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Transcriptional Termination Enhances Protein Expression in Human Cells

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SUMMARY

Transcriptional termination of mammalian RNA polymerase II (Pol II) requires a poly(A) (pA) signal and, often, a downstream terminator sequence. Termination is triggered following recognition of the pA signal by Pol II and subsequent pre-mRNA cleavage, which occurs either at the pA site or in transcripts from terminator elements. Although this process has been extensively studied, it is generally considered inconsequential to the level of gene expression. However, our results demonstrate that termination acts as a driving force for optimal gene expression. We show that this effect is general but most dramatic where weak or noncanonical pA signals are present. We establish that termination of Pol II increases the efficiency of pre-mRNA processing that is completed posttranscriptionally. As such, transcripts escape from nuclear surveillance.

INTRODUCTION

We recently presented a dissection of the events that lead to mammalian RNA polymerase II (Pol II) termination (West et al., 2008). During the termination process, the poly(A) (pA) signal is recognized by Pol II and transcripts are cleaved to present an uncapped substrate for 5’→3’ exonucleases (Kaneko et al., 2007; Kim et al., 2004; West et al., 2004). Degradation of the trailing transcript precedes termination, where the Pcf11 protein may play a key role (Luo et al., 2006; West and Proudfoot, 2008; Zhang and Gilmour, 2006). At least two closely related termination pathways exist that differ in the primary nascent RNA cleavage event, which depends on the downstream terminator (West et al., 2008). Some terminators act to pause Pol II, and in this case cleavage at the pA site acts as the 5’→3’ exonuclease entry site and precedes termination. Transcripts from other terminators, such as that downstream of the human β-globin gene, are cotranscriptionally cleaved directly over the terminator sequence (Dye and Proudfoot, 2001). In this case, pA site cleavage occurs on transcripts subsequently released from the template DNA after Pol II has terminated.

Many aspects of pre-mRNA processing and transcription are known to influence gene expression (Proudfoot et al., 2002). Transcripts are capped at their 5’ ends to protect them from 5’→3’ degradation; the splicing reaction competes with degradation pathways, which target unspliced transcripts (Bousquet-Antonelli et al., 2000); and 3’ end processing is important, because transcripts that fail to be cleaved and polyadenylated properly are retained in the nucleus and degraded (Hilleren et al., 2001; Milligan et al., 2005; Saguez et al., 2008; Vodala et al., 2008). The most obvious way that transcription impacts on gene expression levels is through the rate of Pol II initiation, which can be modulated by combinations of promoter or enhancer strength and trans-activating factors (Kadonaga, 2004). Elongation rate may also determine gene expression patterns by influencing alternative splicing (Cramer et al., 1997). Failed termination on a gene can impair the expression of downstream genes by reducing the accessibility of the promoter to Pol II (Gregex et al., 2000). This process, known as transcriptional interference, is particularly relevant in lower eukaryotes, as they often have closely spaced genes. Whereas transcriptional interference reduces the expression of the downstream gene, failure to terminate transcription of the upstream gene is not thought to affect its own expression. Furthermore, it may be of little relevance in higher eukaryotes where most genes are positioned far apart. Significantly, we now show that transcriptional termination on a gene is required for its own optimal expression.

RESULTS

The β-Globin Terminator Enhances Gene Expression

To analyze the effect of termination on gene expression, we used the well-characterized human β-globin gene. Two plasmids were employed (Figure 1A): one containing the β-globin gene and its terminator sequence (βTERM) and one without the terminator (βΔTERM), the absence of which dramatically reduces termination efficiency (Dye and Proudfoot, 2001). In both cases, transcription is driven by the HIV promoter, transactivated by Tat. HeLa cells were transfected with βTERM or βΔTERM along with a cotransfection control plasmid encoding the adenovirus VA RNA. To measure β-globin mRNA expression, nuclear and cytoplasmic mRNA was analyzed using real-time PCR analysis (Figure 1A). In the presence of the terminator element (βTERM), levels of both nuclear and cytoplasmic β-globin mRNA were enhanced. We previously observed little difference in β-globin mRNA levels from these constructs, using probe-based RNA mapping techniques (Gromak et al., 2006). We suspect that β-globin mRNA was in excess of the probe level used in these experiments, and tested this assumption by using a large excess of probe to analyze β-globin mRNA by northern blot (Figure 1B).
This experiment also revealed an enhancing effect of Pol II termination.

We next analyzed the effect of termination on the levels of β-globin protein. HeLa cells were transfected with βTERM or βΔTERM and a control plasmid expressing an HA-tagged protein (RBM21) which measures transfection efficiency. Following this, β-globin and RBM21 proteins were detected by western blotting (Figure 1C). Similar levels of RBM21 protein were detected in each case, demonstrating equal transfection efficiency. However, 10-fold more β-globin protein was detected in the βTERM protein sample as compared to the βΔTERM sample. We note that this is a greater effect than seen at the mRNA level, which may reflect additional translational regulation. These data indicate a positive function for termination in gene expression.

On βΔTERM, Pol II does not terminate efficiently and so may reduce new rounds of initiation (and gene expression) by reading around the plasmid and back into the promoter sequence, causing transcription interference. To measure interference, we performed hybrid selection nuclear run-on (NRO) analysis (Dye and Proudfoot, 1999) on HeLa cells transfected with βΔTERM and VA (Figure 1D). Radiolabeled nascent transcripts were hybridized to a biotinylated probe complementary to the U3 region of the HIV promoter. U3 is upstream of the promoter (P) region and therefore only transcribed by Pol II that fails to terminate and reads around the plasmid. Selection of the RNA hybrids with streptavidin-coated magnetic beads purifies transcripts continuous with the U3 region, which include P transcripts resulting from readthrough transcription. P transcripts deriving from new rounds of initiation will not be selected (see diagram). Selected transcripts (S) and those that escaped selection (NS) were hybridized to separate filters containing antisense M13 DNA probes. The majority of U3 signal was in the selected fraction, demonstrating efficient selection. Even so, most P signal was not selected, showing that it mainly derives from new rounds of initiation and not from readthrough transcription. Importantly, we controlled against RNA degradation as a cause for the appearance of P signal in the NS fraction (see Figure S1 available online). We repeated the experiment on βTERM transfected HeLa cells (Figure 1D) and no U3 transcripts were selected, presumably because termination prevents readthrough transcription into the U3 sequence. Quantitation of the P signals in the NS βTERM and βΔTERM fractions, relative to VA, revealed that transcription interference only reduces initiation to 67%. Consequently, only 33% of the P signal is due to transcriptional readthrough. This result was also confirmed by analysis of linear templates (Figure S2). Together, these data exclude the possibility that a transcriptional interference effect accounts for the changes in protein and mRNA levels.

Enhancement of Gene Expression Is a General Function of Terminators

We next analyzed the effect of three other terminator elements on gene expression: the mouse serum albumin (MSA) terminator

Figure 1. The β-Globin Terminator Enhances Gene Expression

(A) The upper diagram shows βTERM. Promoter (arrow), exons (white box), pA signal (pA), and terminator (TERM) are shown. Distances between the pA site and terminator and the length of the terminator are shown. The lower diagram shows β-globin mRNA and the primers used for reverse transcription (dT) and real-time PCR (e2f/e3r) detection. The graph shows the relative level of nuclear and cytoplasmic β-globin mRNA from βTERM and βTERM samples, after equalizing to VA levels. mRNA levels were set at 1 for βTERM. Error bars show standard deviation from the mean (SDM).

(B) Northern blot analysis of cytoplasmic RNA from βTERM and βΔTERM samples. mRNA levels are shown (βTERM is given a value of 1). SDM is shown.

(C) Western blot analysis of HeLa cells transfected with βTERM or βΔTERM as well as the RBM21 expression construct. β-globin and RBM21 proteins are indicated. Quantitation is shown where βTERM is given a value of 1.

(D) Hybrid selection NRO analysis of HeLa cells transfected with βTERM or βΔTERM as well as VA. Diagrams show U3 and P regions of the HIV promoter. The selection probe (black) selects U3 transcripts and promoter (P) transcripts that result from readthrough transcription (left diagram). P transcripts resulting from newly initiated Pol II are not selected (right diagram). The top data panels show transcripts not selected by probe (NS) and the lower panels show selected (S) transcripts. NRO M13 probes are shown above the relevant slot. Percent initiation is shown and given a value of 100% for βTERM. M is an empty M13 vector that shows background signal. SDM is shown.

Enhancement of Gene Expression Is a General Function of Terminators

We next analyzed the effect of three other terminator elements on gene expression: the mouse serum albumin (MSA) terminator
Termination Enhances Gene Expression Irrespective of the pA Signal Used

The other cis-acting sequence required for termination is the pA signal (Whitelaw and Proudfoot, 1986). It is generally thought that the rate of processing at the pA site correlates with termination efficiency and is a key determinant of gene expression levels (Edwards-Gilbert et al., 1993). We explored the effects of the β-globin terminator element in the presence of pA signals that are processed relatively inefficiently. We replaced the β-globin pA signal in βTERM and βΔTERM with either the MSA or the human PMScl100 pA signal, forming ATERM, AΔTERM, PMTERM, and PMΔTERM. We have shown that the MSA pA signal is inefficient (West et al., 2006b) and that the PMScl100 pA signal contains an AUUAAA sequence instead of the consensus AAUAAA hexamer, which would be predicted to reduce its efficiency.

To compare the relative efficiencies of the β-globin, MSA, and PMScl100 pA signals, we performed a pA site competition assay on three constructs containing either of the three test pA signals followed by a synthetic pA signal (SPA) (Figure 3A). The SPA is only processed if the competing upstream site is relatively weak. HeLa cells were transfected with the three competition constructs (called βSPA, MSApSPA, and PMScl100pSPA) and cytoplasmic RNA was isolated. Processing at the proximal test pA site and the distal SPA was then quantitated by RT-PCR. As compared to βSPA, 7- to 10-fold more processing at the SPA was observed when the MSA or the PMScl100 pA signal was positioned upstream. This result confirms our previous data demonstrating that MSA pA signal is weak (West et al., 2006b) and also shows that the PMScl100 pA signal is relatively weaker than the β-globin signal. Termination was then analyzed on ATERM, AΔTERM, PMTERM, and PMΔTERM using NRO (Figure 3B). As expected, this is inefficient on AΔTERM and PMΔTERM shown by the high signals over probes A and U3, which detect transcripts from Pol II that fails to terminate. Surprisingly, termination was very efficient on both ATERM and PMTERM, as shown by the low A and U3 signals. Thus, in this system, the β-globin terminator element promotes efficient termination irrespective of pA signal strength.

Next, we analyzed nuclear and cytoplasmic β-globin mRNA in HeLa cells transfected with ATERM, AΔTERM, PMTERM, or PMΔTERM (Figure 3C). We observed ~4-fold more nuclear and ~8-fold more cytoplasmic β-globin mRNA from ATERM as compared to AΔTERM and 10- to 15-fold more nuclear and...
cytoplasmic β-globin mRNA in PMTERM samples as compared to PMΔTERM samples. A substantial increase in protein levels was also observed (Figure 3D). These experiments reveal that termination can enhance gene expression even more in the presence of weak pA signals.

The effects of the β-globin terminator on gene expression from weak and strong pA signals were then directly compared. HeLa cells were transfected with βΔTERM, βTERM, AΔTERM, or ATERM and nuclear and cytoplasmic β-globin mRNA was analyzed (Figure 3E). Comparison of βΔTERM and AΔTERM samples revealed similar levels of nuclear mRNA, but levels of cytoplasmic mRNA were lower for AΔTERM, consistent with the weaker MSA pA. However, both nuclear and cytoplasmic levels of β-globin mRNA were similar in βTERM and ATERM samples, albeit much greater than with inefficient termination. Again, these results were confirmed at the protein level (Figure 3F). Thus, the β-globin terminator enhances gene expression from the MSA pA signal more than for the β-globin pA signal. As such, mRNA levels correlate more with termination efficiency than pA signal strength.

The above result was unexpected, because it has been suggested that gene expression correlates with pA signal strength (Edwalds-Gilbert et al., 1993). These data are rationalized by our recent observation that mammalian Pol II termination requires cleavage of nascent RNA, either within terminator transcripts or at the pA site (West et al., 2008). In the former case, pA site cleavage is not necessary for the termination process. Therefore, the inefficient MSA or PMSc100 pA signals do not reduce the efficiency of Pol II termination. This predicts that weak pA signals will only inhibit termination when pA site cleavage is solely

Figure 3. Termination Enhances Gene Expression Irrespective of the pA Signal Used

(A) HeLa cells were transfected with constructs containing the β-globin (ipA), MSA (MSApA), or PMSc100 (PMSc100pA) pA signals upstream of the SPA. Diagrams show the primers used for reverse transcription (dT) and PCR of proximal (e3f/e3r) or distal (SPA/pAR) signals. pA signal strength was determined as a ratio of mRNA processed at either the proximal (P) or distal (D) pA signal. ipA is given a value of 1. Error bars show SDM.

(B) NRO analysis of HeLa cells transfected with ATERM, ATERM, or PMTERM. M13 probes are shown above the relevant slot and their position on the plasmid is shown in the diagram. Relative termination was quantitated by dividing the signal over readthrough probes A and U3 by those for probes P, B3, and B4. Values are set to 1 for AΔTERM and PMTERM.

(C) RT-PCR analysis of nuclear and cytoplasmic β-globin mRNA from HeLa cells transfected with βΔTERM or ATERM (left blot) and PMΔTERM or PMTERM (right blot). β-globin and RBM21 control proteins are indicated and quantitated.

(D) Western blot analysis of β-globin and RBM21 proteins in HeLa cells transfected with AΔTERM or ATERM. The lower panel on the left-hand side was exposed for longer, given the lower levels of β-globin present. SDM is shown.

(E) RT-PCR analysis of nuclear and cytoplasmic β-globin mRNA from HeLa cells transfected with βΔTERM, βTERM, or ATERM. Primers are as in Figure 1A. Values for the ΔTERM constructs are set at 1. Error bars show SDM.

(F) Western blot analysis of β-globin and RBM21 proteins in HeLa cells transfected with AΔTERM or ATERM. Primers are as in Figure 1A. Error bars show SDM.

(G) NRO analysis of AMA4. M13 probe positions are shown in (B). The table shows quantitation (performed as for [B]) of the experiment and, for comparison, others on βTERM, βΔTERM, βMAZ4, AΔTERM, and ATERM. SDM is shown.

(H) Western blot analysis of β-globin and RBM21 proteins in HeLa cells transfected with AΔTERM or AMA4. SDM is shown.
Termination Dramatically Enhances Erythropoietin Expression

The data so far show that Pol II termination is required for optimal \( \beta \)-globin expression. We next analyzed the effects of Pol II termination on the expression of a different human gene, erythropoietin (EPO). EPO does not contain a recognizable pA signal and instead uses an AAGAAC hexamer (Lin et al., 1985). This would not normally be expected to function, considering that single mutations in the AAUAAA hexamer are often enough to inactivate 3' end processing (Sheets et al., 1990). Nevertheless, polyadenylated species were previously observed corresponding to use of this site (Lin et al., 1985), and we confirmed its use in our system by 3' RACE (data not shown). Given the strong effects of termination on gene expression from weak pA signals, EPO provides a valuable further test of our findings.

EPO was cloned into \( \beta D \)TERM and \( \beta \)TERM in place of the human \( \beta \)-globin gene, still retaining the HIV promoter, forming E\( \Delta \)TERM and ETERM, respectively. These constructs and VA were transfected into HeLa cells and efficient termination on ETERM was confirmed by using a previously described RT-PCR assay that recapitulates NRO analysis (West and Proudfoot, 2008). Nuclear RNA was isolated and reverse transcribed with primer RTr, and cDNA was real-time PCR amplified using primers RTr and RTf to detect RNA beyond the terminator region (Figure 4A). We observed 10-fold less readthrough RNA for ETERM (indicative of efficient termination) as compared to E\( \Delta \)TERM.

We next analyzed nuclear and cytoplasmic EPO mRNA from HeLa cells transfected with E\( \Delta \)TERM or ETERM together with

Figure 4. Termination Enhances Erythropoietin Expression
(A) The diagram shows ETERM with nomenclature as for \( \beta \)TERM. The graph shows RT-PCR quantitation of readthrough RNA in HeLa cells transfected with E\( \Delta \)TERM or ETERM. The value for E\( \Delta \)TERM was set at 1. Primers used for reverse transcription (RTr) and PCR (RTf/RTr) are shown in the diagram. Error bars show SDM.
(B) RT-PCR quantitation of nuclear and cytoplasmic EPO mRNA from HeLa cells transfected with E\( \Delta \)TERM or ETERM as well as VA. Values for E\( \Delta \)TERM are set at 1. The diagrams show primers used for reverse transcription (dT) and PCR (EPf/EPr). Error bars show SDM.
(C) Western blot analysis of EPO protein secreted from HeLa cells transfected with E\( \Delta \)TERM or ETERM. EPO and the RBM21 control protein are indicated. Quantitation is shown (E\( \Delta \)TERM is given a value of 1).
(D) RT-PCR quantitation of readthrough RNA from C\( \beta D \)TERM, C\( \beta \)TERM, CE\( \Delta \)TERM, or CETERM. The \( \Delta \)TERM samples are given a value of 1. Primers are as in (A). Error bars show SDM.
(E) RT-PCR analysis of cytoplasmic \( \beta \)-globin and EPO mRNA in HeLa cells transfected with C\( \beta \)TERM, C\( \beta D \)TERM, CE\( \Delta \)TERM, or CETERM. The \( \Delta \)TERM samples are given a value of 1. The diagrams show primers for reverse transcription (dT) and PCR (e2f/e3r for \( \beta \)-globin and EPf/EPr for EPO). Error bars show SDM.
(F) Western blot analysis of EPO protein from HeLa cells transfected with CE\( \Delta \)TERM or CETERM. EPO and the RBM21 control protein are indicated and quantitated. SDM is shown.
VA (Figure 4B). As for β-globin, we observed much higher levels of nuclear (8-fold) and cytoplasmic (15-fold) EPO mRNA in the ETERM sample as compared to ΔTERM. Levels of secreted EPO protein were also much greater (over 30-fold) for ETERM as compared to ΔTERM (Figure 4C). These data match our finding that termination dramatically enhances gene expression from weak pA signals and provides evidence that transcriptional termination is generally required for optimal gene expression.

Termination Enhances Gene Expression Independent of the Promoter

We next investigated whether termination enhances gene expression in the context of a different promoter with distinct properties to the HIV promoter. The CMV promoter was chosen as it supports high levels of transcription but induces relatively slow elongation (Cramer et al., 1997). This contrasts with the HIV promoter, activated by Tat, which promotes highly processive Pol II elongation (Nogues et al., 2002; Parada and Roeder, 1996). We replaced the HIV promoter in βTERM, βΔTERM, ETERM, and ΔTERM with the CMV promoter, to form CβTERM, CβΔTERM, CETERM, and CEΔTERM, respectively. We analyzed termination efficiency on these constructs using RT-PCR to quantitate readthrough RNA (Figure 4D). There was little difference in the level of readthrough RNA between CβTERM and CβΔTERM, which indicates that termination is equally efficient on these constructs. However, we observed significantly less readthrough RNA from CETERM as compared to CEΔTERM, indicating a difference in termination efficiency. These data suggest that termination of the β-globin gene does not require a terminator when transcription is from the CMV promoter, but a terminator is still required to terminate transcription of the EPO gene. Because CMV-driven transcription is relatively non-processive, the strong β-globin pA signal is sufficient to induce termination without additional elements. In contrast, the non-canonical EPO pA signal still requires the terminator sequence for efficient termination.

If termination enhances gene expression, the above results predict that no difference in expression would be observed between CβTERM and CβΔTERM because the process is equally efficient on each construct. However, expression should be greater for CETERM than for CETERM, because the terminator element improves termination on this construct. This was tested by transfecting HeLa cells with CβTERM, CβΔTERM, CETERM, or CETERM and measuring cytoplasmic mRNA levels (Figure 4E). Little difference in β-globin mRNA levels was observed between the CβTERM and CβΔTERM samples, showing that the β-globin terminator does not further enhance gene expression if termination is already efficient. Crucially, 2.5-fold more EPO mRNA was recovered from the CETERM samples as compared to CETERM, and a corresponding increase in EPO protein expression was observed (Figure 4F). These effects on EPO expression are not as great as those observed with the HIV promoter. However, this is in line with the fact that the difference in termination between CETERM and CETERM is also less than that between ETERM and ΔTERM (compare Figures 4A and 4D). We conclude that, whereas a terminator is not always necessary for termination when transcription is driven by the CMV promoter, it remains the case that an enhanced termination process increases gene expression. This important observation shows that increasing termination enhances gene expression irrespective of the promoter.

Mechanism of Increased Gene Expression by Efficient Pol II Termination

We sought to establish why termination enhances gene expression. Figure 1D shows that inefficient termination only reduces transcription initiation efficiency, through interference effects, by 33%. Yet, we demonstrate a significantly larger reduction of gene expression, implying that synthesized transcripts are degraded before they are translated. The surveillance mechanism is likely to be a nuclear process because nuclear mRNA levels are affected.

It is well established that Pol II transcription and pre-mRNA processing are coupled (Proudfoot et al., 2002). Because removal of terminator elements inhibits gene expression, we tested whether pre-mRNA splicing efficiency is also reduced. β-globin pre-mRNA splicing was analyzed in HeLa cells transfected with βTERM and βΔTERM (Figure 5A). To be confident that changes are due to termination, we also analyzed CβTERM and CβΔTERM, which share the same sequence differences as βTERM and βΔTERM but support similar levels of termination (Figure 4D). Nuclear RNA was reverse transcribed with dT to detect cleaved and polyadenylated transcripts, with primer l2r to detect unspliced transcripts or with pAR to detect transcripts not yet cleaved at the pA site. These cDNAs were amplified with primers e1f and e2r to detect spliced (S) and unspliced (US) RNA (Figure 5A). For the dT primed cDNA, only spliced RNA was detected in each case, indicating that the majority of cleaved and polyadenylated transcripts are also spliced. We next amplified the l2r and pAR cDNA with primers e1f and e2r to analyze the splicing status of pre-mRNAs. A higher ratio of spliced to unspliced transcripts was recovered from βTERM samples as compared to βΔTERM. Because the ratio of spliced and unspliced transcripts was similar for CβTERM and CβΔTERM, which both terminate equivalently, termination is likely to account for splicing differences between βTERM and βΔTERM. We next analyzed splicing of intron 2 using the same RNA samples. Because intron 2-retaining pre-mRNAs are more than 1 kilobase larger than spliced transcripts, primers spanning this region are susceptible to PCR competition. To circumvent this, intron 2-retaining and spliced transcripts were detected from the same pAR primed cDNA, using separate PCR primer pairs: e2f/e3r and e2f/l2r to detect spliced and unspliced transcripts, respectively (Figure 5B). There was a higher ratio of spliced to unspliced transcripts for βTERM compared to βΔTERM. Again, a similar ratio was observed for CβTERM and CβΔTERM. We conclude that termination enhances splicing of both β-globin gene introns.

A potential criticism of the above result could be that pre-mRNA is degraded in the βTERM sample more efficiently than for βΔTERM. This is unlikely, given the lack of change between CβTERM and CβΔTERM samples. Even so, we repeated our analysis on a further two constructs (βΔTERM1m and βTERM1m) which contain a mutated first intron (Figure 5C). This mutation prevents splicing but not termination (Dye and
Proudfoot, 1999), and so allows us to look at differences in the stability of the two pre-mRNAs. Only unspliced transcripts were observed in the analysis and the abundance of pAR and I2r primed cDNAs was unchanged, showing that these pre-mRNAs do not have significantly different stabilities.

The Effect of Termination on Pre-mRNA Splicing Is Posttranscriptional

The enhanced splicing as a result of termination suggests a posttranscriptional effect. We therefore analyzed cotranscriptional splicing on βTERM and ΔTERM using a modified NRO protocol to incorporate bromo-labeled UTP (brU) into nascent RNAs which were purified using a brU-specific antibody (Lin et al., 2008). We purified brU-labeled RNA from HeLa cells transfected with βTERM or ΔTERM and examined the levels of transcripts containing intron 1 and intron 2 (Figure 5D). Cotranscriptional splicing is expected to reduce the level of intron-containing RNAs that are recovered. cDNA was synthesized with primers e2r or e3r and PCR amplification was with the e1f/I1r or e2f/I2r primer pairs to detect intron 1 and intron 2, respectively. After subtracting the background, obtained from minus antibody controls, we observed little difference in the levels of intron 1 and intron 2 between the βTERM and ΔTERM samples. We also directly analyzed spliced exons 2 and 3 but recovered no above-background signal (data not shown and Figure S4). These data reveal little difference in the cotranscriptional splicing of βTERM and ΔTERM transcripts. The difference in the levels of spliced transcripts observed in total nuclear βTERM and ΔTERM samples is therefore likely to reflect posttranscriptional splicing as a result of termination.

The Exosome Degrades Some Transcripts When Termination Is Inefficient

We next asked what degrades the transcripts when termination is inefficient. To this end, we depleted the nuclear exosome subunit PMScl100 using RNA interference (RNAi). Western blot analysis of PMScl100 protein in cells that had been mock treated or transfected with PMScl100-specific siRNAs showed that levels were depleted by 2- to 3-fold (Figure 6A). Equal levels of actin were observed showing that loading was equivalent. These data were substantiated by quantitative RT-PCR analysis of PMScl100 mRNA, which was reduced to 38%. We observed a similar effect with a further two PMscl100-specific short hairpin RNAs (data not shown), which also resulted in similar phenotypes to those described below.

The effect of this depletion was tested in situations where termination and splicing are inefficient and for strong and weak pA signals.

Figure 5. Termination Enhances Pre-mRNA Splicing

(A) RT-PCR analysis of intron 1 splicing in HeLa cells transfected with βTERM, βΔTERM, CβTERM, or CΔTERM. The diagram shows positions of the primers used in this experiment. The primer used for cDNA synthesis is indicated in brackets beside each panel with the PCR primer pair indicated to its left. Unspliced (US) and spliced (S) products are indicated. Real-time PCR quantitation of the ratio of spliced to unspliced (S/US) is shown. SDM is shown.

(B) RT-PCR analysis of intron 2 in HeLa cells transfected with βTERM, βΔTERM, CβTERM, or CΔTERM. Primers are indicated as in (A). It should be noted that different cycle numbers were used for the separate PCR reactions. Real-time PCR quantitation of the ratio of spliced to unspliced (S/US) is shown. SDM is shown.

(C) RT-PCR analysis of pre-mRNA stability in HeLa cells transfected with βTERMm1 or βΔTERMm1. Primers are indicated as in (A). Real-time PCR quantitation is shown. SDM is shown.

(D) BrUNRO analysis of cotranscriptional splicing. The top diagrams show the procedure, where immunoprecipitation of brU (star) detects cotranscriptional splicing (right) or introns that are not spliced during transcription (left). The lower diagrams show the primers used for reverse transcription (e2r and e3r) and PCR (e1f/I1r and e2f/I2r) to detect intron 1 and 2, respectively. Quantitation shows the signal (set at 1 for βTERM) obtained after subtracting the minus antibody control value. Error bars show SDM.
transfected with βΔTERM or AΔTERM and levels of cytoplasmic β-globin mRNA were analyzed by RT-PCR (Figure 6B). We observed increased levels of cytoplasmic mRNA in PMScl100-depleted cells as compared to mock treated cells, identifying PMScl100 as part of the mechanism that suppresses gene expression when termination is inefficient. Interestingly, the effect of exosome depletion was greater for AΔTERM than for βΔTERM. This is in line with our finding that termination enhances gene expression to a greater degree for weaker pA signals. PMScl100 depletion has little effect on βTERM mRNA levels (West et al., 2006a), which is consistent with the termination process reducing the susceptibility of transcripts to degradation. Depletion of the cytoplasmic exonuclease Xrn1 had little effect on mRNA levels (data not shown), confirming a nuclear surveillance process.

We next determined the timing of degradation in relation to 3' end processing. Mock and PMScl100-depleted cells were transfected with AαTERM, and RNA samples were reverse transcribed with pAR (to detect uncleaved) or dT (to detect cleaved and polyadenylated RNAs). Subsequent PCR was with the e3f and e3r primer pair (Figure 6C). As before, PMScl100 depletion substantially increased the level of RNA cleaved at the pA site (dT primed). However, there was much less of an effect on uncleaved transcripts. These data show that PMScl100 targets AαTERM transcripts for degradation after cleavage at the pA site. Presumably, the exosome requires free RNA termini to degrade a transcript. For AΔTERM, and other cases where there is no terminator transcript cleavage, this is primarily provided by pA site cleavage. Where terminator transcripts are cleaved, we have shown this to provide additional targets for the exosome (West et al., 2006a).

Collectively, the above results show that inefficient termination promotes the degradation of transcripts by the exosome after pA site cleavage. These data predict that termination releases mRNA from this decay, which can exist close to transcription sites (Hilleren et al., 2001). We finally employed a technique that separates chromatin-associated transcripts from those released into the nucleoplasm (West et al., 2008). We included constructs with either strong or weak pA signals in the analysis. Nuclei were isolated from HeLa cells transfected with βΔTERM, AαTERM, βTERM, or ATERM. Primers are as in Figure 1A. The proportion of mRNA in each fraction is shown superimposed onto the levels of total nuclear β-globin mRNA obtained from the experiment shown in Figure 3E. Error bars show SDM.
of transcripts by termination enhances gene expression. The relevance of this observation to the enhanced gene expression is emphasized by the close correlation between the levels of released polyadenylated RNA and cytoplasmic mRNA (compare Figures 6D and 3E).

**DISCUSSION**

The data presented in this study show that termination releases transcripts from the DNA template, which promotes their processing and subsequent gene expression. Previous studies identified the pA signal as a key determinant of gene expression levels and termination efficiency (Edwards-Gilbert et al., 1993). Although consistent with these data, we show that weak pA signals have no effect on the termination process when the β-globin terminator is used in conjunction with the HIV promoter. This is presumably because cleavage of terminator transcripts obviates the need to cleave at the pA site by enabling termination to occur irrespective of pA signal strength. When termination is reliant on pA site cleavage, the strength of the pA signal determines its efficiency (Edwards-Gilbert et al., 1993; Gromak et al., 2006; Orozco et al., 2002).

Our studies show that the CMV promoter reduces the necessity for terminator elements, as termination on CjTERM and CjΔTERM is equivalent. However, a terminator element is still required to terminate transcription of the EPO gene when the CMV promoter is used. This could be accounted for by the differences in the EPO and β-globin pA signals. The strong β-globin pA signal is rapidly processed to drive efficient pA site-dependent termination on CjΔTERM. However, the EPO pA signal is not sufficiently strong to do the same on CEΔTERM so that, in this case, efficient Pol II termination depends on the terminator. A strong pA signal may permit Pol II termination to occur when transcription initiates from the CMV promoter, if elongation is slow enough to negate the need for a pause element. Such pause sites are normally needed for pA site cleavage-dependent termination when transcription is from the HIV promoter. In support of this being the case, CMV transcription promotes splicing patterns that are typical of slow elongation (Cramer et al., 1997). Furthermore, a higher percentage of β-globin exons are cotranscriptionally spliced when transcription is driven by the CMV promoter, as compared to when it is from the HIV promoter (Figure S4). These data suggest that Pol II is less processive when initiating at the CMV as compared to the HIV promoter, which is known to promote highly efficient elongation (Nogues et al., 2002; Parada and Roeder, 1996).

Our results show that a variety of unspliced pre-mRNA accumulates when Pol II termination is inefficient, suggesting an influence of termination on pre-mRNA processing. Data in Figure 5 suggest that many introns may not be removed until after termination. Indeed, it has been shown that artificial release of pre-mRNA from transcription sites can have a positive effect on splicing of β-globin gene transcripts (Bird et al., 2005). We have also shown that 3' end processing, another event with a robust connection to transcription, can also occur posttranscriptionally (West et al., 2008). The present study shows that when these processes occur after termination, the transcripts are less susceptible to exosome degradation. Effectively, termination promotes escape from a nuclear surveillance process by releasing transcripts from sites of synthesis, a theory substantiated by our finding of high levels of released transcripts upon termination (Figure 6D). Further evidence that termination may be involved in mRNA release comes from experiments in yeast which identify 3' end formation signals as important mediators of RNA tethering to transcription sites (Abruzzi et al., 2006). Unlike the situation in mammals, 3' end formation signals are often the sole termination sequences in yeast.

We show in these studies that gene expression can be greatly enhanced by transcriptional termination. As indicated in the model (Figure 7), we predict that Pol II release from the DNA template facilitates pre-mRNA processing and further allows pre-mRNA/mRNA to escape surveillance. Our findings may have wide-ranging implications for in vivo protein production. This may be especially true in situations where efficient protein expression is difficult or expensive to achieve. Efficient termination may also be required to optimize gene delivery for gene therapy applications. It seems likely that Pol II termination represents a key stage in maintaining high levels of gene expression.

**EXPERIMENTAL PROCEDURES**

**Nuclear Run-On Analysis**

NRO and hybrid selection NRO have previously been described (Ashe et al., 1997; Dye and Proudfoot, 1999). M13 probes were P, U3, and VA (Dye and Proudfoot, 1999), B3 and B4 (Ashe et al., 1997), and A (West et al., 2004). Template U3 selection probe was made by inserting an AvaI/PvuII restriction fragment, from βTERM, into pGEM4, and the upstream U3 probe was made by PCR amplification of βTERM with primers U3S' and U3T7. These clones were transcribed by SP6 and T7 polymerase (Dye and Proudfoot, 1999). The brUNRO protocol was performed as described (Lin et al., 2008).
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RT-PCR
cDNA was made using SuperScript III (Invitrogen), and 1 μl of the 20 μl reaction was analyzed by real-time PCR (10 pmol of each oligo, 1 μl of cDNA, 7.5 μl of SYBR green mix (QIAGEN), and water to a final volume of 15 μl) or semiquantitative PCR (Taq polymerase, Bioline) (1 μl of 10 mM dNTPs, 10 pmol of each primer, 1.5 mM magnesium chloride, 1 X manufacturer’s buffer). Experiments were quantitated after subtraction of values obtained from minus RT samples.

Western Blotting
Fifty percent of lysate from a confluent 5 cm dish of HeLa cells was used for analysis. For spotted EPO, 10–100 μl of culture media was used. Membranes were probed with anti-human β-globin (Santa Cruz Biotechnology) at 1:1000, anti-EPO (Santa Cruz Biotechnology) at 1:1000, anti-PMSc100 (Abcam) at 1:1000, and anti-actin (Sigma) at 1:1000 or anti-HA (Santa Cruz Biotechnology) at 1:1000. Secondary antibodies were anti-mouse (Sigma) at 1:2000 or anti-rabbit (Sigma) at 1:2000. Signals were detected with an ECL kit (GE Healthcare) and quantitated using ImageQuant software.

Northern Blotting
The protocol is available at http://www.narrykim.org/Northern_blot_analysis_for_microRNA.pdf. RNA samples were RNase H cleaved using primer 4.5 and dT. RNA was fractionated on a 6% gel and products were detected using 5'-32P-labeled e3r primer.

Transfections
Semiconfluent HeLa cells, in 5 or 10 cm plates, were transfected with 1–5 μg of reporter plasmid, 1–2 μg of VA plasmid, and 1.5 μg of Tat plasmid. Lipofectamine 2000 (Invitrogen) was used.

RNA Isolation
The procedures for isolating nuclear and cytoplasmic RNA (West and Proudfoot, 2008) and for separating nuclear RNA into chromatin-associated and released fractions (Dye et al., 2006) have been described.

Plasmids
Tat (Adams et al., 1988), VA (Dye and Proudfoot, 1999), and iTERM and iΔTERM (previously called iΔ5-7 and iΔ5-10) (Dye and Proudfoot, 2001); iMAZ4, iZAM4, and iMfMAZ4 (previously called pMAZ4, pZAM4, and pmMAZ4) (Gromak et al., 2006); and ATERM and iATerm (previously called iΔ5-10ApA and iΔ1b plasmids (West et al., 2006b) have all been described. ATERM was made by inserting a TERMS/TERMS' PCR product into a vector prepared by PCR amplification of iΔ5-10ApA using APP/RTf primers. PMfATERM and PMfTERM were made by inserting a PCR product, generated by PMf/PMf amplification of HeLa cell DNA, into vectors prepared by F/e3 PCR amplification of iATerm or iTERM, respectively. AMAZ4 was made by inserting an APf/APR PCR product into a vector generated by PCR amplification of iMAZ4 with the F/e3r primer pair. The EPO gene was amplified from HeLa cell genomic DNA using primers E5′/E3′. EΔTERM was made by inserting EPO into a vector prepared by PCR amplification of iΔTERM with primers TAR3' and RIT. ETERM was made by inserting EPO into a vector prepared by PCR amplification of iTERM using primers TAR3' and TERMS'. The RBM21 expression plasmid was a kind gift from Chris Norbury. RBM21 is a member of the recently discovered family of noncanonical poly(A) polymerases. The iPA and MSA competition clones are described elsewhere (West et al., 2006b). The PMSc100a competition clone was made by inserting a PMf/PMf PCR product into a vector made by PCR amplification of the iPA competition clone using primers SPAI and e3. For the CMV promoter constructs, the HIV promoter was removed by an Aval/Atfl digestion and the CMV promoter, obtained by BglII/HindIII digest of pCDNA3.1 (Invitrogen), was inserted. iTERMM1 and iATERMm1 were made by ligating a PCR product generated by pAR/TERMS' and pAR/RTf amplification of HIVIII/VS1-SAmut (Dye and Proudfoot, 1999).

RNA Interference
RNA interference of PMSc100 was previously described (West et al., 2006a).

Primers
Primer sequences are in Table S1.

SUPPLEMENTAL DATA
The Supplemental Data include four figures and one table and can be found with this article online at http://www.cell.com/molecular-cell/supplemental/S1097-2765(09)00035-5.

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