tRNA$^{\text{Sec}}$ is transcribed by RNA polymerase II in Trypanosoma brucei but not in humans

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ABSTRACT

Nuclear-encoded tRNAs are universally transcribed by RNA polymerase III (Pol-III) and contain intragenic promoters. Transcription of vertebrate tRNA$^{\text{Sec}}$ however requires extragenic promoters similar to Pol-III transcribed U6 snRNA. Here, we present a comparative analysis of tRNA$^{\text{Sec}}$ transcription in humans and the parasitic protozoa Trypanosoma brucei, two evolutionary highly diverged eukaryotes. RNAi-mediated ablation of Pol-II and Pol-III as well as oligo-dT induced transcription termination show that the human tRNA$^{\text{Sec}}$ is a Pol-III transcript. In T. brucei protein-coding genes are polycistronically transcribed by Pol-II and processed by trans-splicing and polyadenylation. tRNA genes are generally clustered in between polycistrons. However, the trypanosomal tRNA$^{\text{Sec}}$ genes are embedded within a polycistron. Their transcription is sensitive to $\alpha$-amanitin and RNAi-mediated ablation of Pol-II, but not of Pol-III. Ectopic expression of the tRNA$^{\text{Sec}}$ outside but not inside a polycistron requires an added external promoter. These experiments demonstrate that trypanosomal tRNA$^{\text{Sec}}$, in contrast to its human counterpart, is transcribed by Pol-II. Synteny analysis shows that in trypanosomatids the tRNA$^{\text{Sec}}$ gene can be found in two different polycistrons, suggesting that it has evolved twice independently. Moreover, intron-encoded tRNAs are present in a number of eukaryotic genomes indicating that Pol-II transcription of tRNAs may not be restricted to trypanosomatids.

INTRODUCTION

All eukaryotes have at least three RNA polymerases (Pol-I, Pol-II and Pol-III) that are specialized to transcribe different sets of genes (1). With few exceptions, Pol-I synthesizes the rRNAs whereas Pol-II produces mRNAs, small nuclear (sn) RNAs, small nucleolar (sno) RNAs and microRNAs. Nuclear encoded tRNAs, on the other hand, are believed to be exclusively and universally transcribed by Pol-III, which also synthesizes 5S rRNA, U6 snRNA and some other small RNAs.

Transcription of most eukaryotic tRNA genes does not require control sequences outside of the gene but depends on two intragenic promoter elements termed Box A and B. However, the tRNA that specifies selenocysteine (Sec)—the focus of our study—represents an exception. tRNA$^{\text{Sec}}$ mediates insertion of the rare amino acid Sec in response to a small number of UGA stop codons that have been recoded to Sec by the presence of a SECIS element in the 3' UTR of a mRNA (2,3). Sec-containing proteins, termed selenoproteins, occur in all three domains of life but during evolution have been lost in some clades such as fungi and plants. Transcription of tRNA$^{\text{Sec}}$ has so far only been studied in vertebrates, and in contrast to other tRNAs it was shown to depend on three upstream regulatory regions: the TATA box motif at $-30$, the PSE (proximal sequence element) located around position $-70$ and a distal AE (activator element) located further upstream (4–7). A consensus intragenic B box can still be found whereas a functional A box is absent (Supplementary Figure S3B). The PSE and AE promoter elements are not restricted to the tRNA$^{\text{Sec}}$ gene but also occur in spliceosomal snRNA genes that are either transcribed by Pol-III (U6 snRNA) or Pol-II (U1, U2, U4 and U5 snRNAs), respectively. The PSE and the AE are known to recruit the same set of basic transcription factors for either Pol-III or Pol-II transcribed genes (8,9).

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Thus, it is the presence or absence of the TATA box that determines which polymerase transcribes these genes. If the TATA box is absent the gene is transcribed by Pol-II whereas if it is present, such as in the case of the tRNA\textsuperscript{Sec} and U6 snRNA genes, it will be transcribed by Pol-III (10).

The notion that Pol-II and Pol-III independently transcribe distinct set of genes has recently been challenged. Chromatin immunoprecipitation studies have shown that in human cells Pol-II is physically associated with the upstream regions of the Pol-III transcribed U6 snRNA genes. Moreover, while U6 snRNAs were clearly transcribed by Pol-III their expression was inhibited by inactivation of Pol-II. More recently these results were confirmed by genome-wide study that showed that the association of Pol-II with the upstream region of Pol-III transcribed genes is not restricted to the U6 snRNA genes, but is also found for many other Pol-III transcribed genes, including tRNA genes. Furthermore, the study also showed that the same is true for many transcription factors that are usually associated with Pol-II transcription (12).

We have previously shown that the machinery and the mechanism of Sec-insertion into selenoproteins is conserved between mammals and the protozoan parasite Trypanosoma brucei (13). According to the recently revised eukaryotic phylogeny, eukaryotes are divided into six supergroups (14–15). Mammals and most of the popular model organisms such as yeast, Drosophila and nematodes belong to the supergroup of the Opisthokonta, whereas T. brucei is a representative of the supergroup of the Excavata. This suggests that the Sec-insertion machinery is conserved within eukaryotes. Thus, we wondered whether the same is true for the unusual way in which the tRNA\textsuperscript{Sec} is transcribed. Transcription in T. brucei shows some substantial differences when compared to other eukaryotes (16–18). Trypanosomes have orthologs of all three eukaryotic polymerases (19). However, in addition to tRNAs, Pol-I also transcribes the mRNA that code for the variant surface glycoproteins and for procyclins, the two major stage-specific surface proteins (20). Moreover, protein-coding genes are arranged in large clusters that are co-transcribed by Pol-II. Polycistronic transcription results in mRNA precursors that need to be processed into individual mature mRNAs, whereby the 5'-ends of mRNAs are formed by trans-splicing (21,22). Thus each open reading frame (ORF) of a polycistronic pre-mRNA has at least one 5'-splice acceptor site consisting of an AG dinucleotide that is preceded by a polypyrimidine tract of variable length. Both of these elements mediate the trans-splicing reaction in which a capped spliced leader (SL) sequence of 39 nt is added to the 5'-end of each mRNA [for review see (23)]. As a result, all mature mRNAs in T. brucei have an identical 39-nt SL-sequence at their 5'-end. To complete mRNA processing addition of a poly(A) tail is required.

There is no consensus polyadenylation site in the 3'-untranslated region, rather polyadenylation occurs within a short region 100–400 nt upstream of the trans-splice acceptor site of the downstream gene. As in other organisms trypanosome Pol-III transcribes tRNA genes, which contain intragenic box A and B promoter elements. Unlike in other organisms, all U snRNA genes are transcribed by Pol-III, and the A and B boxes of a few tRNA genes, in addition to promoting transcription of the tRNAs, also function as upstream promoter elements for the U3 and U6 snRNA genes as well as for the 7SL RNA gene. Interestingly, in these cases the tRNAs are transcribed in the opposite directions than the three genes mentioned above (24).

In this study we performed a comparative analysis of tRNA\textsuperscript{Sec} transcription in human cells and in T. brucei. We confirm that the human tRNA\textsuperscript{Sec} is transcribed by Pol-III. However, transcription of the tRNA\textsuperscript{Sec}, unlike the otherwise similar Pol-III-mediated transcription of the human U6 snRNA genes, does not seem to require Pol-II. Surprisingly and in contrast to all other tRNAs studied so far, transcription of the tRNA\textsuperscript{Sec} of T. brucei, is mediated by Pol-II, indicating that the mode of transcription of the tRNA\textsuperscript{Sec} is not conserved within eukaryotes.

**MATERIALS AND METHODS**

**Production of transgenic HeLa cells**

Human tRNA\textsuperscript{Sec} (Chr. 19, GeneID 7234) and tRNA\textsuperscript{Tyr} (accession M55612.1) with and without T-stretch insertion (Figure 1) were overexpressed in HeLa cells using the pGEM-T Easy Vector (Promega). Each tRNA gene was expressed carrying 600 bp of its own 5' and 300 bp of its own 3' flanking region. HeLa cells were grown at 37°C with 5% CO\textsubscript{2} in Dulbecco’s modified Eagle’s medium (DMEM, Invitrogen) supplemented with 10% FCS, 100 U/ml penicillin and 100 μg/ml streptomycin.

Transgenic cells were obtained by seeding 1.5 × 10\textsuperscript{5} HeLa cells each into six-well plates. Transfection was done the next day using 500 ng each of the tRNA expression plasmids mixed with 250 ng of the pcDNA3.1 plasmid (Invitrogen) containing an insert encoding HA-EGFP and 6 μl each of DreamFect (OZ Biosciences). One day later the efficiency of transfection (~60%) was checked by monitoring GFP expression and total RNA was isolated as described (25). The RNAi plasmids were generated by insertion of double-stranded oligonucleotides (19 bp in length) encoding short hairpin RNAs into the pSUPERpuro vector between the BglII and HindIII sites (OZ Biosciences). One day after the transfection, (26). Four RNAi constructs were produced: two of them were directed against either the sequence 5'TAAAGAAGGTGAAGACAA3' or the sequence 5'ACATAAGATCCCGAACA3' of the core subunit of human Pol-II (NM_000938.1) and two other ones targeting the core subunit of human Pol-III (NM_007055.2), either the region 5'GGAGGAAATCTCTCTCAGGAAA 3' or the region 5'ACGCTGAGAGTGAA3', respectively. Transgenic HeLa cells were obtained by seeding 2 × 10\textsuperscript{5} cells each into six-well plates. Transfection was done the next day using 400 ng of each of the RNAi plasmids and 4 μl each of DreamFect (OZ Biosciences). One day later the cells were put under antibiotic selection by addition of 1.5 μg/ml puromycin. After 2 days of selection the antibiotic was removed and
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Transcription in permeabilized T. brucei cells

Transcription was analyzed using T. brucei rhodesiense Ytat 1.1 maintained at 28°C in SM medium containing 10% fetal bovine serum. We used the Ytat 1.1 strain since the analysis of transcription in permeabilized cells was originally established in this strain. Lyssolecithin-permeabilized cells (27) were incubated with 32P-labeled UTP or CTP for 15 min at 28°C. Subsequently labeled RNA was isolated as described (25) and hybridized to denatured DNA spotted onto nitrocellulose membrane. Each spot contained 5 µg of DNA: the tRNA Sec gene and the tRNA Leu gene were cloned into pTZ18U, the U6 snRNA, the tubulin and the SL genes were prepared as described (27). Membranes were hybridized overnight at 68°C in an aqueous buffer (5× SET, 10× Denhardt’s, 1% SDS, 10 µg/ml yeast RNA), and then washed three times for 30 min each at 68°C in 2× SSC and 0.1% SDS. Blots were exposed to a PhosphorImager screen, developed and analyzed using OptiQuant software (Perkin Elmer).

Production of transgenic T. brucei cells

Pol-III activity was ablated by RNAi using a stem loop construct based on a pLew 100 (28) derivative containing the puromycin resistance gene (29). As insert we used a 480-bp fragment (nt 301–780) of the largest subunit of trypanosomal Pol-III (Tb10.70.4870). The RPB9 RNAi cell line allowing ablation of Pol-II activity was obtained from L. Vanhamme (30). Ectopic expression of tagged tRNA Sec and tRNA Met-i (Figure 4) was based on the same pLew100 derivative. The tagged tRNA genes were prepared by PCR mediated site directed mutagenesis. The tRNA Sec gene encoded on the shorter intergenic region (Figure 3) was expressed in the context of 308 nt of its own 5′-side was fused to 268 bp of the 5′-flanking region of a trypanosomal tRNA Leu. It has previously been shown that the tagged tRNA Met-i can efficiently be expressed in this genomic context (31). The inserts of all constructs were verified by sequencing. All transgenic cell lines are based on procyclic T. brucei 29-13 that was grown at 27°C in SDM-79 (32) supplemented with 15% FCS and the required antibiotics. Transformation, cloning and selection of transgenic cell lines were done as described (33).

RT-PCR analysis in T. brucei

RT analysis to determine the splice acceptor and polyadenylation sites was performed using the

Figure 1. An intragenic T-stretch abolishes transcription of full-length human tRNA Sec. (A) Predicted secondary structure of the human tRNA Tyr and tRNA Sec, respectively. Arrows indicate the positions corresponding to the 5′-half of the tRNA Tyr (pre-tRNA Tyr), the mature wild-type tRNA Tyr (wt-tRNATyr) and the abortive transcript corresponding to the 5′-half of the tRNA Tyr (pre-tRNA Tyr). The positions of the intron-containing tRNA Tyr (pre-tRNA Tyr) and the mature wild-type tRNA Tyr (wt-tRNATyr) and the abortive transcript corresponding to the 5′-half of the tRNA Tyr (pre-tRNA Tyr) are indicated. Right panel, same as in the left panel but analysis was done for the human tRNA Sec. The positions of the wild-type (wt-tRNA Sec) and the abortive transcript corresponding to the 5′-half of the tRNA Sec (short-tRNA Sec) are indicated. For the experiments on the left panel the cell line expressing the wild-type tRNA Tyr. The bottom panels serve as loading controls and show the ethidium bromide stained gel segment that contains the tRNAs.

after another 24 h of incubation total RNA was isolated as described above.

The relative RNAi-induced downregulation of Pol-II and Pol-III mRNAs when compared to the Pol-I transcribed 18S rRNA was quantified using real-time quantitative PCR (qPCR). One microgram of total RNA was reverse transcribed in 20 µl StrataScript 6.0 RT buffer containing 1 mM dNTPs, 300 ng random hexamers, 40 U RNasin (Promega), and 50 U StrataScript 6.0 reverse transcriptase (Stratagene) according to manufacturer’s protocol. Reverse transcribed material corresponding to 25 ng RNA was amplified using Brilliant® II Fast SYBR® Green QPCR Master Mix (Stratagene) and the following primers: for Pol II 5′ CCAGAGCTGGAGTATCCTAGTGTTTT3′ (forward) and 5′ TTAGCTAGCTTGGCCGTCTTACC3′ (reverse); for Pol III 5′ GCTGGCTCTGTCTACCTGCTAAC3′ (forward) and 5′ CTTGTAGCGGCCATTCA GCA3′ (reverse); 18S rRNA was detected using a commercial available TaqMan® Gene Expression Assay (Applied Biosystems, catalog no. 431-9413E) and Brilliant® II Fast QPCR Master Mix (Stratagene).
ImProm-II system (Promega) following the manufacturer's procedure. Primers for the 3'-RACE of the Tb09.160.1090 encoding cDNA were: 5'TTGAATTCGATTTGAGCACCTGCTTTTTTTTTTTTTTTTTT (1. PCR, reverse), 5'TTGAATTCGATTTGAGCACCTGCTTTTTTTTTTTTTTTTTT (2. PCR, reverse), 5'TAAGAGCTAGAAGCAGG3' (1. PCR, forward), 5'ACCAATTTCTATCCATTTACAC (2. PCR, forward). Primers for the 5'-RACE of the Tb09.160.1070 encoding cDNA: 5'TTGAATTCGATTTGAGCACCTGCTTTTTTTTTTTTTTTTTT (1. PCR, reverse), 5'TTGAATTCGATTTGAGCACCTGCTTTTTTTTTTTTTTTTTT (2. PCR, forward), 5'AAGAGCTAGAAGCAGG3' (1. PCR, forward), 5'TGCTACTCAGGAAGTTGCCG3' (2. PCR, forward), 5'TGCCATTATTAGAAACAGTTTCTGTAC3' (1. And 2. PCR forward).

Northern analysis

Denaturing polyacrylamide gels (Figures 1, 2, 4 and 6) were processed for northern blot analysis as described (34,35). The indicated 32P-5' end labeled oligonucleotides were used as probes (T. brucei: Tb, H. sapiens: Hs): 5' AC CAGCTGAGCTCATGGC3' (Tb-tRNA Sec), 5'TACGGGTTGAATCCCGCA3' (Tb-tagged tRNA Sec) 5'TAGCTCCTCGGCGGGTCCGAA3' (Tb-tRNA Ile), 5'TGCCCTTGAGCA3' (Tb-tagged tRNA Met/C0i), 5'TGCTACCAGCTGATCGC3' (Hs-tRNA Sec), 5'TGCCCTGCCGCGGGTTCGAA3' (Tb-SL RNA), 5'TACGGGTTGAATCCCGCA3' (Tb-tRNA Sec), 5'TGCTACCAGCTGATCGC3' (Hs-tRNA Sec), 5'TGCTACCAGCTGATCGC3' (Hs-U6 snRNA), 5'TGCCCTGCCGCGGGTTCGAA3' (Hs-U2 snRNA). Signals were quantitated as described above.

RESULTS

An intragenic T-stretch abolishes transcription of full-length human tRNA Sec

Transcription of vertebrate tRNA Sec and the multiple U6 snRNA genes (36) is very similar: both require a TATA box, the PSE and the AE and share several transcription factors. However, in the case of the tRNA Sec...
surprisingly little attention has been paid to the question whether it is transcribed by Pol-III. Early experiments showed that transcription of the tRNA\textsuperscript{Sec} is resistant to 1 μg/ml of α-amanitin suggesting that it is transcribed by Pol-III (4,6). However, it was not shown that under these conditions Pol-II-dependent transcription was inhibited. Moreover, it is known that short T-stretches act as termination signals for Pol-III. Consequently, tRNA genes are generally flanked at their 3'-end by short T-stretches. However, in case of the human tRNA\textsuperscript{Sec} the first T-stretch (T\textsubscript{4}) occurs only 45-nt downstream of the 3'-end of the gene. Finally, recent studies with human U6 snRNA have shown that even though its transcription is mediated by Pol-III, it also depends on active Pol-II (11). In summary, these observations underscore the complexity of tRNA\textsuperscript{Sec} and U6 snRNA transcription modes and prompted us to reinvestigate whether human tRNA\textsuperscript{Sec} is indeed transcribed by Pol-III. Practically this was achieved by using novel methods that for the most part were not available at the time the pioneering studies mentioned above were performed (4,6).

In order to identify the polymerase responsible for transcription of human tRNA\textsuperscript{Sec}, we designed a tRNA\textsuperscript{Sec} gene variant containing a Pol-III termination signal consisting of five thymidine residues at position 37 in the region of the tRNA that encodes the anticodon loop (Figure 1A). If Pol-III transcribes the variant tRNA\textsuperscript{Sec} transcription should prematurely terminate within the T-stretch, whereas if the tRNA is transcribed by Pol-II the full-length tRNA carrying the T-stretch insertion should be obtained. To show that the assay works as intended, we also designed a human tRNA\textsuperscript{Tyr} gene variant containing five thymidines at the same relative position as in the variant tRNA\textsuperscript{Sec} gene (Figure 1A). In the tRNA\textsuperscript{Tyr} gene, this position coincides with the 5'-end of its intron. Constructs containing the corresponding wild-type tRNA genes and their variants containing the synthetic T-stretch insertions were transfected into HeLa cells. Twenty-four hours later expression of the transgenes was analyzed by northern blotting. Overexpression of wild-type tRNA\textsuperscript{Tyr} gene resulted in the accumulation of large amounts of intron-containing precursor tRNA\textsuperscript{Tyr} and, to a lesser extent, of the spliced form (Figure 1B). The accumulation of precursor rather than mature tRNA\textsuperscript{Tyr} is most likely caused by overloading of the tRNA splicing machinery. Overexpressing the tRNA\textsuperscript{Tyr} variant, on the other hand, resulted in the accumulation of large amounts of a shorter fragment, whose size is consistent with a molecule representing the 5'-half of the tRNA\textsuperscript{Tyr}, extended by an unknown number of T residues derived from termination within the T-stretch insertion (Figure 1B), as expected for a Pol-III transcript. The analogous experiments were also done for the human tRNA\textsuperscript{Sec}. The extent of overexpression was less than what was observed for the tRNA\textsuperscript{Tyr}. However, also in this case the T-stretch containing tRNA\textsuperscript{Sec} variant gene led to the accumulation of a short fragment, whose length also corresponds to the expected length of the 5'-half of the tRNA\textsuperscript{Sec} carrying the T-stretch nucleotides. Furthermore, no band corresponding to the full length tRNA\textsuperscript{Sec} containing the added 5-nt long T-stretch was detected. These results show that human tRNA\textsuperscript{Sec} responds to a typical Pol-III termination signal and therefore suggest that it is transcribed by Pol-III.

**RNAi of Pol-III inhibits expression of human tRNA\textsuperscript{Sec}**

It recently became clear that both Pol-III and Pol-II are required for efficient expression of the human U6 snRNA genes (11). In order to analyze whether this might also be the case for the human tRNA\textsuperscript{Sec} gene, we performed RNAi experiments. HeLa cells were transfected with constructs allowing overexpression of short hairpin (sh) RNAs designed to induce RNAi-mediated ablation of the Pol-II or Pol-III core subunits, respectively. For each of the polymerases, the knockdown was performed independently with two shRNA expressing plasmids targeting different regions of the corresponding mRNAs. Following transfection, the cells were incubated for two days in the presence of puromycin in order to enrich for cells expressing the transgenic shRNAs. Figure 2A shows that, as expected, the Pol-II or Pol-III mRNA levels were specifically downregulated in the corresponding RNAi cell lines but not in cells transfected with a control plasmid. Pol-II and Pol-III are essential, and RNAi directed against the corresponding mRNAs is therefore expected to be lethal. Thus, RNA was isolated and analyzed 4 days after transfection at the time point when the cells were still completely viable. Figure 2 shows that ablation of Pol-II did neither affect the level of tRNA\textsuperscript{Sec} nor the one of tRNA\textsuperscript{Tyr}. However, consistent with the notion that both tRNAs are transcribed by Pol-III their levels dropped to ~40% in cell lines downregulated for Pol-III. As control for a Pol-II transcript we analyzed the levels of the U2 snRNA which were reduced to ~55% in the Pol-II RNAi cell lines but unaffected by ablation of Pol-III. Finally, we also analyzed the Pol-III transcribed U6 snRNA. Interestingly, its expression was reduced to ~45% in Pol-III RNAi cell lines and also by 25% in the Pol-II RNAi cells. This latter result supports the recent suggestion that while human U6 snRNA is transcribed by Pol-III, its expression also requires active Pol-II (11). Moreover, the results confirm that human tRNA\textsuperscript{Sec} is transcribed by Pol-III and suggest that, while there are many shared features between the transcription mode of the tRNA\textsuperscript{Sec} and the U6 snRNA, the requirement for an active Pol-II is not one of them.

**Unique tRNA\textsuperscript{Sec} gene loci in T. brucei**

Previous work has shown that the machinery and the mechanism of Sec-insertion into selenoproteins is conserved between mammals and *T. brucei* (13). This raises the question whether this conservation also extends to the transcription of tRNA\textsuperscript{Sec} genes. The large majority of trypanosomal tRNA genes occurs in clusters of two to five or more genes separated by short intergenic regions. Within clusters, tRNA genes can be arranged in head-to-head, tail-to-tail or head-to-tail orientations (34,37). Trypanosomal tRNA gene clusters are confined to genomic regions of at least 5 kb in length which are devoid of protein-coding genes (this is also true for the few tRNA genes that do not occur in clusters). Some,
but not all, tRNA gene-containing loci coincide with strand switch regions where the transcription of two polycistronic transcription units either converges or diverges (38). The *T. brucei* genome encodes two identical tRNA(sec) genes, which unlike all other tRNAs are found in the intergenic regions (1640 and 833 bp in length, respectively) between three adjacent protein-coding genes of a polycistronic transcription unit (Figure 3).

Sequence analysis indicates that the trypanosomal tRNA<sup>sec</sup> genes appear to lack consensus sequences for the internal A and B boxes, as well as any upstream Pol-III promoter elements. The peculiar genomic arrangement, together with the apparent absence of functional promoter elements, suggest that the trypanosomal tRNA<sup>sec</sup> genes might be transcribed as part of a polycistronic RNA in conjunction with the protein-coding genes.

This is further supported by the fact that no histone variants, that mark the boundaries of polycistronic transcription units in *T. brucei*, are found in chromatin associated with the tRNA<sup>sec</sup> genes (39).

To analyze the situation in more detail for the tRNA<sup>sec</sup> gene situated within the shorter intergenic region we determined the polyadenylation site of the upstream mRNA and the splice acceptor site of the downstream mRNA, respectively (Figure 3). Moreover, using RT–PCR we showed that the whole intergenic region together with the flanking ORFs is transcribed as one RNA molecule (Supplementary Figure S1). Interestingly, deep sequencing of poly(A)-enriched SL-containing cDNA libraries of procyclic and bloodstream *T. brucei* revealed a small number of molecules consisting of the SL sequence attached to the 5'-flanking region of the two tRNA<sup>sec</sup> genes (data not shown). This suggests that the transcripts that contain the tRNA<sup>sec</sup> are processed from a polycistronic precursor like mRNAs by trans-splicing and polyadenylation. The resulting trans-spliced RNA fragments could then be further processed like other tRNA precursors by RNAse P and a combination of endo- and exonucleases, respectively. This situation would be reminiscent of the Pol-II-transcribed snoRNAs of other organisms that are frequently encoded in introns and nucleolytically processed after splicing (40).

**Ectopic expression of trypanosomal tRNA<sup>sec</sup> requires an external promoter**

If the trypanosomal tRNA<sup>sec</sup> genes lack a Pol-III promoter and instead are transcribed by Pol-II, they should be transcriptionally silent when integrated outside of a polycistron. To test this prediction we integrated a tagged version of one of the two tRNA<sup>sec</sup> genes (Figure 4A) including its flanking regions and an upstream tetracycline (tet)-inducible Pol-I promoter into a non-transcribed intergenic rDNA region (Figure 4B). Figure 4C shows that in this genomic context expression of the tagged tRNA<sup>sec</sup> depended on the presence of tet, indicating that this gene does not contain an internal promoter. A weak signal is detected in uninduced cells, which could be due to leaky Pol-I transcription in the absence of tet. It should be mentioned here that the intensity of this signal was always very weak and for unknown reasons somewhat variable. Supplementary Figure S4 shows an example of an experiment where tRNA<sup>sec</sup> expression was strictly tet dependent. Moreover, the experiments in Figure 4C show that the Pol-I-transcribed tRNA<sup>sec</sup> is correctly processed since it co-migrates with the endogenous wild-type tRNA<sup>sec</sup> (Figure 4C, middle panel). As control we tested expression of a tagged initiator tRNA<sup>met</sup> (31) in the context of the same construct. In this case, as expected for Pol-III-directed transcription, expression was constitutive and therefore independent of an active Pol-I promoter (Figure 4C).

**Integration of the tRNA<sup>sec</sup> gene into a polycistron is sufficient for its expression**

The experiments described in Figure 4C raise the question whether the tRNA<sup>sec</sup> gene would be expressed when placed in a different polycistron than the one it naturally resides in. In order to test this hypothesis we transplanted the same tagged tRNA<sup>sec</sup> gene cassette that was used for the experiment in Figure 4C into the polycistron that encodes the Tb-VDAC (voltage-dependent anion channel) genes. This polycistron was chosen since previous studies have shown that the VDAC genes are not essential for normal growth of *T. brucei* in SDM-79 medium (41). The Southern analysis in the left panel of Figure 4D shows that, as expected, the cassette consisting of the tRNA<sup>sec</sup> gene followed by the G418 resistance gene replaced one allele of the Tb-VDAC locus. Subsequent northern analysis using a specific oligonucleotide probe showed that the tagged tRNA<sup>sec</sup> is expressed and correctly processed under these conditions (Figure 4D, right panel). Thus, whereas ectopic expression of the tRNA<sup>sec</sup> gene outside of a polycistron requires an external promoter (Figure 4C) placing it into a polycistron allows it to be expressed. This observation strongly suggests that tRNA<sup>sec</sup> is transcribed by co-expression with Pol-II transcribed protein-coding genes.
Amanitin inhibits transcription of trypanosomal tRNA⁶⁰⁰

To determine which RNA polymerase is responsible for transcription of the trypanosomal tRNA⁶⁰⁰ gene we performed nascent transcript labeling assays in lysolipid-permeabilized cells (27). RNA from untreated and α-amanitin-treated cells was synthesized in the presence of radioactive UTP or CTP and hybridized to dot blots containing Pol-II and Pol-III transcribed genes. Figure 5 shows that maximum inhibition of transcription of the tRNA⁶⁰⁰ gene as well as of the Pol-II-transcribed tubulin genes is reached at 10 μg/ml α-amanitin. In contrast, expression of the Pol-III-transcribed tRNA⁶⁰⁰ and U6 snRNA is to a large extent insensitive to 10 μg/ml α-amanitin.
RNAi of Pol-II but not of Pol-III affects transcription of trypanosomal tRNA^Sec

The question of which RNA polymerase transcribes trypanosomal tRNA^Sec was also addressed in a manner analogous to the experiment with human cells shown in Figure 2. Thus, we used RNAi cell lines allowing inducible downregulation of subunit RBP9 of Pol-II (30) or of the largest subunit of Pol-III, respectively. Induction of the RBP9-RNAi cell line with tet leads to a growth arrest after ~24 h and subsequent cell death. Ablation of the largest subunit of Pol-III causes a slow growth phenotype after ~48 h (Figure 6A). Changes of the steady-state levels of tRNA^Sec, Pol-III-transcribed tRNA^Sec as well as Pol-II-transcribed SL RNA were analyzed in uninduced and induced RNAi cell lines by northern blotting (Figure 6B). The steady-state levels of each of the tested RNAs were quantified after normalization to a Pol-I-transcribed small rRNA (M6 rRNA), which was used as an internal control.

Figure 5. Transcription of the tRNA^Sec gene is β-amanitin-sensitive. (A) UTP-labeled RNA was synthesized in permeabilized trypanosomes in the absence and presence of 10 and 200 μg/ml of β-amanitin and hybridized to nitrocellulose filters containing immobilized cloned DNA of the indicated genes (pTZ18: vector control; SL: spliced leader). (B) PhosphorImager quantitation of the results as shown in panel (A). The samples without β-amanitin were set to 1. Values represent means of two experiments. The variation between the values of two experiments was ~15%.

DISCUSSION

Eukaryotes are divided into six supergroups: humans belong to the Opisthokonta and T. brucei to the Excavata. Only a few species outside the opisthokont clade are known to have a tRNA^Sec. These include Chlamydomonas reinhardtii, Dictyostelium discoideum, Tetrahymena and members of the apicomplexans such as Plasmodium falciparum and Toxoplasma gondii. These species represent three supergroups: the Archea, Opisthokonta (C. reinhardtii), the Amoebozoa (D. discoideum) and the Chromalveolata (Tetrahymena and apicomplexans). In none of these species transcription of the tRNA^Sec gene has been analyzed. However, sequence comparison shows that the putative tRNA^Sec B box region (37,42) is conserved in most species, as would be expected if the gene is transcribed by Pol-III. The only exceptions are T. brucei, L. major and D. discoideum (Supplementary Figure S2). The fact that the tRNA^Sec gene of D. discoideum, similarly to the ones of trypanosomatids, appears to have a deficient B box indicates that Pol-II transcription of tRNA^Sec may occur in the Archea. However, without experimental evidence it remains possible that the B box of the D. discoideum tRNA^Sec is functional even though it deviates from B box consensus sequence. In summary, the sequence analysis shown in Supplementary Figure S2 suggests that Pol-III-mediated transcription of tRNA^Sec represents the ancestral situation and that Pol-II-mediated transcription of tRNA^Sec, as observed in trypanosomatids, is a derived trait. It should be emphasized in that context that as far as we can tell all other trypanosomal tRNAs are transcribed by Pol-III.

Did this shift to Pol-II-mediated transcription of tRNA^Sec occur by random genetic drift in the ancestor of trypanosomatids or does it reflect an adaptation that has functional importance? Selenoprotein synthesis requires at least four dedicated factors: phosphoseryl-tRNA^Sec kinase, phosphoseryl-tRNA:selenocysteinyl-tRNA synthase, tRNA^Sec-specific elongation factor and selenophosphate synthetase (13,43). The synteny of the genes encoding these four proteins is conserved in the trypanosomatid species T. brucei, T. cruzi and Leishmania major (44). However, this is not the case for levels in the RNAi cell line ablated for the RNA polymerase that should not affect their transcription. This is potentially highly interesting since it may indicate an as yet unknown cross talk between the two RNA polymerases. It could, for example, be that both RNA polymerases compete for a common rate-limiting transcription factor. However, it is important to emphasize that ablation of either RNA polymerase is expected to have dramatic consequences on the physiology of the cells. The interpretation of these unexpected results is therefore very difficult and requires more elaborate investigations that are beyond the scope of this study.

However, in summary, the RNAi results are consistent with the experiments in permeabilized cells (Figure 5) and show that trypanosomal tRNA^Sec is transcribed by Pol-II.
the tRNA_{Sec} genes: they are found within a polycistron in all three species, but the flanking genes in *L. major* are different from those in *T. brucei* and *T. cruzi* (Supplementary Figure S3A). This genetic arrangement shows that integration of the tRNA_{Sec} gene into a polycistron is a relatively recent event that evolved twice independently in the trypanosomatid lineage and suggests that is has been positively selected for.

Pol-III-mediated transcription of eukaryotic tRNA_{Sec} genes shows some peculiarities. Unlike other tRNA genes it requires upstream promoter elements (Supplementary Figure S3B) (5,45). These elements are very similar to the ones required for transcription of the U6 snRNA genes (9). It is interesting to note that transcription of the trypanosomal U6 snRNA gene, while still dependent on Pol-III, is different than in other eukaryotes since it requires an upstream inverted tRNA gene as a promoter element (Supplementary Figure S3C) (24). Why trypanosomal U6 snRNA is transcribed in a different way than in other systems is not known, but it should be

**Figure 6.** Effect of RNAi-mediated ablation of Pol-II and Pol-III activities on steady state levels of different RNAs. (A) Growth of uninduced and induced procyclic *T. brucei* RNAi cell lines downregulated for RPB9 (30) or the largest subunit of Pol-III. Inset: downregulation of the mRNA encoding the largest subunit of Pol-III was verified by northern blot analysis 24 h after induction of RNAi. (B) Northern analyses of total RNA isolated from uninduced (0) and induced (24, 48 h) RPB9 and Pol-III RNAi cell lines. RNA was resolved in 8 M urea on a 10% polyacrylamide gel and hybridized with oligonucleotides specifically detecting the transcripts indicated on the right. The tRNA region of the corresponding ethidium bromide stained gel is shown at the bottom. (C) Quantitation of the northern blots shown in (B). Signals were normalized to the cytosolic M6 rRNAs not affected by ablation of either RPB9 or Pol-III. For tRNA_{Sec} and tRNA_{Ile} the means of three experiments are shown. The signal in the uninduced cells was set to 1. Standard errors and the relevant *P*-values (Student’s *t*-test, one-tailed, paired) are indicated.
considered that trypanosomatids appear to lack many transcription factors that are conserved in other eukaryotes (46). Thus, it is possible that the Pol-II-mediated transcription of the trypanosomal tRNA<sup>Sec</sup> is connected to the fact that the standard eukaryotic U6 snRNA transcription mode is not operational in <i>T. brucei</i>. Most of the <i>T. brucei</i> genome codes for large Pol-II-transcribed polycistrons which may have predisposed the tRNA<sup>Sec</sup> gene to be transcribed by Pol-II. All that needs to be postulated for such a scenario is the integration of the tRNA<sup>Sec</sup> gene into a polycistron. 

tRNA<sup>Sec</sup> is unusual in many respects, so we wondered if there was any evidence for Pol-II-mediated transcription of conventional tRNAs. Analyzing the genomic organization of tRNA genes in <i>Caenorhabditis elegans</i> (http://www.wormbase.org, release WS201) and <i>Drosophila melanogaster</i> (http://flybase.org/) we found in both organisms a few cases where tRNAs are encoded within introns of Pol-II-transcribed genes. Interestingly, in <i>C. elegans</i> one of the tRNA genes that is found within an intron is tRNA<sup>Sec</sup> (http://www.wormbase.org/db/get?name=WBGene00023106;class=Gene), although unlike in trypanosomatids it is not present in a polycistron. Intron-encoded tRNA genes are embedded in Pol-II transcription units and therefore must be transcribed by Pol-II, although it is possible that they still contain internal Pol-III promoters and may be independently transcribed by Pol-III. That Pol-II-mediated transcription of tRNAs is in principle possible has recently been shown in mouse where insertion of a circularly permuted tRNA gene into a protein-coding gene yielded a functional tRNA, a large fraction of which was transcribed by Pol-II (47). Thus these findings indicate that Pol-II transcription of tRNA genes may not be restricted to trypanosomatids but may be more widespread in eukaryotes.

**SUPPLEMENTARY DATA**

Supplementary Data are available at NAR Online.

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