



# Life and Death of mRNA Molecules in *Entamoeba histolytica*

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In eukaryotic cells, the life cycle of mRNA molecules is modulated in response to environmental signals and cell-cell communication in order to support cellular homeostasis. Capping, splicing and polyadenylation in the nucleus lead to the formation of transcripts that are suitable for translation in cytoplasm, until mRNA decay occurs in P-bodies. Although pre-mRNA processing and degradation mechanisms have usually been studied separately, they occur simultaneously and in a coordinated manner through protein-protein interactions, maintaining the integrity of gene expression. In the past few years, the availability of the genome sequence of *Entamoeba histolytica*, the protozoan parasite responsible for human amoebiasis, coupled to the development of the so-called “omics” technologies provided new opportunities for the study of mRNA processing and turnover in this pathogen. Here, we review the current knowledge about the molecular basis for splicing, 3' end formation and mRNA degradation in amoeba, which suggest the conservation of events related to mRNA life throughout evolution. We also present the functional characterization of some key proteins and describe some interactions that indicate the relevance of cooperative regulatory events for gene expression in this human parasite.

**Keywords:** *Entamoeba*, mRNA decay, mRNA processing, P-bodies, polyadenylation, protozoan parasite, splicing

## INTRODUCTION

The metabolism of messenger RNA (mRNA) is a complex process that is essential for gene expression regulation and mRNA turnover in response to environmental signals and cell-cell communication in eukaryotic cells. During pre-mRNA synthesis by RNA polymerase II (RNA Pol II) in the nucleus, they are modified to generate mature transcripts that can be exported to the cytoplasm and translated to proteins. First, the 5' end of nascent mRNA is capped by a 7-methyl guanosine linked by a 5'-5' triphosphate bridge to the first nucleoside of the transcript (capping). These reactions are catalyzed by three enzymes: RNA triphosphatase, guanylyltransferase, and RNA (guanine-7-)-methyltransferase (RNMT) (Cowling, 2010). Then, introns are removed and exons are ligated by the catalytic activity of the spliceosome components that include five small nuclear RNA (snRNAs), namely U1, U2, U4, U5, and U6, and small nuclear ribonucleic proteins (snRNPs) (splicing) (Shi, 2017). Finally, a phosphodiester bond is hydrolyzed at the 3' end of mRNA and a poly(A) tail is added by the coordinated activity of a large set of polyadenylation factors that recognize specific motifs in RNA 3' untranslated region (3'UTR) (cleavage/polyadenylation)

(Xiang et al., 2014). After translation, the elimination of mRNA molecules is necessary to ensure proper course of gene expression and prevent the accumulation of transcripts (Christie et al., 2011). Pathways of mRNA decay depend on the formation of RNA-protein complexes in microscopically detectable cytoplasmic structures, called processing bodies (P-bodies) (Sheth and Parker, 2003), in which mRNAs are translationally repressed (silenced) or degraded; their re-incorporation into ribosomes is also possible (Eulalio et al., 2007). Transcript decay involves 3' end deadenylation by CAF1 and CCR4/NOT1–5 complex (or by PARN, PAN2 and PAN3 deadenylases) followed by 5' end decapping by DCP1–DCP2 complex and Lsm1–7 proteins, and 5'–3' digestion by exonuclease XRN1; alternatively, deadenylated transcripts can be degraded from the 5' end by the exosome complex, while the scavenger-decapping DCP enzyme hydrolyzes the remaining cap structure (Labno et al., 2016). During translation, aberrant mRNAs with premature termination codons can be detected and eliminated through the nonsense-mediated decay (NMD) pathway (Rebbapragada and Lykke-Andersen, 2009).

Although pre-mRNA processing reactions have usually been studied separately, they occur co-transcriptionally, simultaneously and in a coordinated manner. Moreover, a large set of data has shown that they are interconnected with transcription, translation, and mRNA degradation; protein-protein interactions establish a functional link between the different molecular machineries and promote reciprocal regulation events to maintain the integrity of gene expression. Consequently, each of these processes plays a major role throughout the life cycle of mRNA. Thus, in addition to protect mRNA from 5' to 3' exonuclease cleavage, the m7G cap interacts with the cap-binding complex (CBC), which regulates spliceosome assembly, transcription termination, 3' end processing, RNA export, and NMD in the nucleus. In the cytoplasm, CBC recruits eIF4G, RNA helicase eIF4A, and other proteins to promote translation initiation. Moreover, eIF4G interacts with poly(A) binding protein PABP1 bound to the poly(A) tail to create a mRNA pseudo-circularization and enhance the processivity of the ribosome. Furthermore, it has been recently demonstrated that 2'O methylated cap (cap 1) acts as a signature of self RNA molecules (Ramanathan et al., 2016). Several data indicate that U1 snRNP, the more abundant splicing factor, inhibits 3' end processing. Notably, its interaction with PAP inhibits poly(A) tail synthesis and promotes degradation of U1A pre-mRNA (Gunderson et al., 1994, 1997). Moreover, its binding to the 5' splice site (5'ss) of the terminal intron, avoids the use of premature cleavage and polyadenylation to protect the integrity of the transcriptome (Furth et al., 1994). Other data indicate that splicing and 3' end processing factors may recruit each other and form a stabilized complex on the target pre-mRNA, resulting in reciprocal stimulation of efficiency. Thus, interactions between U2AF65 and CFIm59 (Millevoi et al., 2006), or U1A and CPSF160 (Lutz et al., 1996), enhance the polyadenylation reaction, while CPSF (Kyburz et al., 2006) and PAP (Vagner et al., 2000) stabilize U2AF65 to the terminal intron to stimulate splicing. On the other hand, exon–exon junction complexes (EJC) participate in mRNA degradation, as part of

the CBC whose CBP80 component interacts directly with the NMD factor, up-frameshift 1 (UPF1), enhancing the efficiency of this process (Isken and Maquat, 2008). CFIm may bridge 3' processing with capping through the binding of CFIm25 with CBP20 (Yang et al., 2011).

Until recently, little was known about mRNA metabolism in *Entamoeba histolytica*, the protozoan responsible for human amoebiasis. The availability of the *E. histolytica* genome sequence and the development of the so-called “omics” technologies have provided new opportunities for the study of mRNA processing and turnover in this parasite. To our knowledge, capping has not been described in *E. histolytica*, although preliminary searches in parasite genome database suggest the presence of genes that encode proteins with similarities to human capping enzymes. In this review, we focus on the current knowledge about the molecular basis for splicing, 3' end formation and mRNA degradation, and describe some interactions between these events.

## WHAT IS KNOWN ABOUT SPLICING IN *E. HISTOLYTICA*

### Splicing Factors

There are nearly four thousand introns in the 8333 annotated genes of *E. histolytica* (Weedall and Hall, 2011), most of them flanked by highly conserved 5' and 3' splice sites (ss), GUUUGU and UAG, respectively, but their branch point sequences (BS) lack such degree of conservation (Wilihoeft et al., 2001; Hon et al., 2013). Whereas, no minor U12 introns have been identified in amoeba and most likely neither in the eukaryotic ancestor (Collins and Penny, 2005; Bartschat and Samuelsson, 2010), the majority of the main spliceosome components have been predicted and identified.

Molecular evidence and cloning confirmed the presence of U2, U4, U5, and U6 snRNAs (Miranda et al., 1996; Davis et al., 2007), however no significant homology with eukaryotic U1 snRNAs has led to the conclusion that such small nuclear RNA is absent in *Entamoeba* (Dávila et al., 2008). Nonetheless bioinformatic analyses predicted the presence of the three U1 snRNP U1-A, U1-C, and U1-70k factors, suggesting that activation of the 5'ss might be due to direct interaction of snRNP proteins or by U6 snRNA-5'ss complementarity substitution as demonstrated in other systems (Kandels-Lewis and Seraphin, 1993; Förch et al., 2002; Rhode et al., 2006; Huang et al., 2012). *In vivo* expression of tag-cloned U1-A and cross-linking immunoprecipitation (CLIP) assays of nuclear proteins coupled to mass spectroscopy allowed the identification of at least 32 splicing factors in trophozoites (Table 1), namely U2, U4, and U5 snRNP, integral SmD1, SmD3, and SmF proteins; the U1 snRNP components and auxiliary factors U1-70k and TIA-1/TIAR; the U2 snRNP and related components U2-A', SF3a120, SF3a60/Prp9, SF3b1, SF3b3, U2AF65, and U2AF35; the U5 snRNP components Prp8 and Prp6 [which was previously identified and cloned (Hernandez-Rivas et al., 2000)]; the U6 snRNP integral components LSm2 and LSm5; two alleles

**TABLE 1** | Comparison of splicing factors in *Entamoeba histolytica* vs. human and yeast.

Particle/class	Splicing factor	Remodeling	<i>E. histolytica</i> protein	Locus <sup>a</sup>	UniProtKB
Sm/LSm snRNP	SmD1		snRNP Sm D1	EHL_052090	B1N466
	SmD3		snRNP	EHL_163710	C4M3V1
	SmF		snRNP F	EHL_060400	C4M6J5
	LSm2		U6 snRNA-associated Sm-like LSm2	EHL_068580	C4LU49
	LSm5		hypothetical protein	EHL_076840	B1N3I3
U1 snRNP U1-related No U1 snRNA	U1A, HA-tag		U1 snRNP-specific protein	EHL_050780	C4LTU8
	U1-70K		U1 snRNP subunit	EHL_153670	C4LSE9
	p68	A-B (U1-5'ss)	EhDEAD20	EHL_096390	C4LWF2
	TIA-1/TIAR		RNA-binding protein TIA-1	EHL_056660	C4M9T1
U2 snRNP U2-related U2 snRNA	U2A'		leucine rich repeat protein	EHL_167290	C4MAF8
	SF3a120		splicing factor	EHL_058680	C4LWT7
	SF3a60/Prp9 <sup>PILC</sup>		splicing factor 3A subunit 3	EHL_038600	C4LZP4
	SF3b1 <sup>PILC</sup>		splicing factor 3B subunit 1	EHL_049170	C4MAD8
	SF3b3 <sup>PILC</sup>		splicing factor 3b subunit 3	EHL_048160	C4M4A7
	U2AF65		U2 snRNP aux. fact. large subunit	EHL_098300	C4LXB3
	U2AF35		U2 snRNP auxiliary factor	EHL_192500	C4M1H0
	Prp43	ILS-disassembly	EhDExH9	EHL_184530	C4M6S9
	Prp43	ILS-disassembly	EhDExH13	EHL_090040	C4MA27
	Prp43	ILS-disassembly	EhDExH7	EHL_096230	C4LWD6
U5 snRNP U5 snRNA	Prp5	E-A (U2-3'ss)	EhDEAD3	EHL_013960	C4LXN8
	Snu114 <sup>PILC</sup>	B-B <sup>act</sup>	U5 snRNP subunit	EHL_021380	B1N373
	Brr2 <sup>PILC</sup>	B-B <sup>act</sup> ; C-Post splicing	EhDExH10/U5 snRNP-specific 200kd	EHL_045170	C4LTD0
	Brr2 <sup>PILC</sup>	B-B <sup>act</sup> ; C-Post splicing	EhDExH1	EHL_131080	C4LXH6
	220K/Prp8 <sup>PILC</sup>		splicing factor Prp8	EHL_060350	C4M6K0
	102K/Prp6		pre-mRNA splicing factor	EHL_093960	C4LYI7
U4/U6 snRNP	Prp28	A-B	EhDEAD4	EHL_021440	C4M058
	CPR6		peptidyl-prolyl cis-trans isomerase	EHL_020340	C4M7U6
U4/U6 snRNA	CPR6		peptidyl-prolyl cis-trans isomerase	EHL_125840	O15729
U4/U6-U5 tri-snRNP	65K/SAD1		ubiquitin C-term hydrolase	EHL_152110	C4LSP9
	Prp38		PRP38 family protein	EHL_000490	C4LZA0
Prp19C/IBC	Prp19 <sup>PILC</sup>		WD domain containing protein	EHL_130870	C4LXF5
	CDC5 <sup>PILC</sup>		myb-like DNA-binding	EHL_000550	C4LZA6
	Aquarius		regulator of nonsense transcripts	EHL_193520	C4M4V4
	Syf1 <sup>PILC</sup>		Hypothetical protein	EHL_073300	C4LXJ5
	RBM22 <sup>PILC</sup>		pre-mRNA splicing factor cwc2	EHL_126150	C4LW00
EJC	CWC22 <sup>#,PILC</sup>		cell cycle control protein	EHL_093720	C4LYG3
	Sub2p/UAP56	E-A (U2-3'ss)	EhDEAD18	EHL_151600	C4LSK1
RES complex	MGC13125 <sup>PILC</sup>		EF-hand calcium-binding	EHL_150550	C4M234
Complex B <sup>act</sup>	Prp2	B <sup>act</sup> -B*	EhDExH4	EHL_033720	C4M435
Complex C	Abstrakt		EhDEAD1	EHL_175030	C4LZM8
Step 2 factors	Prp22 <sup>PILC</sup>	Post splicing-ILS	EhDExH3	EHL_077640	C4M8N6
	Prp16	C-Post splicing	EhDExH5	EHL_122790	C4M5M5

<sup>a</sup>AmoebaDB. *E. histolytica* splicing factors, U snRNAs and components of the post-catalytic/intron lariat spliceosome complexes (PILS in superscript) were described by Miranda et al. (1996), Hernandez-Rivas et al. (2000), Davis et al. (2007), Dávila et al. (2008), Fourmann et al. (2013), and Valdés et al. (2014). Previously undetected additional *Entamoeba* PILS components (shaded) were identified in the ProteomeXchange repository PXD001080. # indicates that CWC22 is also part of the Prp19C. Transitions of spliceosome complexes remodeling by the respective DEXH/D-box helicases are indicated (Liu, 2002; Marchat et al., 2008; Hahn et al., 2012; Wahl and Luhrmann, 2015).



## Intron Lariat Debranching Enzyme

Intron lariat debranching enzyme, or Dbr1, is a member of the calcineurin-like metallophosphoesterases (MPEs) superfamily of binuclear metal-ion-center-containing enzymes that hydrolyse phosphomono-, phosphodi-, or phosphotriesters in a metal-dependent manner. From bacteriophages to humans, the MPE domain is found in Mre11/SbcD DNA-repair enzymes, mammalian phosphoprotein phosphatases, acid sphingomyelinases, purple acid phosphatases, nucleotidases, and bacterial cyclic nucleotide phosphodiesterases. Despite this functional diversity, MPEs show a remarkably similar structural fold and active-site architecture composed of five sequence blocks that allow metal coordination in the conserved motif D[X]H[x]nGD[x]nGNH[D/E] [x]nH[x]nGH[X]H (Matange et al., 2015). Alanine scanning assays identified the yeast Dbr1 RNA debranching active-site *in vivo* and *in vitro*, which in *E. histolytica* correspond to residues Cys14, His16, Asp45, Asn90, His91, His180, His230, and His232; in all debranching enzymes in nature, cysteine substitutes an aspartic acid residue in position 14 (Matange et al., 2015; Schwer et al., 2016).

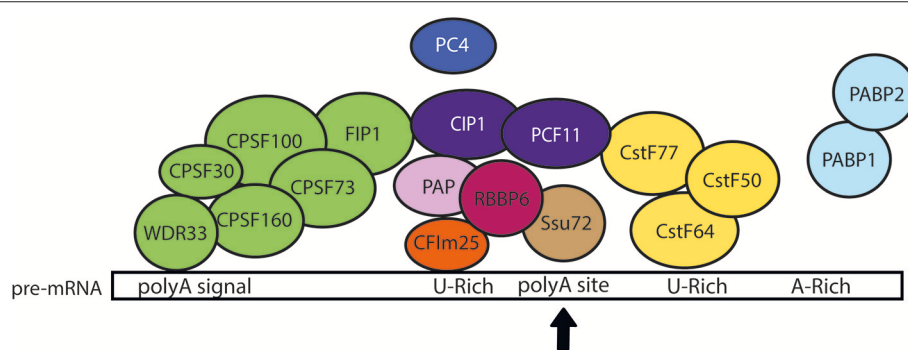
Compared to different Dbr1 orthologs, *E. histolytica* Dbr1 is the shortest protein due to its truncated C-terminus; i.e., it is  $\approx 50$  residues shorter than *S. cerevisiae* Dbr1. Thanks to its small size, *Entamoeba* Dbr1 has been able to co-crystallize with synthetic branched RNAs and analogs, providing insights of enzyme-lariat interactions. Initial structural studies confirmed the MPE  $\beta$  metal binding pocket (Montemayor et al., 2014) however there was no metal in the A pocket. Subsequent structures revealed the 2nd metal ion in the A pocket (Clark et al., 2016; Ransey et al., 2017). Importantly, this approach identified within the MPE the lariat recognition loop (LRL) whose recognition module, unique to Dbr1 enzymes, comprises residues Ile132, Tyr133, Glu138, Pro141, Tyr144, and Pro148. Dbr1-analogs co-crystals showed that Dbr1 prefers 2' purines in the branch, although the pocket could accommodate pyrimidines. In addition, there

are few sequence-specific interactions at the BS, confirming recognition of atypical BS. Finally, the interactions between RNA and the LRL are stabilized by secondary contacts between residues 141–144 of the LRL and residues Phe292, Pro293, and Phe337 of the carboxy-terminal domain (CTD) of Dbr1; and intricate hydrogen bonds centered in Arg158 aid to stabilize further the conformation of the LRL (Montemayor et al., 2014). The structural data was confirmed by Dbr1 activity *in vivo*. Whereas, *E. histolytica* wild type Dbr1 was able to complement *Saccharomyces cerevisiae* Dbr1-deletant strains relieving intron lariat accumulation, none of the constructs carrying Cys14Ala/Ser substitutions or 141-146Ala substitutions, or CTD or LRL deletions relieved intron lariat accumulation (Montemayor et al., 2014). The presence of *E. histolytica* Dbr1 in intron large post-spliceosomal complexes along with U2, U5 and U6 snRNP components, and the proteins Ntr1/TFIP11 and Prp43 (Yoshimoto et al., 2009) or the Drn1/Ygr093w protein that transiently binds Dbr1 to post-spliceosomal complexes is still unproven (Garrey et al., 2014), although our previous findings point to this possibility (Valdés et al., 2014).

## UNDERSTANDING POLYADENYLATION IN *E. HISTOLYTICA*

### Cis-Elements for Pre-mRNA 3' End Formation

One of the first reports about mRNA polyadenylation in *E. histolytica* was published in 1993 and describes the existence of a putative polyadenylation motif TAATT and a 12 pyrimidine stretch in the 3'UTR of parasite genes (Bruchhaus et al., 1993). Then, other groups showed that alternative polyadenylation sites and poly(A) tail size represent efficient postranscriptional mechanisms for gene expression regulation (Urban et al., 1996; López-Camarillo et al., 2003). But the publication of the first version of the *E. histolytica* genome sequence in 2005 (assembly of



**FIGURE 2 |** Model of the pre-mRNA 3' processing complex in *E. histolytica*. The core 3' processing complex is composed of four main complexes: CPSF (green), CstF (yellow), CFIm (orange), and CFIlm (purple) that bind *cis*-elements within pre-mRNA 3' UTR. Based on the current knowledge in other eukaryotic cells, we hypothesize that the WDR33 subunit of CPSF complex recognizes the polyadenylation signal (polyA signal) located upstream of the cleavage site (polyA site marked here with a black arrow), while CstF64 recognizes the U-rich downstream element. We also propose that the binding of CFI25 to the upstream U-rich motif promotes the recruitment of CFIm subunits (CIP1 and PCF11) and interactions between CPSF and CstF, allowing the RNA cleavage by CPSF73 and the poly(A) tail synthesis by PAP. Additional factors, such as FIP1, PC4, RBBP6, Ssu72, and PABP, would also contribute to the regulation of cleavage/polyadenylation reaction (López-Camarillo et al., 2005). Interactions between EhCFIm25 and EhPAP have been experimentally confirmed *in vitro* (Pezet-Valdez et al., 2013). Interestingly, the interaction of EhCstF77 with U1-A provided the first evidence for a link between mRNA polyadenylation and splicing in *Entamoeba* (Valdés et al., 2014).

~23 Mb that predicted 9938 coding genes comprising 49% region of the genome) (Loftus et al., 2005) represented the critical step to identify motifs in the mRNA 3'UTR and the polyadenylation machinery in this parasite.

A small-scale *in silico* analysis of cDNA and genomic sequences revealed that *E. histolytica* 3' UTRs contain three conserved motifs: (i) the consensus UA(A/U)UU polyadenylation signal or variants located 10–30 nt upstream the poly(A) site, (ii) the U-rich tract located 1–30 nt upstream the poly(A) site, and (iii) a U-rich element located 3–30 nt downstream the poly(A) site (López-Camarillo et al., 2005). Computational examination of a larger number of cDNA and genomic sequences confirmed this molecular array and suggested the presence of an additional distal A-rich element (Figure 2) (Zamorano et al., 2008). Study of the alternative usage of poly(A) sites using RNA-Seq indicated that microheterogeneity in poly(A) sites is likely to be stochastic in *E. histolytica* and only a small fraction of alternative polyadenylation isoforms appeared to be genuine (Hon et al., 2013). Interestingly, genes with alternative poly(A) sites may have a large impact on global gene expression in *E. histolytica* since most of them participate in DNA condensation, DNA binding, translation, splicing, mRNA binding, protein folding and protein transport; other genes are related to signaling, oxidation/reduction, calcium ion binding, cell cycle, and intracellular transport. Indeed, the upstream shift in poly(A) site selection resulting from the silencing of the polyadenylation factor EhCFIm25, was confirmed for thioredoxin and 60S ribosomal protein L7 transcripts and related to specific phenotypical changes and parasite death (Ospina-Villa et al., 2017).

## Polyadenylation Factors

Analyses of the 9938 coding genes predicted in the first version of the genome indicated that *E. histolytica* has genes that encode proteins with homology to the majority of polyadenylation factors described in human and yeast (Table 2): the cleavage and specificity factor (CPSF160, 100, 73, and 30), the cleavage stimulating factor (CstF77, 64, and 50), the 25 kDa subunit of the cleavage factor Im (CFIm) and both C1P1 and PCF11 subunits of CFIIIm, as well as FIP1, poly(A) polymerase (PAP), poly(A) binding protein (PABP), RBBP6 (Mpe1 in yeast), WDR33 (Psf2 in yeast), PNAS-120 (Ssu72 in yeast), and PC4 (Sub1 in yeast) (Figure 2) (López-Camarillo et al., 2005, 2014). In human cells, WDR33 and CPSF30 are the CPSF subunits that binds the polyadenylation signal (Chan et al., 2014; Schonemann et al., 2014). CPSF73 is the endonuclease responsible for RNA cleavage (Mandel et al., 2006). CstF77 interacts with CPSF160, promoting their cooperative RNA binding during the assembly process (Murthy and Manley, 1995). CFIm25 regulates the selection of distal poly(A) sites, contributes to the recruitment of polyadenylation factors and is necessary for poly(A) tail synthesis (Brown and Gilmartin, 2003; Kubo et al., 2006). Although CFIIIm subunits are the less characterized polyadenylation factors, evidence suggest that Pcf11 is required for degradation of the 3' product following cleavage (West and Proudfoot, 2008), while Clp1 interacts with both CPSF and CFIm and likely tethers them to CFIIIm (de Vries et al., 2000). PAP is responsible

**TABLE 2 |** Polyadenylation factors in human and *E. histolytica*.

<i>H. sapiens</i>		<i>E. histolytica</i>		
Protein	Access number <sup>a</sup>	Locus <sup>b</sup>	Protein	Access number <sup>a</sup>
<b>CLEAVAGE AND POLYADENYLATION SPECIFIC FACTORS</b>				
CPSF160	Q10570	EHI_160110	CPSF160	C4M386
CPSF100	Q9P210	EHI_033130	CPSF100	C4M6Y0
CPSF73	Q9UKF6	EHI_136700	CPSF73	C4M297
CPSF30	O95639	EHI_067580	CPSF30	C4M9G4
FIP1	Q6UN15	EHI_052180	FIP1	C4M765
WDR33	Q9C0J8	EHI_170080	WDR33	C4M1D0
<b>CLEAVAGE STIMULATING FACTORS</b>				
CstF77	Q12996	EHI_098370	CstF-77	B1N2W3
CstF64	P33240	EHI_151900	CstF-64	C4LSN8
CstF50	Q05048	EHI_152770	CstF-50	C4LSW0
<b>CLEAVAGE FACTORS IM</b>				
CFIm68	Q16630	–	–	–
CFIm59	Q8N684	–	–	–
CFIm25	O43809	EHI_077110	CFIm25	C4M2T1
<b>CLEAVAGE FACTORS IIIM</b>				
CIP1	Q92989	EHI_008100	CIP1	C4LYE5
PCF11	O94913	EHI_045130	PCF11	C4LTC6
<b>OTHER POLYADENYLATION FACTORS</b>				
PAP-B	Q9NRJ5	EHI_012040	PAP	Q51D88
Ssu72	Q9BZS6	EHI_027340	Ssu72	C4M1T3
PC4	P53999	EHI_192520	PC4	C4M1H2
PABP1	P11940	EHI_198750	PABP1	C4LWS1
		EHI_033250	PABP2	C4M6Y2
RBBP6	Q7Z6E9	EHI_014000	RBBP6	C4LXP1
Symplekin	Q92797	–	–	–

<sup>a</sup>UniProtKB; <sup>b</sup>AmoebaDB. Data about parasite proteins were obtained from (López-Camarillo et al., 2005, 2014).

for the addition of the polyadenosine tail (Raabe et al., 1991) and its activity is accelerated by PABP (Wahle, 1991). RBBP6 associates with other core polyadenylation factors through its unusual ubiquitin-like domain and modulates expression of mRNAs with AU-rich 3' UTR (Di Giammartino et al., 2014). PC4 (Sub1 in yeast) associates with the polyadenylation factor CstF64 to modulate transcription termination and polyadenylation initiation (Calvo and Manley, 2001, 2003).

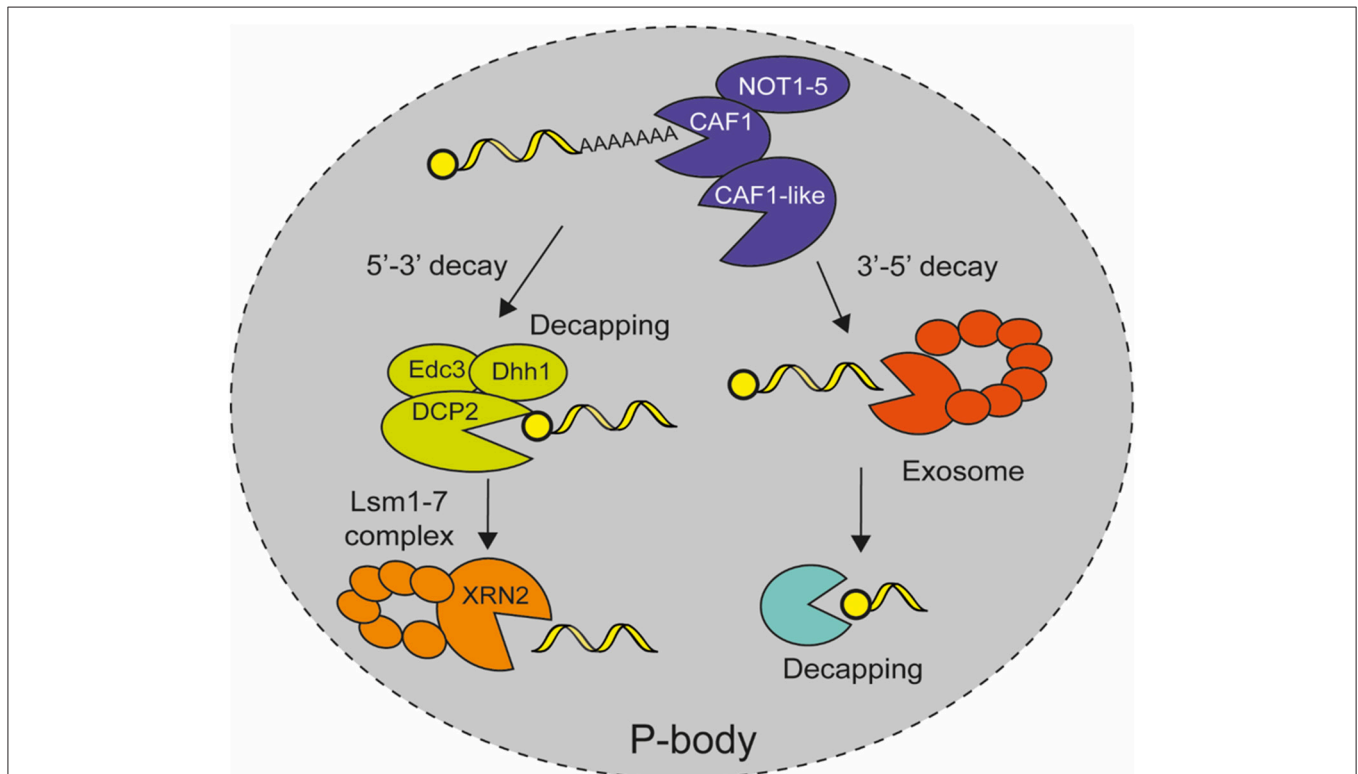
The presence of these proteins in *E. histolytica* suggests that 3' end processing of parasite mRNA could be performed as it has been described in other eukaryotic cells. Accordingly, EhPAP has the conserved PAP central catalytic domain with the three invariant aspartate residues involved in nucleotide transfer and the F/YGS motif responsible for ATP binding, confirming that it belongs to the polymerases-like superfamily of nucleotidyl transferases (García-Vivas et al., 2005). In the predicted three-dimensional model, both functional domains fold as a U-shaped structure that likely orients the incoming ATP and RNA molecules for poly(A) tail extension. In agreement with its expected role in the poly(A) tail synthesis, EhPAP was

able to bind RNA 3' end although it has a divergent RNA-binding domain (RBD). Moreover, it was located in punctuate nuclear *foci* and in cytoplasmic dots, as it has been described for other polyadenylation factors (García-Vivas et al., 2005; López-Camarillo et al., 2007).

As the human homolog, the EhCFIm25 protein is an unconventional Nudix protein lacking three of the four conserved E residues and the last G residue of the Nudix box, which suggests that it is not able to cleave RNA. Despite the absence of a classical RBD, EhCFIm25 is able to bind the 3' UTR of *E. histolytica* transcripts and this interaction involves the participation of the conserved Leu135 and Tyr236 residues (Ospina-Villa et al., 2015). EhCFIm25 recognizes the GUUG motif in mRNA 3' end, while the human protein binds the UGUA sequence; consequently, aptamers containing this motif specifically identify the parasite protein, suggesting that they could be used as molecular tools for diagnosis or therapeutic purposes (Ospina-Villa et al., 2018). Interestingly, EhCFIm25 interacts with EhPAP (Pezet-Valdez et al., 2013), which indicates that it may be introduced into the processing complex in the early steps of the cleavage/polyadenylation reaction. EhCFIm25 controls the selection of the distal poly(A) site during mRNA 3' end formation; consequently, its silencing by dsRNA or its blocking by aptamers alter parasite proliferation and virulence, demonstrating for the first time the relevance of polyadenylation

factors as biochemical targets in *E. histolytica* (Ospina-Villa et al., 2017, 2018). Other works have also recently reported that targeting polyadenylation factors represents a valuable strategy for the control of the protozoan parasites *Trypanosoma brucei* (CPSF-30), *Toxoplasma gondii*, and *Plasmodium falciparum* (CPSF-73) (Hendriks et al., 2003; Sidik et al., 2016; Palencia et al., 2017; Sonoiki et al., 2017).

EhPC4 is the homolog of the human positive coactivator 4, a multifunctional protein that establishes an important link between transcription and polyadenylation. On one hand, its binding to promoters facilitates the recruitment of transcription factors to stimulate the pre-initiation complex assembly (Conesa and Acker, 2010); on the other hand, its interaction with EhCstF64 avoids premature transcription termination and polyadenylation initiation until the polyadenylation motifs have been transcribed (Calvo and Manley, 2001). Moreover, it mediates chromatin organization and heterochromatin gene silencing by interacting with histones H3 and H2B (Das et al., 2006, 2010). As homologous proteins, the EhPC4 protein contains a single-strand DNA (ssDNA) binding region whose residue K127 is required for DNA interaction, and a dimerization domain in the so-called PC4 domain at the C-terminus (Hernandez de la Cruz et al., 2014). Interestingly EhPC4 and its potential partner, EhCstf-64, were significantly up-regulated in virulent trophozoites (Santi-Rocca et al., 2008). Consistently,



**FIGURE 3 |** Model for mRNA decay in *E. histolytica*. After mature mRNAs are exported to the cytoplasm where they are eventually translated in a regulated manner, they are later degraded in cytoplasmic P-bodies like structures. The mRNA degradation pathway starts with transcript deadenylation by the CAF1/NOT complex. Then, DCP2 mRNA decapping enzyme removes the cap structure from the 5' end of the mRNA with the help of accessories proteins Edc3 and Dhh1, which allows 5'-3' exoribonuclease XRN2 with Lsm protein complex to degrade the rest of mRNA body. Alternatively, the deadenylated transcript is degraded in a 3'-5' direction by the catalytic subunit Dis3 of the exosome complex and the cap structure is eliminated by DCPs protein (López-Rosas et al., 2012, 2014).

the overexpression of EhPC4 induced the modulation of proteins with key functions in cytoskeleton dynamics, cell migration and invasion in trophozoites. Among them, the up-regulation of a 16-kDa actin-binding protein (EhABP16) which is a putative member of the cofilin/tropomyosin family involved in actin polymerization was associated with an increase in parasite migration of trophozoites and destruction of human SW480 colon cells, confirming that EhPC4 has an impact on parasite virulence (Hernandez de la Cruz et al., 2014). On the other hand, the overexpression of EhPC4 significantly increased cell proliferation, DNA replication and DNA content of trophozoites, promoting the formation of giant multinucleated trophozoites. EhPC4 modulates the expression of genes involved in carbohydrate and nucleic acid metabolism, chromosome segregation and cytokinesis, evidencing the relevance of this factor in polyploidy and genome stability in *E. histolytica* (Hernández de la Cruz et al., 2016). The role of EhPC4 in mRNA 3' end formation and its relevance for the events mentioned above remain to be investigated.

## MOLECULAR EVENTS FOR MRNA DECAY IN *E. HISTOLYTICA*

### mRNA Degradation Machineries

*E. histolytica* has most of the factors that are involved in mRNA degradation in eukaryotic cells, including proteins involved in deadenylation, decapping, and exonuclease activity, but it lacks several components (Table 3) (López-Rosas et al., 2012). The reduced mRNA deadenylation machinery includes the CAF1/NOT complex with the five NOT proteins and the poly-A specific ribonucleases CAF1 and CAF1-like, but the carbon catabolite repressor 4 (CCR4) described in yeast and human, as well as PAN2, PAN3, and PARN deadenylases, are missing (Figure 3). EhCAF1 is a ribonuclease D family member, having the CAF1 nuclease domain and the conserved DEDD residues (D<sub>84</sub>E<sub>86</sub>D<sub>206</sub>D<sub>276</sub>) that are important for 3' to 5' exonuclease activity in homologous proteins (Daugeron et al., 2001). Consequently, EhCAF1 is a functional deadenylase that binds 3'UTR and degrades the poly(A) tail of parasite transcripts in *in vitro* assays (López-Rosas et al., 2014).

Although capping has not been described in *E. histolytica*, bioinformatics analyses revealed the existence of a decapping complex that is formed by the catalytic subunit EhDCP2, and EhXRN2, EhLSM1–6, EhEDC3, and EhDHH1 as decapping associated proteins, whereas it also includes DCP1, SCD6, PAT1, and LSM7 in yeast and animals (Table 3; Figure 3) (López-Rosas et al., 2012). EhXRN2 and EhDCP2 have the typical architecture of homologous proteins. Notably, EhXRN2 has the XRN\_N nuclease domain and the internal tower domain with the active site motif KX<sub>2</sub>QQX<sub>2</sub>RR, which is critical for ribonuclease function (Xiang et al., 2009). EhDCP2 has the conserved DCP2 box A domain and the conserved nudix Box (GX<sub>5</sub>EX<sub>7</sub>REUXEEXGU) that are both responsible for cap structure removal (She et al., 2008). In eukaryotic cells, the elimination of the 5' cap compromises mRNA to 5' to 3'

**TABLE 3** | Comparison of mRNA decay machineries between human and *E. histolytica*.

<i>H. sapiens</i>		<i>E. histolytica</i>				
Protein	Access number <sup>a</sup>	Locus <sup>b</sup>	Protein	Access number <sup>a</sup>	References	
<b>DECAPPING FACTORS</b>						
DCP2	Q8IU60	EHL_058810	EhDCP2	C4M5G6	López-Rosas et al., 2012	
Lsm1	O15116	EHL_188020	EhLsm 1	B1N3A8		
Lsm2	Q9Y333	EHL_068580	EhLsm2	C4LU49		
Lsm3	P62310	EHL_151310	EhLsm3	C4LSH4		
Lsm4	Q9Y4Z0	EHL_049370	EhLsm4	C4LUD9		
Lsm5	Q9Y4Y9	EHL_076840	EhLsm5	B1N3I3		
Lsm6	P62312	EHL_188130	EhLsm6	C4M187		
Lsm7	Q9UK45	EHL_025840	EhLsm7	C4M939		
Edc3	Q96F86	EHL_198940	Ehedc3	C4LWU0		
Dhh1	P26196	EHL_093900	Ehdhh1	C4LY11		
XRN2	Q9H0D6	EHL_133330	EhXRN2	C4MB40		
<b>DEADENYLATION FACTORS</b>						
CAF1	Q9UIV1	EHL_048150	EhCAF1	Q56AY2		López-Rosas et al., 2012, 2014
CALIF	Q9UFF9	EHL_039000	EhCAF1-like	C4LZS1		López-Rosas et al., 2012
NOT1	A5YKK6	EHL_200810	EhNOT1	C4M3Y6		
NOT2	Q9NZN8	EHL_044180	EhNOT2	C4M790		
NOT3	O75175	EHL_119550	EhNOT3	C4M7Y3		
NOT4	O95628	EHL_080710	EhNOT4	C4M9N9		
<b>EXOSOME FACTORS</b>						
RRP4	Q13868	EHL_163510	EhRRP4	C4M3T2	López-Camarillo et al., 2014	
RRP6	Q01780	EHL_021400	EhRRP6	C4M054		
RRP40	Q9NQ75	EHL_004770	EhRRP40	C4M073		
RRP41	Q9NPD3	EHL_040320	EhRRP41	C4M2G1		
RRP42	Q15024	EHL_000580	EhRRP42	C4LZA9		
RRP43	Q96B26	EHL_188080	EhRRP43	C4M182		
RRP46	Q9NQ74	EHL_086520	EhRRP46	C4M8Y9		
MTR3	Q5RKV6	EHL_126330	EhMTR3	C4LW17		
DIS3	Q9Y2L1	EHL_160720	EhDIS3	C4MAJ9		
<b>NON-SENSE MEDIATED DECAY FACTOR</b>						
UPF1	Q92900	EHL_035550	EhUpf1	C4LXY5	López-Rosas et al., 2012	
<b>RNA INTERFERENCE FACTORS</b>						
AGO2	Q9UKV8	EHL_186850	EhAGO2-1	C4LVQ2	Zhang et al., 2008	
–	–	EHL_125650	EhAGO2-2	C4LVV2		
–	–	EHL_177170	EhAGO2-3	C4LY31		
–	–	EHL_139420	EhRdRP	C4M6W7		
–	–	EHL_179800	EhRdRP	C4M631		
DICER	Q9UPY3	EHL_068740	EhRNAsell	C4LU64	Abed and Ankr, 2005; Zhang et al., 2008	

<sup>a</sup>UniProtKB; <sup>b</sup>AmoebaDB.

exonucleolytic decay, apparently in an irreversible way, hence, decapping activity is tightly regulated (Li and Kiledjian, 2010). The heptameric Lsm1–7 complex associates with the 3' end of deadenylated mRNAs and promotes decapping (Tharun et al., 2000; Tharun and Parker, 2001). The activity of the decapping enzyme is stimulated by accessory proteins, such as Edc proteins,



the DEXD/H-box RNA helicases Dhh1 and Pat1 (Bonnerot et al., 2000; Schwartz et al., 2003).

*E. histolytica* contains seven exosome encoding genes including Rrp41, Rrp43, Rrp46, Mtr3-Rrp42 and the catalytic subunit Dis3, as well as accessory stabilizing Rrp4, and Rrp40 proteins; but it lacks Rrp45 and Csl4 genes (Table 3; Figure 3) (López-Rosas et al., 2012). The EhRRP41 protein colocalizes and physically interacts with EhL-PSP, which also interacts and colocalizes with the EhCAF1 deadenylase. But the fact that EhRRP41 did not coimmunoprecipitate with EhCAF1, suggests the existence of two EhL-PSP-containing complexes. The colocalization of exosome factors (EhRrp41) with EhCAF1 and EhL-PSP in trophozoites showed novel interactions between mRNA degradation protein and suggests the existence of cooperative interactions between mRNA decay machineries in *E. histolytica* (López-Rosas et al., 2014). In yeast and human, the nine subunits of the exosome complex form a ring structure in which Dis3 (RRP44) is the key player in mRNA turnover being the catalytic subunit responsible for exonucleolytic and endonucleolytic activities in the 3'-5' decay of deadenylated transcripts in cytoplasm (Ibrahim et al., 2008). Additionally, the nuclear exosome is involved in 3'-end trimming of rRNA, snRNA, and snoRNA, as well as mRNA surveillance and degradation of cryptic unstable transcripts (Parker and Song, 2004).

*E. histolytica* genome also contains genes for components of the NMD and RNA interference (RNAi) pathways, namely three Ehupf genes (López-Rosas et al., 2012), as well as two EhRdRP, one EhRNaseIII and three EhAGO2 proteins (Abed and Ankri, 2005; Zhang et al., 2008, 2011), respectively (Table 3). The absence of DICER and GW182 homologs suggests that RNA interference may use DICER-independent mechanisms in *E. histolytica* (Zhang et al., 2011). Pompey et al. (2015) recently showed that EhRNaseIII is able to cleave dsRNA to generate shorter fragments in a heterologous system. This suggests that EhRNaseIII in conjunction with other amoebic factors might reconstitute an active DICER-like complex. Congruently, numerous reports involving gene-silencing assays confirmed the functionality of the RNAi pathway in *E. histolytica*.

## P-Body-Like Structures

Several experiments suggest that mRNA decay reactions, namely deadenylation, decapping, and 5'-exonucleolytic decay, take place in microscopically detectable cytoplasmic P-bodies like structures in *E. histolytica* (López-Rosas et al., 2012), as it has been described in other eukaryotic cells (Sheth and Parker, 2003). The EhCAF1 deadenylase, EhXRN2 exoribonuclease and EhDCP2 decapping proteins, as well as the EhAGO2-2 protein, were detected in cytoplasmic foci in immunofluorescence and confocal microscopy experiments (López-Rosas et al., 2012). Additionally biochemical analysis revealed that EhCAF1 coimmunoprecipitated with EhXRN2, thus linking deadenylation to 5'-to-3' mRNA degradation. Interestingly, these cytoplasmic structures also contain polyadenylated transcripts and dsRNA, which is congruent with their role in RNA decay. Moreover their formation depends on the presence of active transcription

and translation (López-Rosas et al., 2012), as well as cellular stress, such as DNA damage, heat shock, and nitric oxide (López-Rosas et al., 2014), which make them *bona fide* P-body structures (Figure 3). Altogether, these data suggest that, as in human cells, the accumulation of transcripts in cytoplasmic P-bodies like structures for silencing or decay, represents a key regulatory process for gene expression regulation in response to specific conditions or signals in *E. histolytica*.

## CONCLUSION

Besides the evolutionary distance between *E. histolytica* and its human host, the screening of parasite genome sequences and the functional characterization of specific factors, revealed that molecular mechanisms regulating mRNA processing and degradation seem to be roughly similar in both organisms. Several subtle differences exist, but canonical factors involved in splicing, polyadenylation and decay are generally conserved in this primitive eukaryote, which highlights that these events are key players for gene expression regulation in eukaryotic cells. The study of a larger number of factors involved in splicing, polyadenylation or mRNA degradation remains to be addressed to elucidate all the relationship among these reactions. In addition to contribute to the better understanding of posttranscriptional regulation in *E. histolytica*, the characterization of these factors and events may also lead to the identification of a biochemical target involved in various mRNA processing pathways, whose inhibition would have a massive impact on parasite survival. On the other hand, recent data indicated the potential of factors involved in polyadenylation as biochemical targets for parasite control, which may open the way for the design of new molecules for the control of this parasitic disease. In this context, the results of the proof-of-concept study in *E. histolytica* may promote the use of aptamers to control *E. histolytica* during the development of amoebiasis or to eradicate residual trophozoites during antibiotic treatment. Further experiments are required to confirm their affinity, evaluate their effect *in vivo* and improve their bioavailability.

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## AUTHOR CONTRIBUTIONS

JV-F, IL-R, CL-C, ER-M, and JO-V reviewed data about mRNA splicing, polyadenylation and decay, respectively. JO-V designed the figures. CL-C and LM designed the review organization, revised and integrated the different parts of the manuscript.

## REFERENCES

- Abed, M., and Ankri, S. (2005). Molecular characterization of *Entamoeba histolytica* RNase, III and AGO2, two RNA interference hallmark proteins. *Exp. Parasitol.* 110, 265–269. doi: 10.1016/j.exppara.2005.02.023
- Bartschat, S., and Samuelsson, T. (2010). U12 type introns were lost at multiple occasions during evolution. *BMC Genomics* 11:106. doi: 10.1186/1471-2164-11-106
- Bonnerot, C., Boeck, R., and Lapeyre, B. (2000). The two proteins Pat1p (Mrt1p) and Spb8p interact *in vivo*, are required for mRNA decay, and are functionally linked to Pab1p. *Mol. Cell. Biol.* 20, 5939–5946. doi: 10.1128/MCB.20.16.5939-5946.2000
- Brown, K. M., and Gilmartin, G. M. (2003). A mechanism for the regulation of pre-mRNA 3' processing by human cleavage factor Im. *Mol. Cell* 12, 1467–1476. doi: 10.1016/S1097-2765(03)00453-2
- Bruchhaus, I., Leippe, M., Lioutas, C., and Tannich, E. (1993). Unusual gene organization in the protozoan parasite *Entamoeba histolytica*. *DNA Cell. Biol.* 12, 925–933.
- Calvo, O., and Manley, J. L. (2001). Evolutionarily conserved interaction between CstF-64 and PC4 links transcription, polyadenylation, and termination. *Mol. Cell* 7, 1013–1023. doi: 10.1016/S1097-2765(01)00236-2
- Calvo, O., and Manley, J. L. (2003). Strange bedfellows: polyadenylation factors at the promoter. *Genes Dev.* 17, 1321–1327. doi: 10.1101/gad.1093603
- Chan, S. L., Huppertz, I., Yao, C., Weng, L., Moresco, J. J., Yates, J. R. III., et al. (2014). CPSF30 and Wdr33 directly bind to AAUAAA in mammalian mRNA 3' processing. *Genes Dev.* 28, 2370–2380. doi: 10.1101/gad.250993.114
- Christie, M., Brosnan, C. A., Rothnagel, J. A., and Carroll, B. J. (2011). RNA decay and RNA silencing in plants: competition or collaboration? *Front. Plant Sci.* 2:99. doi: 10.3389/fpls.2011.00099
- Clark, N. E., Katolik, A., Roberts, K. M., Taylor, A. B., Holloway, S. P., Schuermann, J. P., et al. (2016). Metal dependence and branched RNA cocrystal structures of the RNA lariat debranching enzyme Dbr1. *Proc. Natl. Acad. Sci. U.S.A.* 113, 14727–14732. doi: 10.1073/pnas.1612729114
- Collins, L., and Penny, D. (2005). Complex spliceosomal organization ancestral to extant eukaryotes. *Mol. Biol. Evol.* 22, 1053–1066. doi: 10.1093/molbev/msi091
- Conesa, C., and Acker, J. (2010). Sub1/PC4a chromatin associated protein with multiple functions in transcription. *RNA Biol.* 7, 287–290. doi: 10.4161/rna.7.3.11491
- Cowling, V. H. (2010). Regulation of mRNA cap methylation. *Biochem. J.* 425, 295–302. doi: 10.1042/BJ20091352
- Das, C., Gadad, S. S., and Kundu, T. K. (2010). Human positive coactivator 4 controls heterochromatinization and silencing of neural gene expression by interacting with REST/NRSF and Corest. *J. Mol. Biol.* 397, 1–12. doi: 10.1016/j.jmb.2009.12.058
- Das, C., Hizume, K., Batta, K., Kumar, B. R., Gadad, S. S., Ganguly, S., et al. (2006). Transcriptional coactivator pc4, a chromatin-associated protein, induces chromatin condensation. *Mol. Cell. Biol.* 26, 8303–8315. doi: 10.1128/MCB.00887-06
- Daugeron, M. C., Mauxion, F., and Séraphin, B. (2001). The yeast POP2 gene encodes a nuclease involved in mRNA deadenylation. *Nucleic Acids Res.* 29, 2448–2455. doi: 10.1093/nar/29.12.2448
- David, C. J., Boyne, A. R., Millhouse, S. R., and Manley, J. L. (2011). The RNA polymerase II C-terminal domain promotes splicing activation through recruitment of a U2AF65-Prp19 complex. *Genes Dev.* 25, 972–983. doi: 10.1101/gad.2038011
- Dávila López, M., Rosenblad, M. A., and Samuelsson, T. (2008). Computational screen for spliceosomal RNA genes aids in defining the phylogenetic distribution of major and minor spliceosomal components. *Nucleic Acids Res.* 36, 3001–3010. doi: 10.1093/nar/gkn142
- Davis, C. A., Brown, M. P., and Singh, U. (2007). Functional characterization of spliceosomal introns and identification of U2, U4, and U5 snRNAs in the deep-branching eukaryote *Entamoeba histolytica*. *Eukaryotic Cell* 6, 940–948. doi: 10.1128/EC.00059-07
- de Vries, H., Rügsegger, U., Hübner, W., Friedlein, A., Langen, H., and Keller, W. (2000). Human pre-mRNA cleavage factor II(m) contains homologs of yeast proteins and bridges two other cleavage factors. *EMBO J.* 19, 5895–5904. doi: 10.1093/emboj/19.21.5895
- Di Giammartino, D. C., Li, W., Ogami, K., Yashinskie, J. J., Hoque, M., Tian, B., et al. (2014). RBBP6 isoforms regulate the human polyadenylation machinery and modulate expression of mRNAs with AU-rich 3' UTRs. *Genes Dev.* 28, 2248–2260. doi: 10.1101/gad.245787.114
- Eulalio, A., Behm-Ansmant, I., and Izaurralde, E. (2007). P-bodies: at the crossroads of post-transcriptional pathways. *Nat. Rev. Mol. Cell Biol.* 8, 9–22. doi: 10.1038/nrm2080
- Förch, P., Puig, O., Martínez, C., Séraphin, B., and Valcárcel, J. (2002). The splicing regulator TIA-1 interacts with U1-C to promote U1 snRNP recruitment to 5' splice sites. *EMBO J.* 21, 6882–6892. doi: 10.1093/emboj/cdf668
- Fourmann, J. B., Schmitzová, J., Christian, H., Urlaub, H., Ficner, R., Boon, K. L., et al. (2013). Dissection of the factor requirements for spliceosome disassembly and the elucidation of its dissociation products using a purified splicing system. *Genes Dev.* 27, 413–428. doi: 10.1101/gad.207779.112
- Furth, P. A., Choe, W. T., Rex, J. H., Byrne, J. C., and Baker, C. C. (1994). Sequences homologous to 5' splice sites are required for the inhibitory activity of papillomavirus late 3' untranslated regions. *Mol. Cell. Biol.* 14, 5278–5289.
- García-Vivas, J., López-Camarillo, C., Azuara-Liceaga, E., Orozco, E., and Marchat, L. A. (2005). *Entamoeba histolytica*: cloning and expression of the poly(A) polymerase EhPAP. *Exp. Parasitol.* 110, 226–232. doi: 10.1016/j.exppara.2005.02.017
- Garrey, S. M., Katolik, A., Prekeris, M., Li, X., York, K., Bernards, S., et al. (2014). A homolog of lariat-debranching enzyme modulates turnover of branched RNA. *RNA* 20, 1337–1348. doi: 10.1261/rna.044602.114
- Gu, B., Eick, D., and Bensaude, O. (2013). CTD serine-2 plays a critical role in splicing and termination factor recruitment to RNA polymerase II *in vivo*. *Nucleic Acids Res.* 41, 1591–1603. doi: 10.1093/nar/gks1327
- Gunderson, S. I., Beyer, K., Martin, G., Keller, W., Boelens, W. C., and Mattaj, L. W. (1994). The human U1A snRNP protein regulates polyadenylation via a direct interaction with poly(A) polymerase. *Cell* 76, 531–541. doi: 10.1016/0092-8674(94)90116-3
- Gunderson, S. I., Vagner, S., Polycarpou-Schwarz, M., and Mattaj, I. W. (1997). Involvement of the carboxyl terminus of vertebrate poly(A) polymerase in U1A autoregulation and in the coupling of splicing and polyadenylation. *Genes Dev.* 11, 761–773. doi: 10.1101/gad.11.6.761
- Hahn, D., Kudla, G., Tollervy, D., and Beggs, J. D. (2012). Brr2p-mediated conformational rearrangements in the spliceosome during activation and substrate repositioning. *Genes Dev.* 26, 2408–2421. doi: 10.1101/gad.199307.112
- Hendriks, E. F., Abdul-Razak, A., and Matthews, K. R. (2003). tbCPSF30 depletion by RNA interference disrupts polycistronic RNA processing in *Trypanosoma brucei*. *J. Biol. Chem.* 278, 26870–26878. doi: 10.1074/jbc.M302405200
- Hernández de la Cruz, O., Marchat, L. A., Guillén, N., Weber, C., López Rosas, I., Díaz-Chávez, J., et al. (2016). Multinucleation and polykaryon formation is promoted by the EhPC4 transcription factor in *Entamoeba histolytica*. *Sci. Rep.* 6:19611. doi: 10.1038/srep19611
- Hernandez de la Cruz, O. N., Muñoz-Lino, M., Guillén, N., Weber, C., Marchat, L. A., López Rosas, I., et al. (2014). Proteomic profiling reveals that EhPC4 transcription factor induces cell migration through upregulation of the 16-kDa actin-binding protein EhABP16 in *Entamoeba histolytica*. *J. Proteomics* 111, 46–58. doi: 10.1016/j.jprot.2014.03.041
- Hernández-Rivas, R., Ramírez, C., Guillén, N., and Vargas, M. (2000). DNA cloning of the *Entamoeba histolytica* PRP6 gene: a putative U4/U6 small nuclear ribonucleoprotein particle (snRNP). *Arch. Med. Res.* 31, S294–295. doi: 10.1016/S0188-4409(00)00119-3
- Hon, C. C., Weber, C., Sismeiro, O., Proux, C., Koutero, M., Deloger, M., et al. (2013). Quantification of stochastic noise of splicing and polyadenylation in *Entamoeba histolytica*. *Nucleic Acids Res.* 41, 1936–1952. doi: 10.1093/nar/gks1271
- Huang, S. C., Ou, A. C., Park, J., Yu, F., Yu, B., Lee, A., et al. (2012). RBFOX2 promotes protein 4.1R exon 16 selection via U1 snRNP recruitment. *Mol. Cell. Biol.* 32, 513–526. doi: 10.1128/MCB.06423-11
- Ibrahim, H., Wilusz, J., and Wilusz, C. J. (2008). RNA recognition by 3'-to-5' exonucleases: the substrate perspective. *Biochim. Biophys. Acta* 1779, 256–265. doi: 10.1016/j.bbagr.2007.11.004
- Isken, O., and Maquat, L. E. (2008). The multiple lives of NMD factors: balancing roles in gene and genome regulation. *Nat. Rev. Genet.* 9, 699–712. doi: 10.1038/nrg2402

- Kandels-Lewis, S., and Séraphin, B. (1993). Involvement of U6 snRNA in 5' splice site selection. *Science* 262, 2035–2039. doi: 10.1126/science.8266100
- Kubo, T., Wada, T., Yamaguchi, Y., Shimizu, A., and Handa, H. (2006). Knock-down of 25 kDa subunit of cleavage factor Im in HeLa cells alters alternative polyadenylation within 30-UTRs. *Nucleic Acids Res.* 34, 6264–6271. doi: 10.1093/nar/gkl794
- Kyburz, A., Friedlein, A., Langen, H., and Keller, W. (2006). Direct interactions between subunits of CPSF and the U2 snRNP contribute to the coupling of pre-mRNA 3' end processing and splicing. *Mol. Cell* 23, 195–205. doi: 10.1016/j.molcel.2006.05.037
- Labno, A., Tomecki, R., and Dziembowski, A. (2016). Cytoplasmic RNA decay pathways - Enzymes and mechanisms. *Biochim. Biophys. Acta* 1863, 3125–3147. doi: 10.1016/j.bbamcr.2016.09.023
- Larson, J. D., and Hoskins, A. A. (2017). Dynamics and consequences of spliceosome E complex formation. *Elife* 6:e27592. doi: 10.7554/eLife.27592
- Li, Y., and Kiledjian, M. (2010). Regulation of mRNA decapping. *Wiley Interdiscip. Rev. RNA* 1, 253–265. doi: 10.1002/wrna.15
- Liu, Z. R. (2002). p68 RNA helicase is an essential human splicing factor that acts at the U1 snRNA-5' splice site duplex. *Mol. Cell. Biol.* 22, 5443–5450. doi: 10.1128/MCB.22.15.5443-5450.2002
- Loftus, B., Anderson, I., Davies, R., Alsmark, U. C., Samuelson, J., Amedeo, P., et al. (2005). The genome of the protist parasite *Entamoeba histolytica*. *Nature* 433, 865–868. doi: 10.1038/nature03291
- López-Camarillo, C., López-Rosas, I., Ospina-Villa, J. D., and Marchat, L. A. (2014). Deciphering molecular mechanisms of mRNA metabolism in the deep-branching eukaryote *Entamoeba histolytica*. *Wiley Interdiscip. Rev. RNA* 5, 247–262. doi: 10.1002/wrna.1205
- López-Camarillo, C., Luna-Arias, J. P., Marchat, L. A., and Orozco, E. (2003). EhPgp5 mRNA stability is a regulatory event in the *Entamoeba histolytica* multidrug resistance phenotype. *J. Biol. Chem.* 278, 11273–11280. doi: 10.1074/jbc.M211757200
- López-Camarillo, C., Marchat, L. A., Orozco, E., Azuara-Liceaga, E., and García-Vivas, J. (2007). “Canonical and non canonical poly(A) polymerases: from human to the protozoan parasite *Entamoeba histolytica*,” in *Messenger RNA Research Perspectives*, ed T. Takeyama (Hauppauge, NY: Nova Publishers), 125–144.
- López-Camarillo, C., Orozco, E., and Marchat, L. A. (2005). *Entamoeba histolytica*: comparative genomics of the pre-mRNA 3' end processing machinery. *Exp. Parasitol.* 110, 184–190. doi: 10.1016/j.exppara.2005.02.024
- López-Rosas, I., Marchat, L. A., Olvera, B. G., Guillen, N., Weber, C., Hernández de la Cruz, O., et al. (2014). Proteomic analysis identifies endoribonuclease EhL-PSP and EhRRP41 exosome protein as novel interactors of EhCAF1 deadenylase. *J. Proteomics* 111, 59–73. doi: 10.1016/j.jpro.2014.06.019
- López-Rosas, I., Orozco, E., Marchat, L. A., García-Rivera, G., Guillen, N., Weber, C., et al. (2012). mRNA decay proteins are targeted to poly(A)+RNA and dsRNA-containing cytoplasmic foci that resemble P-bodies in *Entamoeba histolytica*. *PLoS ONE* 7:e45966. doi: 10.1371/journal.pone.0045966
- Lutz, C. S., Murthy, K. G., Schek, N., O'Connor, J. P., Manley, J. L., and Alwine, J. C. (1996). Interaction between the U1 snRNP-A protein and the 160-kD subunit of cleavage-polyadenylation specificity factor increases polyadenylation efficiency *in vitro*. *Genes Dev.* 10, 325–337.
- Mandel, C. R., Kaneko, S., Zhang, H., Gebauer, D., Vethantham, V., Manley, J. L., et al. (2006). Polyadenylation factor CPSF-73 is the pre-mRNA 3'-end-processing endonuclease. *Nature* 444, 53–56. doi: 10.1038/nature05363
- Marchat, L. A., Orozco, E., Guillen, N., Weber, C., and López-Camarillo, C. (2008). Putative DEAD and DEXH-box RNA helicases families in *Entamoeba histolytica*. *Gene* 424, 1–10. doi: 10.1016/j.gene.2008.07.042
- Matange, N., Podobnik, M., and Visweswariah, S. S. (2015). Metallophosphoesterases: structural fidelity with functional promiscuity. *Biochem. J.* 467, 201–216. doi: 10.1042/BJ20150028
- McGuire, A. M., Pearson, M. D., Neafsey, D. E., and Galagan, J. E. (2008). Cross-linking patterns of alternative splicing and splice recognition. *Genome Biol.* 9:R50. doi: 10.1186/gb-2008-9-3-r50
- Millevoi, S., Loulergue, C., Dettwiler, S., Karaa, S. Z., Keller, W., Antoniou, M., et al. (2006). An interaction between U2AF 65 and CF I(m) links the splicing and 3' end processing machineries. *EMBO J.* 25, 4854–4864. doi: 10.1038/sj.emboj.7601331
- Miranda, R., Salgado, L. M., Sánchez-López, R., Alagón, A., and Lizardi, P. M. (1996). Identification and analysis of the u6 small nuclear RNA gene from *Entamoeba histolytica*. *Gene* 180, 37–42. doi: 10.1016/S0378-1119(96)00397-6
- Montemayor, E. J., Katolik, A., Clark, N. E., Taylor, A. B., Schuermann, J.P., Combs, D. J., et al. (2014). Structural basis of lariat RNA recognition by the intron debranching enzyme Dbr1. *Nucleic Acids Res.* 42, 10845–10855. doi: 10.1093/nar/gku725
- Murthy, K. G., and Manley, J. L. (1995). The 160-kD subunit of human cleavage-polyadenylation specificity factor coordinates pre-mRNA 3'-end formation. *Genes Dev.* 9, 2672–2683. doi: 10.1101/gad.9.21.2672
- Ospina-Villa, J. D., Dufour, A., Weber, C., Ramirez-Moreno, E., Zamorano-Carrillo, E., Guillen, N., et al. (2018). Targeting the polyadenylation factor EhCFIm25 with RNA aptamers controls survival in *Entamoeba histolytica*. *Sci. Rep.* 8:5720. doi: 10.1038/s41598-018-23997-w
- Ospina-Villa, J. D., Guillén, N., Lopez-Camarillo, C., Soto-Sanchez, J., Ramirez-Moreno, E., Garcia-Vazquez, R., et al. (2017). Silencing the cleavage factor CFIm25 as a new strategy to control *Entamoeba histolytica* parasite. *J. Microbiol.* 55, 783–791. doi: 10.1007/s12275-017-7259-9
- Ospina-Villa, J. D., Zamorano-Carrillo, A., Lopez-Camarillo, C., Castañón-Sánchez, C. A., Soto-Sánchez, J., Ramirez-Moreno, E., et al. (2015). Amino acid residues Leu135 and Tyr236 are required for RNA binding activity of CFIm25 in *Entamoeba histolytica*. *Biochimie* 115, 44–51. doi: 10.1016/j.biochi.2015.04.017
- Palencia, A., Bougdour, A., Brenier-Pinchart, M. P., Touquet, B., Bertini, R. L., Sensi, C., et al. (2017). Targeting *Toxoplasma gondii* CPSF3 as a new approach to control toxoplasmosis. *EMBO Mol. Med.* 9, 385–394. doi: 10.15252/emmm.201607370
- Parker, R., and Song, H. (2004). The enzymes and control of eukaryotic mRNA turnover. *Nat. Struct. Mol. Biol.* 11, 121–127. doi: 10.1038/nsmb724
- Pezet-Valdez, M., Fernández-Retana, J., Ospina-Villa, J. D., Ramirez-Moreno, M. E., Orozco, E., Charcas-López, S., et al. (2013). The 25 kDa subunit of cleavage factor Im is a RNA-binding protein that interacts with the poly(A) polymerase in *Entamoeba histolytica*. *PLoS ONE* 8:e67977. doi: 10.1371/journal.pone.0067977
- Pompey, J. M., Foda, B., and Singh, U. (2015). A Single RNaseIII Domain Protein from *Entamoeba histolytica* Has dsRNA cleavage activity and can help mediate RNAi gene silencing in a heterologous system. *PLoS ONE* 10:e0133740. doi: 10.1371/journal.pone.0133740
- Raabe, T., Billum, F. J., and Manley, J. L. (1991). Primary structure and expression of bovine poly(A) polymerase. *Nature* 353, 229–234.
- Ramanathan, A., Robb, G. B., and Chan, S. H. (2016). mRNA capping: biological functions and applications. *Nucleic Acids Res.* 44, 7511–7526. doi: 10.1093/nar/gkw551
- Ransley, E., Paredes, E., Dey, S. K., Das, S. R., Heroux, A., and Macbeth, M. R. (2017). Crystal structure of the *Entamoeba histolytica* RNA lariat debranching enzyme EhDbr1 reveals a catalytic Zn(2+)/Mn(2+) heterobinucleation. *FEBS Lett.* 591, 2003–2010. doi: 10.1002/1873-3468.12677
- Rebbapragada, I., and Lykke-Andersen, J. (2009). Execution of nonsense-mediated mRNA decay: what defines a substrate? *Curr. Opin. Cell Biol.* 21, 394–402. doi: 10.1016/j.ccb.2009.02.007
- Rhode, B.M., Hartmuth, K., Westhof, E., and Lührmann R. (2006). Proximity of conserved U6 and U2 snRNA elements to the 5' splice site region in activated spliceosomes. *EMBO J.* 25, 2475–2486. doi: 10.1038/sj.emboj.7601134
- Santi-Rocca, J., Weber, C., Guigon, G., Sismeiro, O., Coppée, J. Y., and Guillén, N. (2008). The lysine- and glutamic acid-rich protein KERP1 plays a role in *Entamoeba histolytica* liver abscess pathogenesis. *Cell. Microbiol.* 10, 202–217. doi: 10.1111/j.1462-5822.2007.01030.x
- Schonemann, L., Kuhn, U., Martin, G., Schafer, P., Gruber, A. R., Keller, W., et al. (2014). Reconstitution of CPSF active in polyadenylation: recognition of the polyadenylation signal by WDR33. *Genes Dev.* 28, 2381–2293. doi: 10.1101/gad.250985.114
- Schwartz, D., Decker, C. J., and Parker, R. (2003). The enhancer of decapping proteins, Edc1p and Edc2p, bind RNA and stimulate the activity of the decapping enzyme. *RNA* 9, 239–251. doi: 10.1261/rna.2171203

- Schwer, B., Khalid, F., and Shuman, S. (2016). Mechanistic insights into the manganese-dependent phosphodiesterase activity of yeast Dbr1 with bis-p-nitrophenylphosphate and branched RNA substrates. *RNA* 22, 1819–1827. doi: 10.1261/rna.05855.2.116
- She, M., Decker, C. J., Svergun, D. I., Round, A., Chen, N., Muhrad D., et al. (2008). Structural basis of dcp2 recognition and activation by dcp1. *Mol. Cell* 29, 337–349. doi: 10.1016/j.molcel.2008.01.002
- Sheth, U., and Parker, R. (2003). Decapping and decay of RNAs occur in cytoplasmic processing bodies. *Science* 300, 805–808. doi: 10.1126/science.1082320
- Shi, Y. (2017). Mechanistic insights into precursor messenger RNA splicing by the spliceosome. *Nat. Rev. Mol. Cell Biol.* 18, 655–670. doi: 10.1038/nrm.2017.86
- Sidik, S. M., Huet, D., Ganesan, S. M., Huynh, M. H., Wang, T., Nasamu, A. S., et al. (2016). A Genome-wide CRISPR Screen in *Toxoplasma* identifies essential apicomplexan genes. *Cell* 166, 1423–1435. doi: 10.1016/j.cell.2016.08.019
- Sonoiki, E., Ng, C. L., Lee, M. C., Guo, D., Zhang, Y. K., Zhou, Y., et al. (2017). A potent antimalarial benzoxaborole targets a *Plasmodium falciparum* cleavage and polyadenylation specificity factor homologue. *Nat. Commun.* 8:14574. doi: 10.1038/ncomms14574
- Tharun, S., He, W., Mayes, A. E., Lennertz, P., Beggs, J. D., and Parker, R. (2000). Yeast Sm-like proteins function in mRNA decapping and decay. *Nature* 404, 515–518. doi: 10.1038/35006676
- Tharun, S., and Parker, R. (2001). Targeting an mRNA for decapping: displacement of translation factors and association of the Lsm1p–7p complex on deadenylated yeast mRNAs. *Mol. Cell* 8, 1075–1083. doi: 10.1016/S1097-2765(01)00395-1
- Urban, B., Blasig, C., Förster, B., Hamelmann, C., and Horstmann, R.D. (1996). Putative serine/threonine protein kinase expressed in complement-resistant forms of *Entamoeba histolytica*. *Mol. Biochem. Parasitol.* 80, 171–178. doi: 10.1016/0166-6851(96)02684-9
- Vagner, S., Vagner, C., and Mattaj, I. W. (2000). The carboxyl terminus of vertebrate poly(A) polymerase interacts with U2AF 65 to couple 3'-end processing and splicing. *Genes Dev.* 14, 403–413.
- Valdés, J., Nozaki, T., Sato, E., Chiba, Y., Nakada-Tsukui, K., Villegas-Sepúlveda, N., et al. (2014). Proteomic analysis of *Entamoeba histolytica* *in vivo* assembled pre-mRNA splicing complexes. *J. Proteomics* 111, 30–45. doi: 10.1016/j.jprot.2014.07.027
- Wahl, M. C., and Luhrmann, R. (2015). SnapShot: spliceosome dynamics, I. *Cell* 162:690.e1. doi: 10.1016/j.cell.2015.07.033
- Wahle, E. (1991). A novel poly(A)-binding protein acts as a specificity factor in the second phase of messenger RNA polyadenylation. *Cell* 66, 759–768. doi: 10.1016/0092-8674(91)90119-J
- Weedall, G. D., and Hall, N. (2011). Evolutionary genomics of *Entamoeba*. *Res. Microbiol.* 162, 637–645. doi: 10.1016/j.resmic.2011.01.007
- West, S., and Proudfoot, N. J. (2008). Human Pcf11 enhances degradation of RNA polymerase II-associated nascent RNA and transcriptional termination. *Nucleic Acids Res.* 36, 905–914. doi: 10.1093/nar/gkm1112
- Wilihoef, U., Campos-Góngora, E., Touzni, S., Bruchhaus, I., and Tannich, E. (2001). Introns of *Entamoeba histolytica* and *Entamoeba dispar*. *Protist* 152, 149–156. doi: 10.1078/1434-4610-00053
- Xiang, K., Tong, L., and Manley, J. L. (2014). Delineating the structural blueprint of the pre-mRNA 3'-end processing machinery. *Mol. Cell Biol.* J. 34, 1894–1910. doi: 10.1128/MCB.00084-14
- Xiang, S., Cooper-Morgan, A., Jiao, X., Kiledjian, M., Manley, J. L., Tong L et al. (2009). Structure and function of the 5'→3' exoribonuclease Rat1 and its activating partner Rai1. *Nature* 458, 784–788. doi: 10.1038/nature07731
- Yang, Q., Gilmartin, G. M., and Doublé, S. (2011). The structure of human cleavage factor I(m) hints at functions beyond UGUA-specific RNA binding: a role in alternative polyadenylation and a potential link to 5' capping and splicing. *RNA Biol.* 8, 748–753. doi: 10.4161/rna.8.5.16040
- Yoshimoto, R., Kataoka, N., Okawa, K., and Ohno, M. (2009). Isolation and characterization of post-splicing lariat-intron complexes. *Nucleic Acids Res.* 37, 891–902. doi: 10.1093/nar/gkn1002
- Zamorano, A., López-Camarillo, C., Orozco, E., Weber, C., Guillen, N., and Marchat, L. A. (2008). *In silico* analysis of EST and genomic sequences allowed the prediction of cis-regulatory elements for *Entamoeba histolytica* mRNA polyadenylation. *Comput. Biol. Chem.* 32, 256–263. doi: 10.1016/j.compbiolchem.2008.03.019
- Zhang, H., Ehrenkauf, G. M., Pompey, J. M., Hackney, J. A., and Singh, U (2008). Small RNAs with 5' -polyphosphate termini associate with a piwi-related protein and regulate gene expression in the single-celled eukaryote *Entamoeba histolytica*. *PLoS Pathog.* 4:e1000219. doi: 10.1371/journal.ppat.1000219
- Zhang, H., Pompey, J. M., and Singh, U (2011). RNA interference in *Entamoeba histolytica*: implications for parasite biology and gene silencing. *Future Microbiol.* 6, 103–117. doi: 10.2217/fmb.10.154

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling Editor declared a shared affiliation, though no other collaboration, with one of the authors JV-F.

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