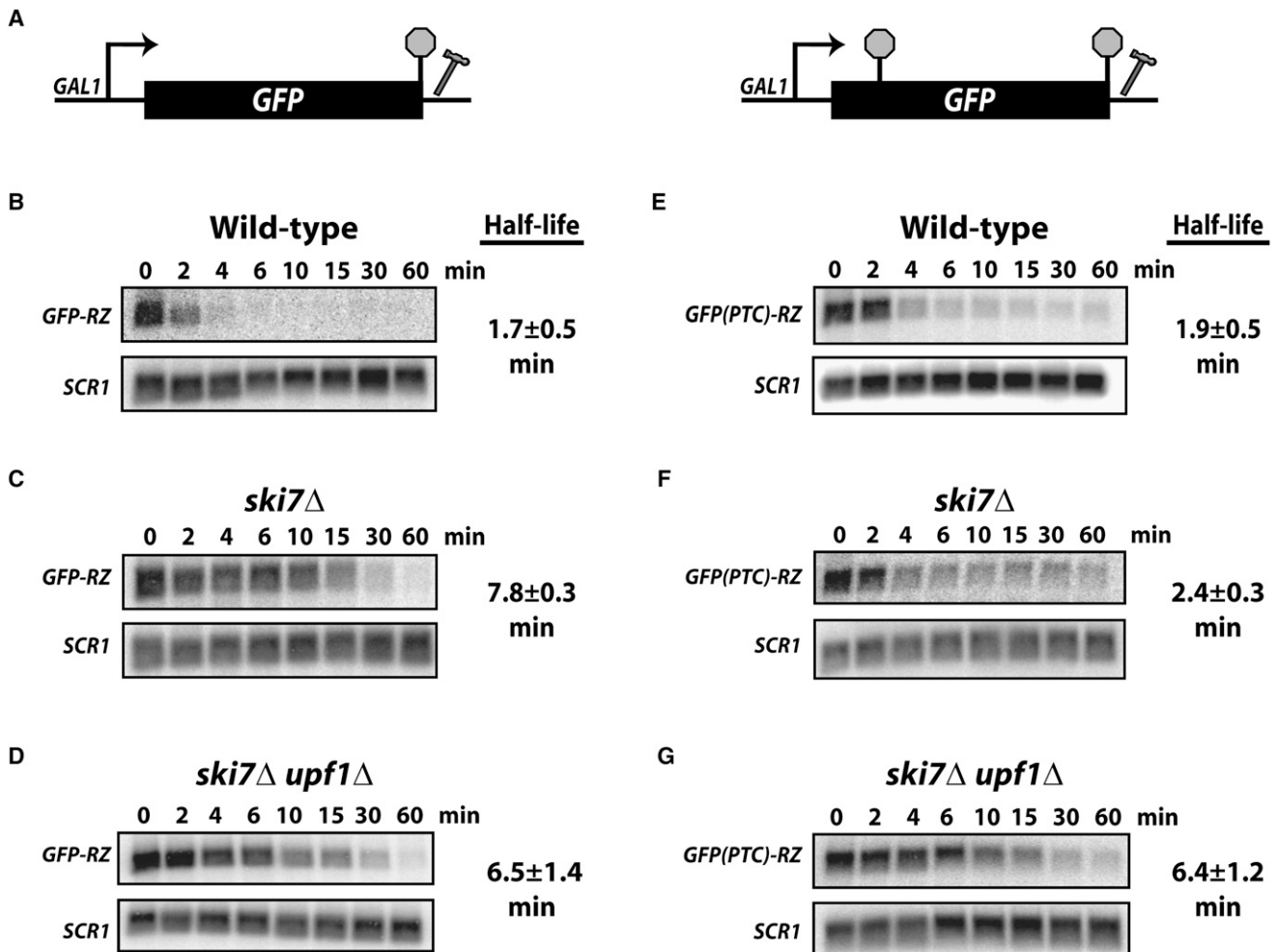


Figure 1. Unadenylated GFP(PTC)-RZ mRNA Is Targeted for NMD

(A) Schematic of GFP-RZ and GFP(PTC)-RZ reporter genes. Natural and premature stop codons (stop signs) and location of the hammerhead ribozyme directly 3' of the GFP ORF are depicted. GFP-RZ and GFP(PTC)-RZ mRNA stability was determined by transcriptional shut-off analysis in wild-type cells (B and E); a mutant lacking cytoplasmic exosome activity, *ski7*Δ (C and F); and cells lacking both Ski7p and Upf1p (D and G). RNA isolated at various times after inhibition of reporter gene transcription (min) was analyzed by northern blot and probed for GFP mRNA and SCR1 RNA (loading control). mRNA half-lives are the average ± standard deviation of four independent experiments.

and eRF3 are well characterized (reviewed in Mangus et al., 2003). Therefore, to determine whether PAB1 itself is necessary for recognition of an mRNA by NMD, we evaluated levels of *PGK1* reporter mRNA in yeast cells lacking Pab1p. Deletion of *PAB1* is lethal, but inviability can be suppressed by a variety of secondary mutations, including deletion of *RRP6* (Dunn et al., 2005).

Levels of *PGK1* reporter mRNA harboring a PTC at several positions within the ORF (Figure 3A) were evaluated in wild-type and *pab1*Δ*rrp6*Δ cells. In wild-type, mRNAs harboring a nonsense codon were less abundant relative to wild-type *PGK1* mRNA, and the decrease in nonsense mRNA was successively less dramatic as the PTC was positioned further 3' within the *PGK1* ORF, as previously reported (Figure 3B; Figure S2; Cao and Parker, 2003; Peltz et al., 1993). Importantly, destabilization of the PTC-containing *PGK1* mRNA in wild-type cells was dependent upon a functional NMD pathway (K.E.B. and R. Parker, unpublished data). Analysis of reporter mRNAs in *pab1*Δ*rrp6*Δ

cells revealed the relative abundance of *PGK1* mRNAs to be essentially identical to levels observed for wild-type (Figure 3C). Specifically, RNA levels were decreased for *PGK1* mRNAs harboring PTCs, and the decrease correlated with the position of the PTC within *PGK1*. Our findings indicate that PTC-containing *PGK1* mRNA is distinguished from wild-type mRNA in the absence of Pab1p.

We ruled out an independent effect of the *rrp6*Δ allele on NMD through analysis of *PGK1* reporter mRNA in *pab1*Δ*rrp6*Δ cells complemented with *PAB1*. We demonstrate that destabilization of PTC-containing *PGK1* mRNA was maintained in these cells (Figure S3). We further analyzed NMD in a second yeast suppressor strain deleted for *PAB1*. In *pab1*Δ*spb8*Δ cells (Boeck et al., 1998), nonsense and wild-type *PGK1* mRNA levels resembled those observed in both wild-type and *pab1*Δ*rrp6*Δ cells (Figure 3D). Thus, PTC-containing mRNAs are detected and destabilized in yeast cells in the absence of Pab1p.

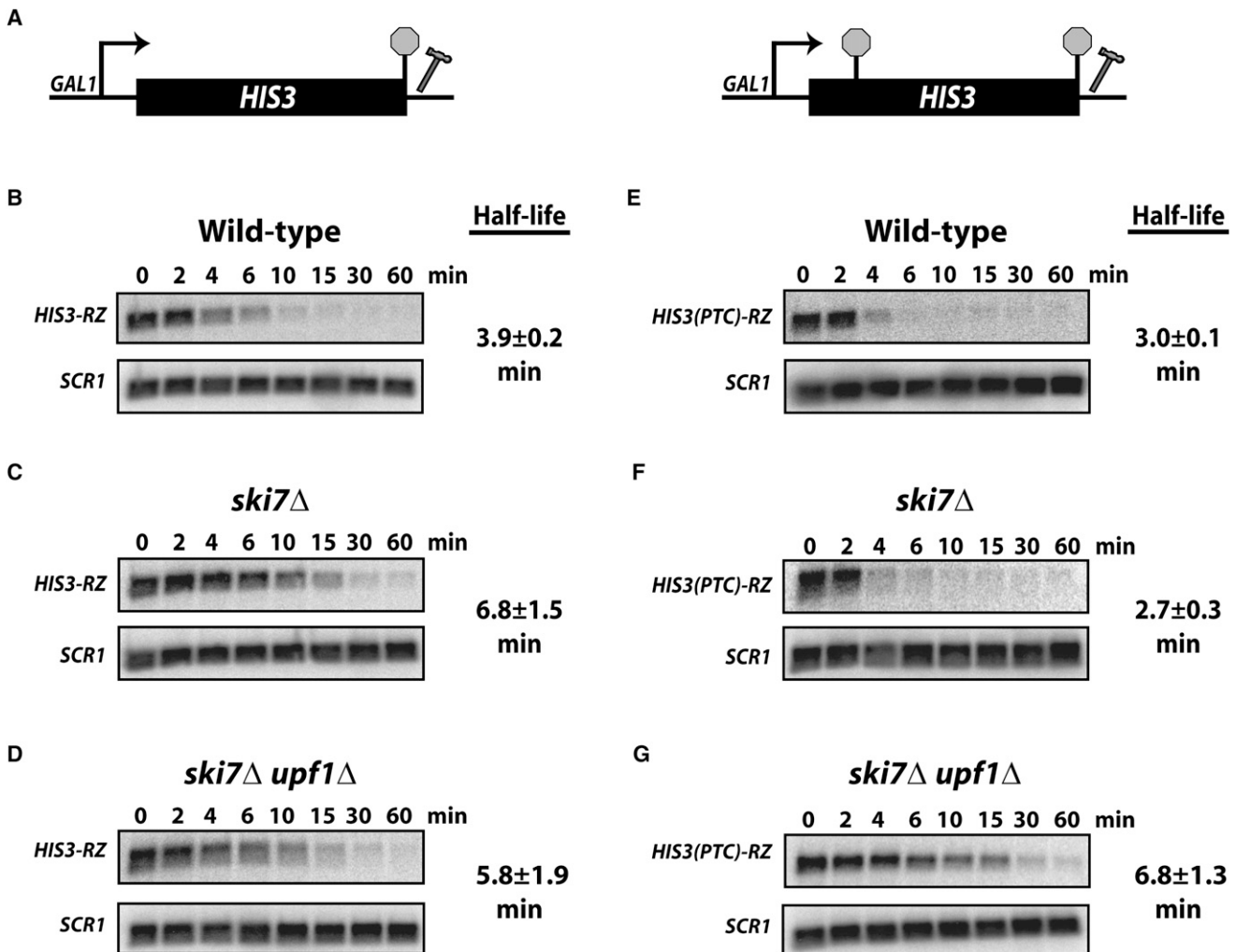


Figure 2. Unadenylated *HIS3(PTC)-RZ* mRNA Is Targeted for NMD
Stability of *HIS3-RZ* and *HIS3(PTC)-RZ* mRNA was determined as described in Figure 1.

Reduction of PTC-Containing mRNA in the Absence of Pab1p Requires the NMD Pathway

To determine if decreased RNA abundance of nonsense-containing *PGK1* mRNAs in *pab1Δ* mutants was a consequence of NMD, we measured RNA levels in *pab1Δrrp6Δ* and *pab1Δspb8Δ* strains that also harbored a lesion in *UPF1*. In *pab1Δrrp6Δupf1Δ* and *pab1Δspb8Δupf1Δ* cells, nonsense *PGK1* mRNA levels were similar to wild-type *PGK1* mRNA (Figures 4A and 4B; see Supplemental Data). These data demonstrate that the reduction in PTC-containing mRNA levels observed in the *pab1Δ* cells requires a functional NMD pathway and that substrates for NMD are efficiently recognized in the absence of Pab1p.

As a second measure of NMD in cells lacking PAB1, we analyzed levels of *CYH2* pre-mRNA, an endogenous NMD target in yeast (He et al., 1993). We observed low levels of *CYH2* pre-mRNA in wild-type and *pab1Δrrp6Δ* cells (Figure 4C). In contrast, *CYH2* pre-mRNA in *pab1Δrrp6Δupf1Δ* mutants was elevated. We conclude that *CYH2* pre-mRNA is targeted for NMD

in the absence of Pab1p. Importantly, *CYH2* mRNA and wild-type *PGK1* mRNA were similarly stable despite the absence of Pab1p or a functional NMD pathway (Figure 4C). Therefore, in the absence of PAB1, the NMD machinery effectively discriminates between normal and nonsense-containing mRNAs.

DISCUSSION

Here we used ribozyme-cleaved reporter mRNA to evaluate the requirement of an mRNA poly(A) tail for NMD in yeast (Dower et al., 2004; Baker and Parker, 2006; Meaux and van Hoof, 2006). We show that unadenylated mRNA can be destabilized by introduction of a PTC and that mRNA instability requires the NMD factor Upf1p (Figures 1 and 2). We further demonstrate that, in yeast lacking the poly(A) tail binding protein, PAB1, mRNAs harboring a PTC are recognized and their levels reduced by the NMD machinery (Figures 3 and 4). Caponigro and Parker (1995) similarly demonstrated that *PGK1* mRNA with a PTC at codon 22 is less stable than wild-type *PGK1* mRNA in *pab1Δspb2Δ*

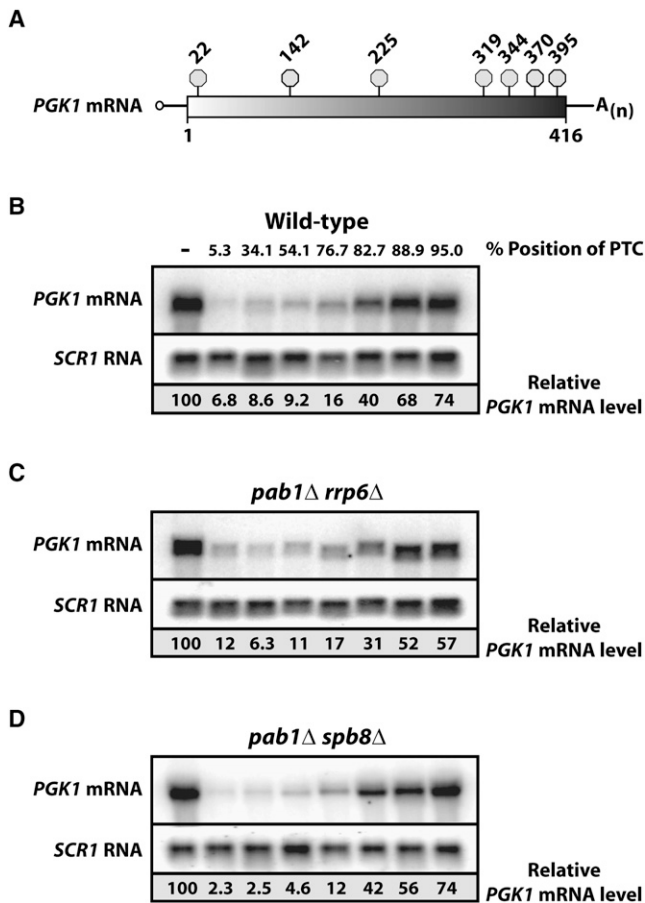


Figure 3. Nonsense-Containing *PGK1* mRNA Is Destabilized in the Absence of PAB1

(A) Schematic of reporter mRNA highlighting positions within the *PGK1* ORF (box) of premature nonsense codons (stop signs). Northern blot analysis of steady-state *PGK1* reporter mRNA in wild-type (B), *pab1Δrrp6Δ* (C), or *pab1Δspb8Δ* (D) cells. PTC location indicated as percent position into *PGK1* ORF. RNA levels were normalized to *SCR1* RNA and shown as percent level relative to *PGK1* mRNA terminating at the natural stop codon for experiment shown; results for multiple analyses are shown in Figure S2.

cells but did not address whether mRNA destabilization was due to NMD. Our findings show that the ability to discriminate between a normal and premature translation termination event can occur independently of an mRNA poly(A) tail or PAB1.

The faux UTR model for recognition of nonsense-containing mRNAs posits that translation termination at a PTC is intrinsically aberrant due to the failure of the terminating ribosome to engage in stabilizing interactions with the mRNA 3'UTR (Amrani et al., 2006). According to the model, stabilizing signals are communicated to the ribosome by the proximal mRNP that includes the poly(A) tail and PAB1. An important tenet of this model is that a stop codon will be recognized as normal only if translation termination occurs sufficiently close to the poly(A) tail and its bound PAB1, and, therefore, in the absence of these elements, ribosomes terminating at a natural stop codon would fail to engage in the stabilizing interactions and be targeted for NMD. We find that unadenylated mRNAs terminating at a natural stop codon

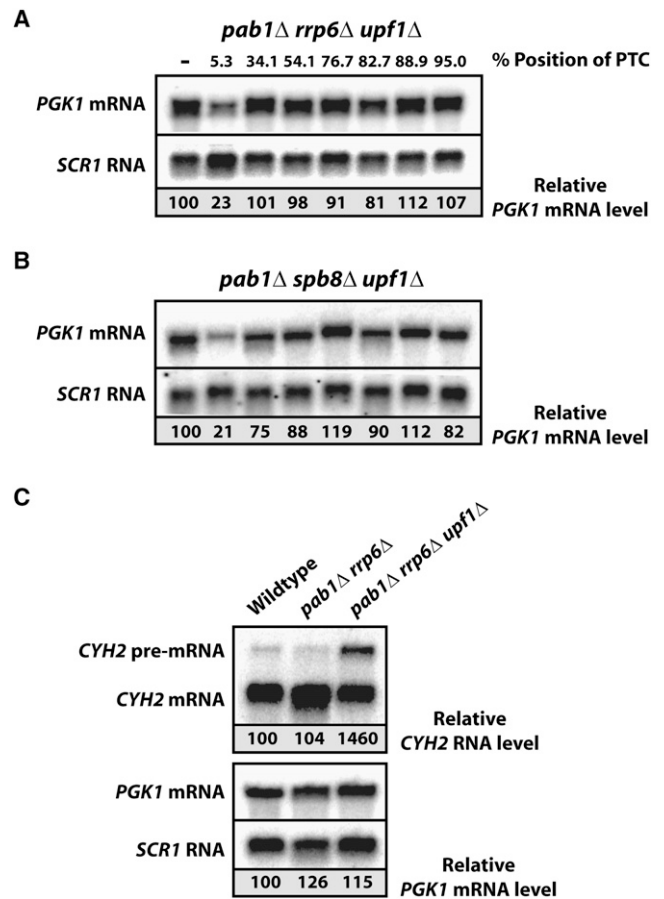


Figure 4. Degradation of Nonsense-Containing mRNA in the Absence of Pab1p Requires a Functional NMD Pathway

PGK1 reporter levels were determined by northern blot analysis of RNA from *pab1Δrrp6Δupf1Δ* (A) and *pab1Δspb8Δupf1Δ* (B). RNA levels were normalized to *SCR1* RNA loading control and shown as percent level relative to *PGK1* mRNA void of a PTC for the experiment shown; results for multiple analyses are shown in Figure S2. (C) Northern blot analysis of endogenous *CYH2* RNA and *PGK1* reporter mRNA levels in wild-type, *pab1Δrrp6Δ*, and *pab1Δrrp6Δupf1Δ* cells. *CYH2* pre-mRNA levels are normalized to *CYH2* mRNA, while *PGK1* mRNA levels are normalized to *SCR1* RNA. Both are indicated as percent level relative to abundance in wild-type.

are not stabilized by inactivation of the NMD pathway in either wild-type or *ski7Δ* cells (Baker and Parker, 2006; Figure 1 and Figure 2C versus Figure 2D). Moreover, normal *PGK1* and *CYH2* mRNA are not targeted to NMD in the absence of PAB1 (Figure 4C). Therefore, transmission of a positive signal from PAB1 to the terminating ribosome is required neither for the stability of a “normal” mRNA nor for its ability to escape NMD.

Our findings are in conflict with interpretations of tethered function analysis used to support the faux UTR model. Tethering of PAB1 to mRNA downstream and proximal to a PTC is sufficient to stabilize an NMD substrate in both yeast and *Drosophila* (Amrani et al., 2004; Behm-Ansmant et al., 2007). Based on these findings, it has been interpreted that proximity of PAB1 to the PTC leads to redefinition of the premature termination event as normal and that PAB1 is critical for signaling proper translation termination. Our findings, however, demonstrate that PAB1 is

dispensable for normal and aberrant translation termination to be distinguished and necessitates reevaluation of this interpretation. Interestingly, mRNA stabilization by tethered PAB1 is not specific to NMD substrates and was first demonstrated for a normal mRNA (Coller et al., 1998), illustrating that enhanced mRNA stability observed when PAB1 is tethered can occur independently of a role for PAB1 in NMD.

In *Drosophila* cells, nonsense-containing mRNA is stabilized by depletion of cytoplasmic PAB1 (PABPC1) by RNA interference (Behm-Ansmant et al., 2007). These data are in opposition to what is anticipated according to the faux UTR model (see above). These findings were, however, interpreted to indicate that PABPC1 was in some way required for NMD. The inconsistency between this conclusion and our findings may indicate a divergence in mechanism for NMD between flies and yeast. However, it is likely that depletion of PABPC1 impacts multiple steps in mRNA metabolism (e.g., 3' end formation, nucleocytoplasmic transport, translation, and stability) that might lead to stabilization of a PTC-containing mRNA indirectly. *Saccharomyces cerevisiae* strains suppressed for the essential function of PAB1 greatly facilitated analysis of PAB1 function in NMD by limiting these complications.

Our results establish that an interaction between the terminating ribosome and PAB1 does not determine whether a stop codon is perceived as normal or premature. Moreover, DSE elements previously defined as critical for NMD of PTC-containing *PGK1* also appear immaterial in our studies, as PTCs downstream of the characterized elements in *PGK1* mRNA still elicit NMD. While mRNAs with extended 3' UTRs in yeast, *Drosophila*, and mammals can be NMD substrates (Muhlrad and Parker, 1999; Behm-Ansmant et al., 2007; Buhler et al., 2006), not all mRNAs with long 3' UTRs are destabilized by the NMD pathway (Behm-Ansmant et al., 2007). The six nucleotides remaining downstream of the natural stop codon after cleavage of *GFP-RZ* mRNA further support the idea that NMD is not dependent on a 3' UTR generated by conventional 3' end formation (Figure 1; Baker and Parker, 2006). Finally, EJC complexes are not required for NMD in yeast, *C. elegans*, and *Drosophila*. Given the various second signals implicated in NMD substrate recognition, we predict that redundancy exists in the ability of aberrant mRNA to trigger NMD, although we can not exclude the possibility that additional elements necessary for NMD substrate discrimination remain to be uncovered. Future research evaluating the importance of coding region sequence and length, and features of the elongating polypeptide or ribosome itself in NMD, are ongoing.

EXPERIMENTAL PROCEDURES

Strains

ski7Δ, *upf1Δ*, and *ski7Δupf1Δ* yeast are isogenic to wild-type BY4741 (Open Biosystems). The *ski7Δupf1Δ* mutant was constructed by crossing *ski7Δ::HYG* (Wilson et al., 2007) to *upf1Δ::NEO* and sporulating.

Wild-type, *pab1Δrrp6Δ*, and *pab1Δspb8Δ* yeast strains have been described (Cao and Parker, 2003; Dunn et al., 2005). *yKB300* (*pab1Δrrp6Δupf1Δ* [*PAB1*]) was generated by deleting *UPF1* in *pab1Δrrp6Δ* cells complemented with *pKB269* (*PAB1*⁺) by the method of Longtine et al. (1998). *yKB301* (*pab1Δrrp6Δupf1Δ*) was made by plating *yKB300* on media containing 5' fluoro-orotic acid to select for loss of *PAB1*⁺*URA3*⁺ plasmid. Loss of the *PAB1*

plasmid was confirmed by western blotting. *pab1Δspb8Δupf1Δ* (*yKB310*) cells were generated by deleting *UPF1* (Longtine et al., 1998).

Plasmids

GFP-RZ plasmid pAV298 contains 1.3 kbp *SpeI* and *XhoI* fragment of *GAL-GFP-RZ* (Dower et al., 2004) in pRS416 (Sikorski and Hieter, 1989). *GFP(PTC)-RZ* plasmid pAV339 is similarly derived from *pKB214* (Baker and Parker, 2006). *HIS3-RZ* has been described (Meaux and van Hoof, 2006). To generate *HIS3(PTC)-RZ* (pAV462), the sequence 5'-TATCTAAGAATCTAACA (PTC in bold) was inserted in the *NdeI* site of *HIS3-RZ*.

Plasmids for wild-type *PGK1* (pRP469) and PTCs at codon positions 22, 142, 225, and 319 have been described (Cao and Parker, 2003), while PTCs at codon positions 344, 370, and 395 were created by site-directed mutagenesis of pRP469 (K.E.B. and R. Parker, unpublished data).

RNA Analysis

Steady-state RNA levels were measured from cells grown in SC-URA+ 2% galactose/1% sucrose at 24°C and harvested at OD₆₀₀ = 0.4–0.5. For RNA decay measurements, yeast strains harboring *GFP-RZ* reporter plasmids were grown at 30°C in SC-URA + 2% galactose to mid-log phase. Media were replaced with SC-URA + 4% glucose and culture aliquots removed over time. RNA was extracted and blotted by standard methods. Northern blots were probed with ³²P 5' radio-labeled oligonucleotides specific for *GFP* (5'-GCTGTTACAACTCAAGAAGGACCATGTGG-3'), *HIS3* (5'-CTACCACGCTCTGGAAAGTGCCTCATCCA-3'), *PGK1* (oRP121; Decker and Parker, 1993), *CYH2* (5'-CCATACCTCTACCACGGGGTGCTTTCTGTGCTTACCG-3'), or the RNA of the signal recognition particle (*SCR1* RNA; 5'-GTCTAGCCCGAGGAGG-3'). RNA levels were quantified using a STORM phosphorimager (GE Healthcare).

Supplemental Data

Supplemental Data include supplemental text, Supplemental Experimental Procedures, four figures, and Supplemental References and can be found with this article online at <http://www.molecule.org/cgi/content/full/29/1/134/DC1/>.

ACKNOWLEDGMENTS

GAL1-GFP-RZ plasmid was provided by Michael Rosbash (Brandeis University, Waltham, MA), polyclonal antibodies to ribosomal protein L5 by John Woolford (Carnegie Mellon University, Pittsburgh, PA), and *pab1Δrrp6Δ* and *pab1Δspb8Δ* yeast by Charles Cole (Dartmouth Medical School, Hanover, NH). We thank Tim Nilsen, Jo Ann Wise, Jonatha Gott, Jeff Coller, and members of the Coller and van Hoof laboratories for critical reading of the manuscript. Funding was provided from the Pew Scholarship program in the Biomedical Sciences and the National Institutes of Health (GM069900) to A.v.H. and by Case Western Reserve University to K.E.B.

Received: June 12, 2007

Revised: September 14, 2007

Accepted: October 18, 2007

Published: January 17, 2008

REFERENCES

- Amrani, N., Ganesan, R., Kervestin, S., Mangus, D.A., Ghosh, S., and Jacobson, A. (2004). A faux 3'-UTR promotes aberrant termination and triggers nonsense-mediated mRNA decay. *Nature* 432, 112–118.
- Amrani, N., Sachs, M.S., and Jacobson, A. (2006). Early nonsense: mRNA decay solves a translational problem. *Nat. Rev. Mol. Cell Biol.* 7, 415–425.
- Baker, K.E., and Parker, R. (2004). Nonsense-mediated mRNA decay: terminating erroneous gene expression. *Curr. Opin. Cell Biol.* 16, 293–299.
- Baker, K.E., and Parker, R. (2006). Conventional 3' end formation is not required for NMD substrate recognition in *Saccharomyces cerevisiae*. *RNA* 12, 1441–1445.

- Behm-Ansmant, I., Gatfield, D., Rehwinkel, J., Hilgers, V., and Izaurralde, E. (2007). A conserved role for cytoplasmic poly(A)-binding protein 1 (PABPC1) in nonsense-mediated mRNA decay. *EMBO J.* 26, 1591–1601.
- Boeck, R., Lapeyre, B., Brown, C.E., and Sachs, A.B. (1998). Capped mRNA degradation intermediates accumulate in the yeast *spb8-2* mutant. *Mol. Cell. Biol.* 18, 5062–5072.
- Buhler, M., Steiner, S., Mohn, F., Paillusson, A., and Muhlemann, O. (2006). EJc-independent degradation of nonsense immunoglobulin- μ mRNA depends on 3' UTR length. *Nat. Struct. Mol. Biol.* 13, 462–464.
- Cao, D., and Parker, R. (2003). Computational modeling and experimental analysis of nonsense-mediated decay in yeast. *Cell* 113, 533–545.
- Caponigro, G., and Parker, R. (1995). Multiple functions for the poly(A)-binding protein in mRNA decapping and deadenylation in yeast. *Genes Dev.* 9, 2421–2432.
- Coller, J.M., Gray, N.K., and Wickens, M.P. (1998). mRNA stabilization by poly(A) binding protein is independent of poly(A) and requires translation. *Genes Dev.* 12, 3226–3235.
- Culbertson, M.R., and Leeds, P.F. (2003). Looking at mRNA decay pathways through the window of molecular evolution. *Curr. Opin. Genet. Dev.* 13, 207–214.
- Decker, C.J., and Parker, R. (1993). A turnover pathway for both stable and unstable mRNAs in yeast: evidence for a requirement for deadenylation. *Genes Dev.* 7, 1632–1643.
- Dower, K., Kuperwasser, N., Merrih, H., and Rosbash, M. (2004). A synthetic A tail rescues yeast nuclear accumulation of a ribozyme-terminated transcript. *RNA* 10, 1888–1899.
- Dunn, E.F., Hammell, C.M., Hodge, C.A., and Cole, C.N. (2005). Yeast poly(A)-binding protein, Pab1, and PAN, a poly(A) nuclease complex recruited by Pab1, connect mRNA biogenesis to export. *Genes Dev.* 19, 90–103.
- Frischmeyer, P.A., and Dietz, H.C. (1999). Nonsense-mediated mRNA decay in health and disease. *Hum. Mol. Genet.* 8, 1893–1900.
- Gatfield, D., Unterholzner, L., Ciccarelli, F.D., Bork, P., and Izaurralde, E. (2003). Nonsense-mediated mRNA decay in *Drosophila*: at the intersection of the yeast and mammalian pathways. *EMBO J.* 22, 3960–3970.
- Gonzalez, C.I., Ruiz-Echevarria, M.J., Vasudevan, S., Henry, M.F., and Peltz, S.W. (2000). The yeast hnRNP-like protein Hrp1/Nab4 marks a transcript for nonsense-mediated mRNA decay. *Mol. Cell* 5, 489–499.
- He, F., Peltz, S.W., Donahue, J.L., Rosbash, M., and Jacobson, A. (1993). Stabilization and ribosome association of unspliced pre-mRNAs in a yeast *upf1* mutant. *Proc. Natl. Acad. Sci. USA* 90, 7034–7038.
- He, F., Li, X., Spatrick, P., Casillo, R., Dong, S., and Jacobson, A. (2003). Genome-wide analysis of mRNAs regulated by the nonsense-mediated and 5' to 3' mRNA decay pathways in yeast. *Mol. Cell* 12, 1439–1452.
- Kuzmiak, H.A., and Maquat, L.E. (2006). Applying nonsense-mediated mRNA decay research to the clinic: progress and challenges. *Trends Mol. Med.* 12, 306–316.
- Leeds, P., Peltz, S.W., Jacobson, A., and Culbertson, M.R. (1991). The product of the yeast *UPF1* gene is required for rapid turnover of mRNAs containing a premature translational termination codon. *Genes Dev.* 5, 2303–2314.
- Lelivelt, M.J., and Culbertson, M.R. (1999). Yeast *Upf* proteins required for RNA surveillance affect global expression of the yeast transcriptome. *Mol. Cell. Biol.* 19, 6710–6719.
- Longtine, M.S., McKenzie, A., 3rd, Demarini, D.J., Shah, N.G., Wach, A., Brachat, A., Philippsen, P., and Pringle, J.R. (1998). Additional modules for versatile and economical PCR-based gene deletion and modification in *Saccharomyces cerevisiae*. *Yeast* 14, 953–961.
- Longman, D., Plasterk, R.H., Johnstone, I.L., and Caceres, J.F. (2007). Mechanistic insights and identification of two novel factors in the *C. elegans* NMD pathway. *Genes Dev.* 21, 1075–1085.
- Mangus, D.A., Evans, M.C., and Jacobson, A. (2003). Poly(A)-binding proteins: multifunctional scaffolds for the post-transcriptional control of gene expression. *Genome Biol.* 4, 223 Published online July 1, 2003. 10.1186/gb-2003-4-7-223.
- Maquat, L.E. (2004). Nonsense-mediated mRNA decay: splicing, translation and mRNP dynamics. *Nat. Rev. Mol. Cell Biol.* 5, 89–99.
- Meaux, S., and van Hoof, A. (2006). Yeast transcripts cleaved by an internal ribozyme provide new insight into the role of the cap and poly(A) tail in translation and mRNA decay. *RNA* 12, 1323–1337.
- Medghalchi, S.M., Frischmeyer, P.A., Mendell, J.T., Kelly, A.G., Lawler, A.M., and Dietz, H.C. (2001). *Rent1*, a trans-effector of nonsense-mediated mRNA decay, is essential for mammalian embryonic viability. *Hum. Mol. Genet.* 10, 99–105.
- Mendell, J.T., Sharifi, N.A., Meyers, J.L., Martinez-Murillo, F., and Dietz, H.C. (2004). Nonsense surveillance regulates expression of diverse classes of mammalian transcripts and mutes genomic noise. *Nat. Genet.* 36, 1073–1078.
- Muhrad, D., and Parker, R. (1994). Premature translational termination triggers mRNA decapping. *Nature* 370, 578–581.
- Muhrad, D., and Parker, R. (1999). Aberrant mRNAs with extended 3' UTRs are substrates for rapid degradation by mRNA surveillance. *RNA* 5, 1299–1307.
- Oliveira, C.C., and McCarthy, J.E. (1995). The relationship between eukaryotic translation and mRNA stability. A short upstream open reading frame strongly inhibits translational initiation and greatly accelerates mRNA degradation in the yeast *Saccharomyces cerevisiae*. *J. Biol. Chem.* 270, 8936–8943.
- Peltz, S.W., Brown, A.H., and Jacobson, A. (1993). mRNA destabilization triggered by premature translational termination depends on at least three cis-acting sequence elements and one trans-acting factor. *Genes Dev.* 7, 1737–1754.
- Pulak, R., and Anderson, P. (1993). mRNA surveillance by the *Caenorhabditis elegans* *smg* genes. *Genes Dev.* 7, 1885–1897.
- Rehwinkel, J., Letunic, I., Raes, J., Bork, P., and Izaurralde, E. (2005). Nonsense-mediated mRNA decay factors act in concert to regulate common mRNA targets. *RNA* 11, 1530–1544.
- Sikorski, R.S., and Hieter, P. (1989). A system of shuttle vectors and yeast host strains designed for efficient manipulation of DNA in *Saccharomyces cerevisiae*. *Genetics* 122, 19–27.
- Tarpey, P.S., Lucy Raymond, F., Nguyen, L.S., Rodriguez, J., Hackett, A., Vandeleur, L., Smith, R., Shoubridge, C., Edkins, S., Stevens, C., et al. (2007). Mutations in *UPF3B*, a member of the nonsense-mediated mRNA decay complex, cause syndromic and nonsyndromic mental retardation. *Nat. Genet.* 39, 1127–1133.
- van Hoof, A., and Green, P.J. (1996). Premature nonsense codons decrease the stability of phytohemagglutinin mRNA in a position-dependent manner. *Plant J.* 10, 415–424.
- Wang, J., Gudikote, J.P., Olivas, O.R., and Wilkinson, M.F. (2002). Boundary-independent polar nonsense-mediated decay. *EMBO Rep.* 3, 274–279.
- Weil, J.E., and Beemon, K.L. (2006). A 3' UTR sequence stabilizes termination codons in the unspliced RNA of Rous sarcoma virus. *RNA* 12, 102–110.
- Welch, E.M., and Jacobson, A. (1999). An internal open reading frame triggers nonsense-mediated decay of the yeast *SPT10* mRNA. *EMBO J.* 18, 6134–6145.
- Wilson, M., Meaux, S., and van Hoof, A. (2007). A genomic screen in yeast reveals novel aspects of nonstop mRNA metabolism. *Genetics* 177, 773–784.
- Zhang, J., Sun, X., Qian, Y., LaDuca, J.P., and Maquat, L.E. (1998a). At least one intron is required for the nonsense-mediated decay of triosephosphate isomerase mRNA: a possible link between nuclear splicing and cytoplasmic translation. *Mol. Cell. Biol.* 18, 5272–5283.
- Zhang, J., Sun, X., Qian, Y., and Maquat, L.E. (1998b). Intron function in the nonsense-mediated decay of β -globin mRNA: indications that pre-mRNA splicing in the nucleus can influence mRNA translation in the cytoplasm. *RNA* 4, 801–815.