Posttranscriptional Regulation of miRNAs Harboring Conserved Terminal Loops

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DOI 10.1016/j.molcel.2008.10.013

SUMMARY

We recently found that hnRNP A1, a protein implicated in many aspects of RNA processing, acts as an auxiliary factor for the Drosha-mediated processing of a microRNA precursor, pri-miR-18a. Here, we provide the mechanism by which hnRNP A1 regulates this event. We show that hnRNP A1 binds to the loop of pri-miR-18a and induces a relaxation at the stem, creating a more favorable cleavage site for Drosha. We found that approximately 14% of all pri-miRNAs have highly conserved loops, which we predict act as landing pads for trans-acting factors influencing miRNA processing. In agreement, we show that 2′O-methyl oligonucleotides targeting conserved loops (LooptomiRs) abolish miRNA processing in vitro. Furthermore, we present evidence to support an essential role of conserved loops for pri-miRNA processing. Altogether, these data suggest the existence of auxiliary factors for the processing of specific miRNAs, revealing an additional level of complexity for the regulation of miRNA biogenesis.

INTRODUCTION

MicroRNAs (miRNAs) are small noncoding RNAs that negatively regulate gene expression of complementary mRNAs (Ambros, 2004; Bartel, 2004; He and Hannon, 2004). They have diverse and unique expression patterns and have been implicated in a number of biological processes (for recent reviews see (Bushati and Cohen, 2007; Chang and Mendell, 2007). Many miRNAs target mRNAs that are involved in proliferation, differentiation, and apoptosis, and accordingly impaired microRNA processing enhances cellular transformation and tumorigenesis (Kumar et al., 2007). The biogenesis of miRNAs involves the cropping and release of hairpin-shaped precursors (pre-miRNAs) in the cell nucleus by the microprocessor complex, comprising the RNase III type enzyme Drosha and its partner DGCR8 (Gregory et al., 2004; Han et al., 2004; Zeng et al., 2005). Subsequent events include the export of pre-miRNAs from the nucleus (Yi et al., 2003; Lund et al., 2004) and further processing in the cytoplasm by the type III ribonuclease Dicer into mature miRNAs (Bernstein et al., 2001; Huttner et al., 2001).

It has been shown that in many physiological and pathological conditions, individual miRNAs are subjected to posttranscriptional regulation, both at the level of Drosha and/or Dicer processing (Obernosterer et al., 2006; Thomson et al., 2006). We have recently shown that hnRNP A1, a protein implicated in many aspects of RNA processing, specifically binds to a miRNA cluster containing pri-miR-18a and promotes production of miR-18a. According to others members of the cluster (Guil and Caceres, 2007). This miRNA is expressed as a cluster of intronic RNAs, the miR-17–18a–19a–20a–19b–1–92 microRNA polycistrone, and overexpression of this cluster accelerates c-myc-induced tumor development in a mouse B cell lymphoma model (He et al., 2005). Thus, the general RNA-binding hnRNP A1 protein acts as an auxiliary factor for the processing of a miRNA precursor, pri-miR-18a, at the level of Drosha processing (Guil and Caceres, 2007).

Here, we have elucidated the mechanism by which hnRNP A1 facilitates miR-18a production. We show that hnRNP A1 binds to the loop of this pri-miRNA and induces a relaxation at the stem, which is important for its processing. Furthermore, we show that 14% of all pri-miRNAs have terminal loops that are well conserved throughout evolution, and we predict that this reflects their requirement for auxiliary factors that bind to this sequence. By using 2′O-methyl oligonucleotides complementary to conserved terminal loops of the corresponding pri-miRNAs, we could efficiently block their processing. Accordingly, we demonstrate that mutations in the terminal loop of pri-miR-18a that do not affect the structural architecture of the stem abrogate its efficient processing. Altogether, these data suggest the existence of auxiliary factors that bind to conserved terminal loops and facilitate the processing of specific miRNAs, revealing an additional level of complexity for the regulation of miRNA production.

RESULTS

Identification of hnRNP A1 Binding Sites in Pri-miR-18a

Our previous data showed that hnRNP A1 facilitates processing of miR-18a in a context-dependent manner, emphasizing the importance of the pri-miRNA sequences surrounding miR-18a in the requirement for hnRNP A1 (Guil and Caceres, 2007). In order
to map the precise binding site/s of hnRNP A1 in pri-miR-18a and to determine whether this binding influences the RNA architecture and/or thermodynamic properties that might facilitate its processing, we analyzed its RNA secondary structure in the presence or absence of recombinant hnRNP A1 protein. Footprint analysis, using Pb(II)-lead ions that cleave single-stranded and relaxed nucleotides, revealed two hnRNP A1 binding regions: a primary one corresponding to the terminal loop of pri-miR-18a and a secondary site that corresponds to the bottom of the stem (Figure 1A). Interestingly, both sites share some similarity with the consensus hnRNP A1 binding site, UAGGGA/U, that was previously identified by SELEX experiments (Burd and Dreyfuss, 1994). These results were confirmed and extended by the use of a variety of structural probes and by footprint analysis of pri-miR-17-18a-19 RNA cluster incubated in the presence of hnRNP A1 protein (+, 50 ng; ++, 100 ng; ++++, 200 ng), treated with Pb (ll)-lead ions (0.5 mM), F and T identify nucleotide residues subjected to partial digest with formamide (every nucleotide) or ribonuclease T1 (G-specific cleavage), respectively. Thick lines on the right-hand side indicate rows of nucleotides protected by hnRNP A1. Positions of selected residues are indicated.

hnRNP A1 Acts to Remodel the Stem Structure of pri-miR-18a Facilitating Drosha-Mediated Processing

In order to define potential structural features that make pri-miR-18a processing dependent on hnRNP A1, we took advantage of a highly related pri-miRNA sequence, pri-miR-18b, which is part of the homologous primary cluster miR106a/C24/C20b located on chromosome X (Tanzer and Stadler, 2004) that was shown to be processed independently of hnRNP A1 (Guil and Caceres, 2007). In the case of pri-miR-18b, we detected an increase in the intensity of Pb(ll)-lead ion cleavages between G54 and G63 that mapped to the UC bulge (Figure S3 and Figure 2B). Thus, the cleavage pattern of pri-miR-18b resembles the structural rearrangements seen in the stem of pri-miR-18a in the presence of added recombinant hnRNP A1 protein, that is, the relaxation of residues between U56 and U60 that are involved in strong Watson-Crick pairing (Figure 1A and Figure S3). To establish the significance of this observation, we introduced two nucleotide mutations on
pri-miR-18a and pri-miR-18b in order to force structural changes in the stems so that the conformation of the mutant pri-miR-18a resembles the one from pri-miR-18b and vice versa (Figure 2B). Footprint analysis confirmed that the designed mutations altered only locally the conformation of the stem loops without perturbing the rest of the structure (Figure S4). We then performed in vitro processing assays on these new substrates in the context of the pri-miR-17-18a-19a minicluster. As previously reported, miR-18a was the only pri-miRNA whose processing was reduced when incubated in extracts from cells depleted of hnRNP A1, since both the neighboring 17 and 19a pri-miRNAs were insensitive to the reduced levels of hnRNP A1 (Figure 2C, lane 3) (see also Guil and Caceres, 2007). Upon depletion of hnRNP A1 achieved with an unrelated set of siRNAs, we observed a similar result, and the accumulation of the remaining RNA containing unprocessed pre-miR-18a becomes more evident (Figure S5B, asterisk). Strikingly, introduction of a bulge in the pri-miR-18a stem (UC → GU) made its processing more efficient and completely independent of the presence of hnRNP A1 (Figure 2C). This experiment clearly shows that a pri-miR-18a with a local structural change in its stem resembling pri-miR-18b (or pri-miR-18a upon addition of hnRNP A1 as shown on Figure 1C) is now processed independently of hnRNP A1. By contrast, the mutation in pri-miR-18b that eliminates the UC bulge (GU → UC) did not make this substrate dependent of hnRNP A1 for its processing but rather abrogated its processing in HeLa cell extracts (Figure 2D). From these experiments, we conclude that the requirement for hnRNP A1 as an auxiliary factor in the processing of pri-miR-18a reflects the ability of this factor to bind and alter the local conformation of the stem in the vicinity of Drosha cleavage sites. These results revealed that subtle structural features in pri-miRNAs that are innate or arise from chaperone activities of RNA binding proteins might facilitate their processing by Drosha.
Conserved Terminal Loops in Pri-miRNAs

Since the footprint analysis showed that hnrNP A1 has a strong binding site on the pri-miR-18a terminal loop, we next focused on the significance of this interaction. It is assumed that the terminal loops of pri-miRNAs are relatively functionally unimportant (Han et al., 2006). This notion is in agreement with the poor phylogenetic conservation that most pri-miRNAs display along their terminal loop regions, which contrasts with the high level of conservation in the mature miRNA sequences (Berezikov et al., 2005). We have noticed that the terminal loop of pri-miR-18a is atypically well conserved across vertebrate species (Figure 3A, compare with pri-miR-27a, which displays no special conservation in the loop, Figure 3B). Phylogenetic analysis of human pri-miRNAs sequences revealed that ~14% (74 out of 533) of the miRNAs analyzed had similar high conservation pattern across the whole pri-miRNA sequence (Figure 3C and Figure S6). It is conceivable that the conservation of the terminal loops indicates the need to preserve a platform for the binding of auxiliary factors required for an efficient processing of these pri-miRNAs.

Oligonucleotides Complementary to Conserved Terminal Loops, LooptomiRs, Block pri-miRNA Processing

In this regard and to evaluate the role of conserved terminal loops in pri-miRNA biogenesis, we performed in vitro processing assays in HeLa extracts with the addition of 2' O-methyl-modified oligonucleotides complementary to sequences in the terminal loops, which we termed LooptomiRs (for Loop Targeting Oligonucleotide anti miRNAs). We found that the Drosha-mediated processing of pri-miR-16-1 and pri-miR-27a, which bear nonconserved terminal loops, was not affected by the addition of complementary looptomiRs (Figures 4A and 4B). This observation was in agreement with a previous study showing that pri-miR-16-1 did not require the terminal loop for its efficient processing (Han et al., 2006). By contrast, looptomiRs designed against a number of conserved terminal loop sequences, including those of pri-miR-18a, pri-miR-101-1, pri-let-7a-1, pri-miR-379, and pri-miR-31, were able to specifically block the processing of their corresponding pri-miRNAs (Figures 4A, 4C, and 4D and Figures S7A and S7B). We believe that this is due to the block exerted by looptomiRs on sequences within the terminal loops that bind auxiliary factors required for the efficient processing of these targeted miRNAs. Furthermore, a looptomiR targeting miR-18a selectively abolishes the processing of pri-miR-18a in the context of the miR-17-18a-19a minicluster (Figure S7C). It is possible that looptomiRs could be used to block access to negative factors that negatively regulate pri-miRNA processing. It is also conceivable that some looptomiRs could potentially change the secondary structure of complementary pri-miRNAs, thus affecting the cleavage by Drosha. However, at least in the case of pri-miR-18a bound to its looptomiR, we did not detect any significant changes in the RNA structure of the region surrounding the Drosha cleavage site (Figure S8).
The above results allowed us to conclude that the conserved terminal loop region of pri-miR-18a is essential for its efficient processing, most likely due to the direct binding of the auxiliary factor hnRNP A1. Moreover, the effect of looptomiRs on the processing of pri-miRNAs with conserved loops suggest a more general role of RNA binding proteins as auxiliary factors in the microRNA processing pathway. In order to find out potential additional auxiliary factors regulating processing of pri-miRNAs harboring conserved terminal loops, we combined RNA chromatography with mass spectrometry. Using this approach, we found that hnRNP A1, which was originally defined as an auxiliary factor for miR-18a, also binds to the apical regions of pri-let-7a-1 and pri-miR-101-1 stem loop (Figure 5 and Figure S9). The specificity of this interaction was demonstrated by the lack of hnRNP A1 binding to the loops of mir-16-1, mir-19a, miR-21, and miR-379 (Figure 5C and Figure S9). Notably, the terminal loop of let-7a-1 has a perfect hnRNP A1 consensus-binding site (UAGGGA/U) (Figure 5D). This loop was also found to bind hnRNP L, whereas PTB was found to bind to the pri-miR-101-1 stem loop. Experiments are currently under way to elucidate the role of these factors in the processing of their corresponding pri-miRNAs.
of pri-miR-18a stem-loop structure in the presence of the specific looptomiR, which is in agreement with the structural analysis of such complex (Figure S8).

**Role of Terminal Conserved Loops in miRNA Processing**

To gain a more clear insight into the role of conserved terminal loops for miRNA processing, we have created pri-miRNAs terminal loop mutants of pri-miR-18a and as a control of pri-miR-16-1 (Figures 6A and 6C). In order to eliminate any potential hnRNP A1 binding site from the pri-miR-18a apical region, we have substituted the region spanning from U24 to C40 with GCAA or UCUCUC loops (miR-loop_mt1 and miR-loop_mt2, respectively). We found that the introduction of mutant sequences in the terminal loop of pri-miR-18a completely abrogated its processing in HeLa extracts, as compared to a wild-type transcript (Figure 6B). This was also true in the context of pri-miR-17-18a-19a minicluster (Figure S11). By contrast, introduction of similar mutant loops to pri-miR-16-1 transcripts didn’t influence the rate of pri-miR to pre-miR processing, reinforcing previous findings that pri-miR-16-1 could be processed in the absence of its terminal loop (Figure 6D) (Han et al., 2006). Importantly, we needed to establish whether the mutant loop sequences did not affect the global architecture and thermodynamics of the pri-mir-18a stem. To address this, we performed detailed structure analysis of pri-miR-18a loop mutants, using Pb(II)-lead ions as a probe, which are able to detect potential fine thermodynamic and structural perturbations within the stem-loop region. We found that the pattern of cleavages obtained for wild-type pri-miR-18a and two loop mutants, apart from the terminal loop regions, were identical (Figure S12). This indicates that introduction of different terminal loops to pri-miR-18a does not change the global architecture of its stem region. Finally, we also observed that the introduction of mutant sequences in the conserved terminal loops of pri-miR-101-1 and pri-let-7a-1 completely abrogated their processing in HeLa extracts, confirming the importance of conserved terminal loop regions for efficient miRNA processing (Figures 7B and 7D).

In summary, we have presented here the mechanism by which an auxiliary factor, hnRNP A1, promotes the Drosha-mediated processing of pri-miR-18a. The conservation of terminal loops of a subset of miRNAs together with the inhibition of processing mediated by LooptomiRs strongly suggest the existence of additional auxiliary factors binding to conserved terminal loop sequences and regulating the processing of specific miRNAs.

**DISCUSSION**

The expression of mammalian miRNAs can be regulated at the posttranscriptional level by modulating nuclear and cytoplasmic miRNA processing events. For instance, during early mouse development, many pri-miRNAs, including pri-let-7a-1, are present at high levels but are not processed by Drosha, suggesting an important role for posttranscriptional regulation of miRNA processing. Furthermore, an analysis of gene expression in tumor tissues showed widespread discrepancies in the levels of miRNAs and their corresponding primary transcripts (Thomson et al., 2006). In mouse and zebrafish, few miRNAs are expressed in early embryos, and large numbers of miRNAs are induced in temporal and spatial patterns during mid- to late embryonic development (Kloosterman et al., 2006). It has been shown this is not due to transcriptional control. Interestingly, the core enzymes (Drosha and DGCR8) are widely expressed, and no posttranslational regulation of Drosha or Dicer has been reported (Thomson et al., 2006). It is possible that the downregulation of...
miRNAs during early development could be attributed to a defect in the relative amount and/or activity of auxiliary factors required for microRNA processing. It has also been suggested that cleavage of pre-miRNAs in the cytoplasm by Dicer is regulated in such a way that the presence of the functional mature miRNA is restricted to only a fraction of the tissues where the pre-miRNA is initially expressed (Obernosterer et al., 2006). In most cases, the mechanism by which this fine regulation of miRNA expression is achieved is not yet understood.

Here, we have shown that hnRNP A1 binding to the pri-miR-18a terminal loop and to a region within the stem rearranges the RNA secondary structure, allowing an efficient processing by the Drosha/DGCR8 complex. The question of how widespread the contribution of hnRNP A1 and other auxiliary factors to pri-miRNA processing events is beginning to emerge. We have also found that hnRNP A1 binds with specificity to the conserved loops of pri-miR-101-1 and pri-let-7a-1, and functional validation of the role of hnRNP A1 in the processing of these miRNAs is now under progress (Figure 5 and Figure S9). Thus, data presented here clearly establishes hnRNP A1 as a positive regulator of miR-18a processing (and perhaps of other miRNAs), acting at the level of Drosha processing. Another example of a positive regulator of miRNA processing is illustrated by the effect of TGF-β and BMP signaling in promoting the expression of miR-21, which results in an induction of a contractile phenotype in human vascular smooth muscle cells. In this situation, TGF-β and BMP-specific SMAD signal transducers are recruited to pri-miR-21 in a complex with the RNA helicase p68 and facilitate its Drosha-mediated processing (Davis et al., 2008). Interestingly, several RNA helicasers and hnRNP proteins were found associated with the microprocessor complex, but their functions remain to be determined (Gregory et al., 2004). In the case of p68 and p72 DEAD-box helicasers,
both proteins were shown to be required for pri-miRNA processing in the mouse (Fukuda et al., 2007). The developmentally regulated RNA-binding protein Lin28 protein has been recently shown to be necessary and sufficient to block the Drosha-mediated cleavage of pri-let-7 miRNAs in embryonic cells (Piskounova et al., 2008; Viswanathan et al., 2008). There is, however, a conflicting report indicating that Lin28 could be acting at the level of Dicer processing (Rybak et al., 2008). In any case, irrespective of the precise mechanism, Lin28 can be classified as a negative regulator of pri-miRNA processing. Interestingly, Lin28 has been shown to bind to conserved nucleotides in the terminal loop region of the Let-7d precursor (Newman et al., 2008). Several hnRNP proteins, among them hnRNP A1, were also found associated with Let-7d, but their functional role was not established (Newman et al., 2008).

Thermodynamic properties and molecular architectures of pri-miRNAs that allow cleavage and release of the pre-miRNAs from their primary transcripts are beginning to be recognized (Krol et al., 2004; Han et al., 2006). It was proposed that a large terminal loop is critical for miRNA processing (Zeng et al., 2005); however, more recent data suggested that the terminal loop is unessential, whereas the flanking single-stranded RNA segments are critical to define the cleavage site. This model predicts that the microprocessor component, DGCR8, functions as a molecular anchor that measures the distance from the dsRNA-ssRNA junction and positions the processing center of Drosha ~11 bp up along the stem (Han et al., 2006). Our findings indicate that the fine structural features of pri-miRNAs (innate or arising from chaperone activities of RNA binding proteins) might be very important in the miRNA biogenesis pathway. A bioinformatic survey revealed that a number of pri-miRNAs are conserved throughout vertebrate evolution not only at the mature miRNA sequence but also at the regions encompassing terminal loops (Figure 3 and Figure S6). Notably, it was recently shown that the processing of pri-miR-375 in zebrafish was effectively blocked by injecting morpholino oligonucleotides targeting the mature miRNA or the miRNA precursor, some of which
overlap the terminal loop, which as shown in Figure S6, is highly conserved (Kloosterman et al., 2007). Results presented in this study support the notion that phylogenetic conservation of pri-miRNA terminal loops reflects the requirement for auxiliary factors that bind to these conserved loops and ensure an optimal pri-miRNA processing. Altogether, our findings open up additional avenues toward a deeper understanding of microRNA biogenesis pathways and their contribution to physiological states and pathological conditions.

**EXPERIMENTAL PROCEDURES**

**Preparation of Plasmids and DNA Templates**
For the structural analysis, RNA substrates were transcribed in vitro from a DNA fragment containing the T7 promoter sequence directly upstream of the pri-miRNA precursor sequence. The DNA fragments were amplified by PCR from human genomic DNA using oligonucleotides, which are listed in the Supplemental Data.

**RNA Probing and Footprint Analysis**
In vitro transcription of RNAs subjected to structure probing was carried out as previously described (Sobczak et al., 2003). Transcripts were 5' end-labeled with T4 polynucleotide kinase (Roche) and [γ-32P]ATP (4,500 Ci/mmol; Amersham Pharmacia Biotech). Transcripts were purified by electrophoresis in a 10% denaturing polyacrylamide gel. Labeled and unlabeled RNAs were visualized by autoradiography and StainsAll staining, respectively. Prior to structure probing transcription, reactions were subjected to a denaturation and renaturation procedure in a buffer containing 2 mM MgCl2, 80 mM NaCl, and 20 mM Tris–HCl (pH 7.2) by heating the sample at 80°C for 1 min and then slowly cooling to 37°C. Limited RNA digestion was initiated by mixing 5 μl of the RNA sample (100,000 c.p.m. or 100 pmol for labeled and unlabeled RNAs, respectively) with 5 μl of a probe solution containing lead ions-2P(d), nucleos 1, or ribonucleases T1 or V1 at concentrations specified in the templates by standard in vitro transcription with T7 RNA polymerase in the RNA substrates for in vitro processing assays were prepared from the DNA Pri-miRNA Substrates and In Vitro Processing Assays described above, along with the sequence ladder generated from the pri-17-transcriptase. The products of the reverse transcription were separated as use of 2 pmol 5'-32P-labeled RNAs, after incubation with the probes, were subjected to high-salt precipitation procedure. To determine the cleavage sites, the products of line hydrolysis and limited T1 nuclease digestion of the same RNA molecule were separated as gapped sites in miRBase structures to derive genomic coordinates for all subregions. Multiple sequence alignments for the human genome (hg18/NCBI36 assembly) with 16 other vertebrate genomes (chimp [November 2003, panTro1], macaque [January 2006, rheMac2], mouse [February 2006, mm8], rat [November 2004, mrd], rabbit [May 2005, oryCun1], dog [May 2005, canFam2], cow [March 2005, bosTaurus], armadillo [May 2005, dasNov1], elephant [May 2005, loxAfr1], tenrec [July 2005, echTel1], opossum [January 2006, monDom4], chicken [February 2004, galGal2], frog [October 2004, xenTro1], zebrafish [May 2005, danRer1], tetraodon [February 2004, tetNig1], and fugu [August 2002, fr1]) were obtained from the UCSC Genome Bioinformatics group (http://genome.ucsc.edu/). Overall conservation scores per bp based upon these alignments (calculated using phastCons) (Siepel et al., 2005) were obtained from the same source. UCSC EvoFold (Pedersen et al., 2006) alignments and secondary structure predictions were used to examine conservation at finer scales. Comparisons of average conservation scores for different miRNA subregions were based upon the mean and 95% confidence intervals for phastCons scores (Piriyapongsa and Jordan, 2007). A total of 526 known miRNAs could be mapped to the current human genome assembly and successfully related to phastCons conservation data. Of this total, 96 pri-miRNAs could not be processed by the current protocol as conservation was so low across all subregions that comparisons were meaningless. The remaining 430 pri-miRNAs were all processed successfully, and 298 (69%) of these showed a significant difference in conservation between stem and loop subregions. Most of these pri-miRNAs show a mean conservation ratio of loop/stem < 1, indicating a relatively poorly conserved loop. Of the 430 processed pri-miRNAs, 132 (31%) did not show a significant difference between stem and loop regions, but many of these also show loop/ stem mean conservation ratios < 1 and/or show low conservation (mean phastCons score < 0.5) across the entire pri-miRNA sequence. Only 74 (17%) miRNAs, including hsa-miR-18a, were found to have a loop/stem ratio close to 1 (within 0.001 from 1) and mean phastCons scores > 0.5 for the entire sequences. This set of 74 sequences therefore constitutes the best candidates for miRNAs with similar processing requirements to hsa-miR-18a (Figure 2C).

The table in Figure 3C shows the candidates ranked by mean conservation ratio and suggests that hsa-miR-18a (ranked 8th out of 74) is among the best-predicted candidates.
A detailed section covering phylogenetic sequence analysis methods used in this paper is presented in the Supplemental Data.

SUPPLEMENTAL DATA

The Supplemental Data include 12 figures and Supplemental Experimental Procedures and can be found with this article online at http://www.molecule.org/supplemental/S1097-2765(08)00728-4.

ACKNOWLEDGMENTS

We are grateful to Javier Martinez (IMBA, Vienna) and Nick Hastie (MRC HGU, Edinburgh) for discussions and critical reading of the manuscript. This work was supported by the MRC, a project grant from the Welcome Trust, and Eursaset (European Alternative splicing Network-FP6). S.G. is the recipient of a Ramon y Cajal contract from the MICINN (Spanish Government).

Received: May 12, 2008
Revised: August 27, 2008
Accepted: October 16, 2008

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