HHS Public Access

Author manuscript

Trends Genet. Author manuscript; available in PMC 2017 December 01.

Published in final edited form as:

Trends Genet. 2016 December ; 32(12): 763–773. doi:10.1016/j.tig.2016.09.006.

Update: Mechanisms underlying *N*^{6}-methyladenosine modification of eukaryotic mRNA

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Summary

Eukaryotic messenger RNA (mRNA) undergoes chemical modification both at the 5′cap [1, 2] and internally [3–14]. Among internal modifications, m^{6}A, by far the most abundant, is present in all eukaryotes examined, including mammals [3–6], flies [15], plants [16, 17] and yeast [18, 19]. m^{6}A modification plays an essential role in diverse biological processes. Over the past few years, our knowledge relevant to establishment and function of this modification has grown rapidly. This review focuses on technologies that have facilitated m^{6}A detection in mRNAs, identification of m^{6}A methylation enzymes and binding proteins, and potential functions of the modification at the molecular level. Regarding m^{6}A function at cellular or organismal levels or in disease, please refer to other recent reviews [20–23].

Methods to detect m^{6}A

Historically, methods used to detect and quantify overall m^{6}A levels on mRNA have included chromatography [3–6], two-dimensional cellulose thin-layer chromatography (2D-TLC) [17, 24], dot-blotting [25], and liquid chromatography-tandem mass spectrometry (LC-MS/MS) [25] (Table 1). Based on these studies, it is now accepted that m^{6}A frequency is 3–5 residues per mRNA [1–5, 26]. Methods employed until recently, however, could not reveal m^{6}A location, a task that has proven challenging. Although the m^{6}A methyl group is found at the Watson-Crick base-pairing site and perturbs Adenosine and Uridine (A/U) or A/T (thymidine) pairing, it does not completely block reverse transcriptase, as does m^{1}A RNA modification [27], and there is no chemical treatment analogous to bisulfite conversion of 5mC available to convert m^{6}A to a different and detectable nucleotide [28]. Therefore, for a long time, it remained unclear which mRNAs even exhibit m^{6}A.

In 2012, however, two groups independently developed technology that coupled RNA immunoprecipitation using an m^{6}A -specific antibody to next generation high throughput sequencing (m^{6}A meRIP-Seq) to map m^{6}A sites in the mammalian transcriptome [29, 30] (Table 1). Initially, m^{6}A was mapped to over 7000 coding and non-coding mammalian

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polyadenylated (polyA) RNAs [29, 30]. Since then, over 10,000 m^6A -methylated polyA RNAs have been reported from various organisms and cell types, ranging from yeast to mammalian reprogrammed pluripotent stem cells [29–39]. A consensus m^6A methylation motif, RRACH (R = G or A; H = A, C or U), was identified from high throughput data [29, 30], in agreement with biochemical studies [40–42]. Recently, the consensus motif was redefined as DRACH (D = A, G or U), based on a study reporting that the nucleotide at the -2 position relative to m^6A can also be U [38]. Many m^6A sites are highly conserved between species, suggesting evolutionary importance of the modification [29, 30]. There is general agreement that m^6A is highly enriched at 3′-UTRs (untranslated regions) [29, 30, 36–38], and early meRIP-seq studies suggested that m^6A is located near stop codons [29, 30, 32]. However, a later study with improved detection resolution suggested that m^6A sites are present in 3′-UTR but there is no preference for m^6A to locate around stop codons [37]. Some m^6A modifications have also been found flanking 5′- and 3′-splice sites of exons, spatially overlapping with binding sites for mRNA splicing factors [43, 44], suggestive of a splicing function. Since N^6, 2 -O-dimethyladenosine (m^6Am), a modification that occurs exclusively on first nucleotide of mRNAs [45], can also be recognized by anti-m^6A antibody, m^6A abundance at 5′-UTRs remained unclear until a recent study distinguished these modifications using improved technology. This study showed m^6Am enrichment at transcription start sites [38]. In contrast, much lower m^6A levels were detected at 5′-UTRs [38]. Nevertheless, the same group later reported that m^6A but not m^6Am at the 5′-UTR regulates cap-independent mRNA translation [46].

One limitation of the original meRIP-seq method is its relatively low resolution: m^6A can be mapped within a 100–200 nt transcript region but precise positions cannot be identified [29, 30]. Efforts from multiple laboratories have improved meRIP-seq resolution. Using yeast as a system, one study (2013) employed an improved computational algorithm to predict m^6A at almost single-nucleotide resolution [31] (Table 1). Additionally, (2014) a photo-crosslinking-assisted m^6A sequencing strategy (PA-m^6A -seq) has been used to improve resolution [36] (Table 1). In 2015, two groups adapted ultraviolet (UV) CLIP (cross-linking immunoprecipitation) to accurately locate tens of thousands of m^6A residues in mammalian mRNAs with single-nucleotide resolution [37, 38] (Table 1). Both studies screened different m^6A antibodies and found that some can induce specific mutational signatures around m^6A residues after UV light-induced antibody/RNA cross-linking and reverse transcription. This approach can map m^6A at single-nucleotide resolution.

Another limitation of meRIP-seq m^6A detection methods is their reliance on antibody-based IP procedures, which are often associated with false positives [31]. To circumvent this problem, alternative technologies have been developed. These include m^6A detection by 1) two-color tiling microarray [47] based on m^6A interference with A/T pairing [48–52] (Table 1); 2) reverse transcription based methods, based on changes in kinetics of specific reverse transcriptases by m^6A base modifications [53, 54] (Table 1); and 3) ligation-based assays such as site-specific cleavage and radioactive-labeling followed by ligation-assisted extraction and thin-layer chromatography (SCARLET) [55, 56] (Table 1). Although these methods cannot yet be carried out in a high-throughput manner comparable to meRIP-seq and some are applicable to only specific transcripts, they provide a complementary approach to confirm specific m^6A sites identified by meRIP-seq.

An important question is, among sites modified by m^{6}A, what fraction of transcripts are m^{6}A -tagged versus untagged. For example, for the long noncoding RNA (lncRNA) *MALAT1 (metastasis-associated lung adenocarcinoma transcript 1)*, four precise m^{6}A sites were mapped using SCARLET technology [56]. The proportion of *MALAT1* transcripts modified at these sites varies between 11% and 77% in HeLa cells, suggesting variation in modification of a potential m^{6}A site could have functional consequences for methylated versus unmethylated RNAs. Recently, one group developed a technology termed m^{6}A-LAIC-seq (m^{6}A-level and isoform-characterization-sequencing) to detect m^{6}A methylated vs. unmethylated mRNA transcripts [39] (Table 1). m^{6}A-LAIC-seq method modifies the standard m^{6}A-meRIP-seq protocol by using excess m^{6}A antibody, including RNA spike-in controls to improve quantification, and sequencing full-length rather than fragmented PolyA RNAs. Use of excess m^{6}A antibody and full-length transcripts ensures that all m^{6}A -containing PolyA RNAs are pulled down in the IP'ed fraction and not in the flow-through. Therefore, the proportion of PolyA RNAs containing m^{6}A is calculated as the ratio of transcripts detected in IP'd vs. flow-through fractions. The authors reported that, for most genes, less than 50% of transcripts contained m^{6}A methylation and proportions differed between cell types. This method for the first time quantified the proportion of m^{6}A methylated vs. unmethylated transcripts on a genome-wide scale. However, since full-length mRNAs were used, m^{6}A locations were not defined; thus the resolution of this method is at the mRNA rather than the m^{6}A site level. Furthermore, this method cannot distinguish m^{6}Am-from m^{6}A-containing mRNAs. Hence, novel methods are required to map a fraction of specific m^{6}A sites.

m^{6}A methyltransferases and demethylases

m^{6}A is a reversible modification. An effort to purify enzymes that synthesize m^{6}A began in the 1990s [57, 58]. Methyltransferase-like 3 or METTL3 (also known as MTA-70) was reported as a putative m^{6}A methyltransferase in 1997 [59]. Not until 2014 did four studies [33, 35, 44, 60] report significant interaction between METTL3 and the previously uncharacterized protein METTL14, which also harbors an MTA domain [33, 35, 44, 60, 61]. Two of them reported that a combination of METTL3 and METTL14 showed remarkably greater *in vitro* methyltransferase activity than did METTL3 or METTL14 alone, suggesting that they functioned synergistically [35, 60] (Fig. 1). This prediction was confirmed by recent reports of the crystal structure of a METTL3/METTL14 heterodimer [62–64]. Those studies focused on the METTL3 or METTL14 methyltransferase domain and adjacent motifs and were based on ligand-free, methyl group donor S-adenosyl methionine (SAM)-bound states [62–64]. Interestingly, previous studies [35, 60] reported that METTL14 displayed higher methyltransferase activity than did METTL3 in *in vitro* methylation assays, suggesting METTL14 as the predominant catalytic subunit. In contrast, structural analysis supports a model in which METTL3 serves as the catalytic subunit, which binds SAM, while METTL14 plays a structural role and potentially functions in RNA substrate binding via the positively charged groove formed between METTL3 and METTL14 [62–64]. One particular structural study suggested that while both METTL3 and METTL14 display a predicted catalytic motif, the METTL14 SAM binding domain is blocked while that of METTL3 is hollow, allowing binding [63]. The authors of that study suggest that high

METTL14 activity in a methylation assay could be due to METTL3 contamination [63], explaining conflicting conclusions emerging from biochemical versus structural studies. As yet, the structure of a METTL3/METTL14 RNA complex has not been solved, an achievement that would provide important information relevant to substrate sequence specificity.

The RRACH motif has been identified as enriched at m^{6}A sites; however, only a small fraction of RRACH motifs exhibit m^{6}A [29, 30]. How METTL3/METTL14 is recruited to a specific transcript and why some RRACH motifs become modified and others do not remains poorly understood. It is hypothesized that RNA binding proteins (RBPs) interacting with METTL3/METTL14 may recruit these proteins. Several METTL3/METTL14-interacting proteins have been identified. The most well-established is Wilms tumor 1 associated protein (WTAP), which is an RBP that displayed high affinity to METTL3/METTL14 [33, 44] (Fig. 1). METTL3/WTAP interactions are conserved in yeast [65]. Although WTAP does not alter METTL3/METTL14 methyltransferase activity *in vitro*, its loss promotes transcriptome-wide m^{6}A depletion in cells [33, 44], demonstrating that it is required for m^{6}A modification and suggesting it may direct METTL3/METTL14 onto targets via RNA-binding activity. Indeed, WTAP PAR-CLIP analysis reported direct WTAP binding to RNA and m^{6}A enrichment at WTAP/RNA binding sites [44]. Nonetheless, how WTAP recognizes RRACH motifs and facilitates methylation of adenosine within them is unknown. In addition to WTAP, thirteen other proteins have been identified in a METTL3-interacting protein network [33]. Knockdown of one, *KIAA1429*, decreased global m^{6}A levels [33]. Functions of other proteins identified in the network remain unknown.

m^{6}A methyl groups are removed by m^{6}A demethylase (Fig. 1). Two members of the alpha-ketoglutarate-dependent dioxygenase Alkb family, Fat mass and obesity-associated protein FTO and Alkylation Repair Homolog 5 (ALKBH5), reportedly remove m^{6}A in an oxidative manner [25, 66]. FTO was first shown to demethylate 3-methylthymine on single-stranded DNA (ssDNA) [67]. Later, a group showed that FTO demethylates 3-methyluridine in ssRNA [68] *in vitro.* In 2011, the same group reported that m^{6}A -modified RNA was the primary FTO substrate [25]. Overexpression of FTO or ALKBH5 in cells decreases global m^{6}A levels, but knockdown or knockout of either only mildly increases m^{6}A levels [25, 66], suggesting the existence of other demethylases or perhaps a synergy between ALKBH5 and FTO that has not been studied. The crystal structures of both FTO and ALKBH5 have been reported, and small molecule inhibitors targeting their demethylase activities have been developed based on these structures [69–71]. For example, the natural product rhein, derived from herbs, is among the most effective FTO m^{6}A demethylase inhibitors [72]. As yet, it is unclear whether FTO or ALKBH5 target the same or different methylated mRNAs.

m^{6}A binding proteins

Like methylated DNA and histone protein tails, m^{6}A-modified RNA is recognized by specific proteins, or readers, that transmit the code to downstream effectors. In 2012, using methylated vs. non-methylated RNA probes as baits, several m^{6}A-interacting proteins in mammalian cells, including members of the YTH domain-containing family, such as YTHDF2 and YTHDF3, were pulled down [30] (Fig. 1). Later, a study demonstrated direct

binding of YTHDF2 to m^{6}A RNA [34]. Since then, additional YTH family proteins were identified as m^{6}A binders, including YTHDF1 and YTHDC1 [73–75] (Fig. 1). In agreement, while biochemical and structural analysis revealed YTH as a general RNA binding domain [76], kinetic analysis demonstrated that the binding affinity between YTH domains to m^{6}A-modified RNA is 10 times higher than that to non-m^{6}A RNA [77, 78]. Furthermore, PAR-CLIP analysis of YTHDF1, YTHDF2 and YTHDC1 identified genome-wide YTH protein binding sites overlapping with the RRACH motif [34, 73, 74]. Together, these studies strongly support direct interaction of YTH proteins and m^{6}A -modified RNA. However, it is noteworthy that YTH domain affinity for m^{6}A is moderate and much lower than that of DNA methylation binding proteins such as Methyl-CpG Binding Domain Protein 1 (MBD1) and Methyl-CpG-binding protein 2 (Mecp2) for 5mC [79]. In addition, YTHDF1/2 CLIP-seq data clearly showed that YTH proteins also bind to RNA sites that lack m^{6}A *in vivo* [34, 74]. Therefore, observations derived from these studies, which have greatly advanced our knowledge of how m^{6}A exerts its function, underscore the importance of using cells engineered to lack m^{6}A as controls in analyzing YTH domain protein function in m^{6}A modification to ensure specificity of effects. While YTHDF1/2 proteins are generally defined as cytoplasmic m^{6}A “readers”, YTHDC1 is a nuclear reader. A different nuclear m^{6}A binding protein was recently reported, the heterogeneous ribonucleoprotein HNRNPA2B1 [80] (Fig. 1). m^{6}A also reportedly binds eukaryotic initiation factor 3 (eIF3), a critical component of translation initiation complex [46] (Fig. 1). The proposed functions of these binding are discussed below.

m^{6}A regulates mRNA activity through diverse mechanisms

m^{6}A destabilizes RNA

Early studies in 1970s hinted that RNA methylation functions in regulating mRNA stability [26, 81]. Multiple recent studies report that loss of m^{6}A methyltransferase activity accompanied by decreased m^{6}A modification increases transcript stability [32–35, 82], suggesting that m^{6}A modification destabilizes RNA (Key Figure, Fig. 2). Multiple underlying mechanisms have been proposed.

One study reports that YTHDF2 binds to m^{6}A, which then translocates mRNA from the translation machinery to processing bodies (P-bodies), where it is degraded [34]. However, a later study challenged this model by showing that YTHDF2 does not interact with core components of the P-body and that, instead, YTHDF2 directly recruits the CCR4-NOT deadenylase complex to destabilize RNAs that contain m^{6}A [83]. These discrepant findings may reflect direct and indirect mechanisms on YTHDF2 regulated m^{6}A-mRNA stability. In addition to YTHDF2, two groups reported that all three YTHDF proteins (YTHDF1–3) regulate HIV-1 RNA expression; one study reported that all three promoted HIV-1 RNA expression [84], while the other reported that they repress HIV-1 RNA expression [85]. One thing that both studies agree on is that all three YTHDF proteins regulate gene expression in the same manner, in contrast to previous studies reporting that YTHDF2 destabilizes mRNA [34], while YTHDF1 promotes protein synthesis [74]. These differences may reflect genome-wide versus gene-specific effects but warrant future investigation.

Another study showed that m^{6}A blocks mRNA binding to the mRNA stabilizer human antigen R (HuR or ELAVL1) [35]. In that study, the authors observed that whether m^{6}A blocks or facilitates mRNA and HuR interaction depends on the distance between m^{6}A and HuR binding sites [35]. When sites are in close proximity, m^{6}A promotes HuR binding, consistent with previous work that identified HuR as a m^{6}A binding protein by employing an m^{6}A site probe next to a HuR-binding U track [30]; while when m^{6}A and HuR binding sites were far apart, the presence of m^{6}A decreased HuR binding [35]. Since predicted RNA motifs favoring m^{6}A modification or HuR binding differ substantially in sequence, endogenous m^{6}A and HuR sites may not always co-localize. Thus, it was proposed that m^{6}A is more likely to block HuR-RNA binding, destabilizing mRNA *in vivo*. Since this work was not performed on a transcriptome-wide scale, future studies should address the scope of this interaction.

m^{6}A alters RNA structure to modulate RNA/protein interaction

It is well-established that secondary and tertiary structure governs RNA function [86, 87]. Since m^{6}A destabilizes A/U pairing [47–52], it is reasonable to predict that m^{6}A can alter thermostability of an RNA duplex to change RNA secondary structure and function. Indeed, using a technology known as *in vivo* click selective 2′-hydroxyl acylation and profiling experiment (icSHAPE), which can determine endogenous RNA secondary structure, one group compared RNA base-pairing status of the m^{6}A consensus motif GGACU in wildtype vs. *METTL3* knockout mESCs [88]. They reported that the GGACU motif is less structured in wildtype ESCs than in ESCs lacking m^{6}A, suggesting that m^{6}A may help transit paired RNA to unpaired [88]. Another study further demonstrated that m^{6}A -mediated RNA structural changes alter RNA/protein interactions [89]. These authors reported that m^{6}A on a stem-loop region of the lncRNA *MALAT1* altered local RNA structure to enhance *MALAT1* binding to the RBP HNRNPC (Heterogeneous Nuclear Ribonucleoprotein C). They named this type of m^{6}A-containing region an “m^{6}A-switch” and identified thousands of potential RNA sequences that could function in a “switch” using sequential HNRNPC-PAR-CLIP followed by m^{6}A-RIP-Seq in wildtype vs *METTL3*/*METTL14* knockdown cells. Most switches were located in introns of coding and non-coding RNAs and potentially regulate alternative splicing [89].

m^{6}A enhances mRNA translation

Several mechanisms have been proposed relevant to m^{6}A effects on translation (Fig. 2). In 2015, a study reported that the m^{6}A binding protein YTHDF1 interacts with eIF3 to promote efficient translation of m^{6}A -modified mRNAs [74]. Later, two studies reported that cellular stress, such as heat-shock, increases m^{6}A modification at mRNA 5′-UTRs and promotes mRNA translation [46, 90]. One study showed that m6A promoted cap-independent mRNA translation in the absence of the cap-binding factor eIF4E, since m^{6}A directly binds eIF3 to recruit the 43S complex, initiating translation [46]. The other study showed that in the nucleus, heat-shock induced 5′-m^{6}A is protected from FTO-mediated demethylation by nuclear-translocated YTHDF2 [90]. This model is supported by observations that the affinity of m^{6}A RNA for the YTH domain is greater than that of m^{6}A RNA for FTO [77, 78, 91]. Yet another study reported that METTL3 directly interacts with the translation initiation factor eIF3 to promote translation of a subset of mRNAs, independent of METTL3

methyltransferase activity or YTHDF1 or YTHDF2 binding [92]. It remains unclear whether and how these mechanisms co-exist in cells. It would now be informative to identify RNA substrates for each of these mechanisms in order to understand the significance of each in normal or conditioned, such as heat-shocked, cells.

About half of mammalian m^{6}A sites are located in coding sequence [29]. One study employed biochemical, structural and single-molecule methods to address the function of m^{6}A modification in mRNA/tRNA interactions using *E. coli* ribosomes as a system [93]. The authors showed that, although X-ray crystallographic analyses indicate that m^{6}A base-pairs with uridine during the decoding process, m^{6}A modification can act as a barrier to tRNA accommodation and translation elongation in a manner that depends on position and context of m^{6}A within codons [93]. These authors propose that such dynamic changes could modulate coupled co-translational processes such as protein folding, suggesting that m^{6}A may allow a single gene to encode proteins of different functional forms.

m^{6}A promotes exon inclusion and enhances mRNA splicing

m^{6}A-related proteins, including METTL3/METTL14/WTAP of the methyltransferase complex, FTO and ALKBH5 demethylases, or m^{6}A binding proteins YTHDF2 and YTHDC1, all reportedly localize in nuclear organelles known as speckles, which are enriched in pre-mRNA splicing factors [25, 34, 44, 59, 66, 75], suggesting a role for m^{6}A RNA modification in mRNA splicing (Fig. 2). Within the METTL3/METTL14/WTAP complex, WTAP is required for METTL3 and METTL14 accumulation in nuclear speckles and most mRNA species bound by WTAP and METTL14 were transcribed from genes known to give rise to mRNAs with multiple splicing variants [44]. Loss of function studies further show that depletion of either METTL3 or WTAP results in transcriptome-wide changes in RNA splicing [44, 80]. Together, these data suggest that m^{6}A methyltransferase activity regulates mRNA splicing.

One study reports that FTO depletion enhances m^{6}A levels in regions flanking 5′- and 3′-splice sites and promotes binding of the splicing factor SRSF2, increasing exon inclusion [94]. *ALKBH5* knockdown cells show loss of phosphorylated SC35, a marker of nuclear speckles, suggesting that ALKBH5 regulates speckle formation, an effect dependent on ALKBH5 demethylase activity [66].

The m^{6}A nuclear reader YTHDC1 reportedly binds the pre-mRNA splicing factors SRSF3 and SRSF10 competitively, and promotes exon inclusion by facilitating SRSF3 but repressing SRSF10 in their nuclear speckle localization and RNA binding [75]. Another nuclear m^{6}A reader HNRNPA2B1 reportedly directly binds a set of m^{6}A-tagged nuclear transcripts and modulates their splicing in a manner comparable to METTL3, as evidenced by a strong positive correlation between global changes in alternative splicing and depletion of either HNRNPA2B1 or METTL3 [80].

m^{6}A promotes mRNA transport into the cytoplasm

ALKBH5 knockout mice show moderate increases in m^{6}A levels and accelerated mRNA export to the cytoplasm [66] (Fig. 2). As a mechanism, the authors of that study focused on the splicing factor ASF/SF2 (Alternative Splicing Factor), as it co-localizes with ALBKH5

in nuclear speckles [66]. It is also well-established that ASF/SF2 hypophosphorylation switches its function from that of a splicing factor to an adaptor protein functioning in mRNA nuclear export [95, 96]. Interestingly, ALKBH5-deficient cells not only show ASF/SF2 hypophosphorylation and loss of ASF localization to nuclear speckles, but relocalization of the ASF/SF2 kinase SRPK1 (Serine/threonine-protein kinase 1) from nucleus to cytoplasm. Thus the authors propose that SRPK1 relocation underlies ASF/SF2 hypophosphorylation, enhancing mRNA transport to the cytoplasm. Importantly, the observed phenotypes in *ALKBH5* knockout cells can only be rescued by the overexpression of wild-type but not mutant ALKBH5 lacking demethylase activity, suggesting that m^{6}A modification regulates mRNA transport. The exact mechanism remains unclear.

m^{6}A levels are associated with usage of alternative polyA (APA) sites

A UV CLIP study that mapped m^{6}A sites in the mammalian transcriptome at single-nucleotide resolution reported a positive correlation between m^{6}A density and the length of the last exon [37] (Fig. 2). The authors then simultaneously knocked down *METTL3*, *METTL14*, and *WTAP* and examined APA usage in a subset of mRNAs. They found that upon global reduction of m^{6}A levels, a greater number of genes showed proximal APA usage, raising the possibility that some m^{6}A residues may inhibit proximal polyadenylation. In agreement, another study measured the fraction of m^{6}A -methylated vs. nonmethylated RNAs and reported that m^{6}A levels are positively correlated with 3′-UTR length [39]. Mechanisms underlying these activities remain undetermined.

An interaction between m^{6}A modification and microRNA pathway (Fig. 2)

It was reported that METTL3-mediated m^{6}A methylation of primary microRNAs facilitates primary microRNA processing by the DGCR8 microprocessor complex [97] (Fig. 2). This group further identified HNRNPA2B1 as a nuclear m^{6}A reader mediating this process [80]. Interestingly, another group reported that m^{6}A levels are regulated by the microRNA machinery and by microRNAs [98]. In that study, the authors proposed that microRNA regulates m^{6}A formation by modulating METTL3/mRNA binding, presumably in the cytoplasm. However, it is unclear how microRNA-modulated METTL3/mRNA binding affects m^{6}A methylation, since METTL14 is a nuclear protein [92] and m^{6}A methylation likely occurs in the nucleus. Nevertheless, these studies suggest cellular interaction of two major RNA regulatory mechanisms: m^{6}A mRNA modification and microRNAs. Detailed mechanisms remain to be investigated.

Concluding Remarks and Future Perspective

There has been an enormous expansion in our knowledge of m^{6}A modification over the last few years. Nonetheless, fundamental questions relevant to regulation and activity of this modification remain (See Outstanding Questions Box). For example, we do not yet know why m^{6}A methyltransferases methylate some but not all mRNAs. We also do not yet comprehend what factors control the extent of m^{6}A modification of a particular mRNA. Mechanisms that maintain the balance between formation and removal of m^{6}A are not yet well defined, nor is it understood how m^{6}A binding proteins compete with the demethylases. While numerous functions of m^{6}A modification are proposed, based largely on genome-

wide data, the ultimate test of mutating endogenous m^6A sites followed by phenotypic analysis is lacking. In addition, although m^6A is present on rRNA, tRNA, snRNA (small nuclear RNA), snoRNA (small nucleolar RNA), and lncRNAs [38, 99], it is not known whether characterized m^6A readers recognize modified RNAs outside the context of mRNAs. In short, our journey down the road to understand m^6A mechanism and function has just begun!

Outstanding Questions

Why m^6A methyltransferases methylate some but not all mRNAs? What factors control the extent of m^6A modification of a particular mRNA?

What maintains the balance between formation and removal of m^6A? How are m^6A levels regulated in cells?

Would characterized m^6A mRNA reader recognize m^6A modified tRNA, rRNA, or snoRNA? Is there any crosstalk between different types of RNAs through m^6A modification?

m^6A regulates mRNA activities through diverse mechanisms. How do these mechanisms co-exist in cells?

Acknowledgments

We thank the NIH for funding P30 CA023168 and R01 GM110090 to J.C.Z.

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Trends

N^6-methyladensone or m^{6}A is the most abundant internal messenger RNA (mRNA) modification that tags tens of thousands eukaryotic transcripts. Technologies to detect m^{6}A have improved rapidly. Now we can map m^{6}A methylome at a single nucleotide resolution and determine the proportion of methylated vs. unmethylated transcripts in a high throughput manner.

The “writer”, “eraser”, and “reader” of m^{6}A modification have been reported. These discoveries have greatly facilitated our understanding towards the functional significance of m^{6}A.

Emerging evidence suggests that m^{6}A plays critical roles in regulating diverse mRNA activities, from processing to localization and translation. Therefore, reversible m^{6}A modification represents a new and crucial layer of gene expression regulation in eukaryotes.

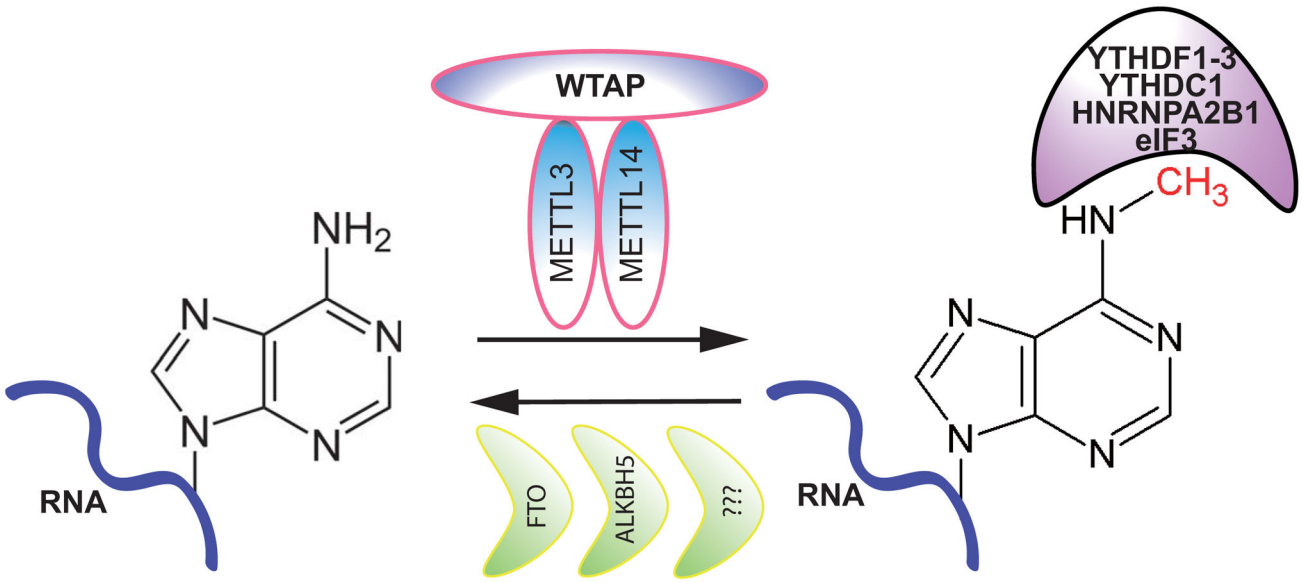
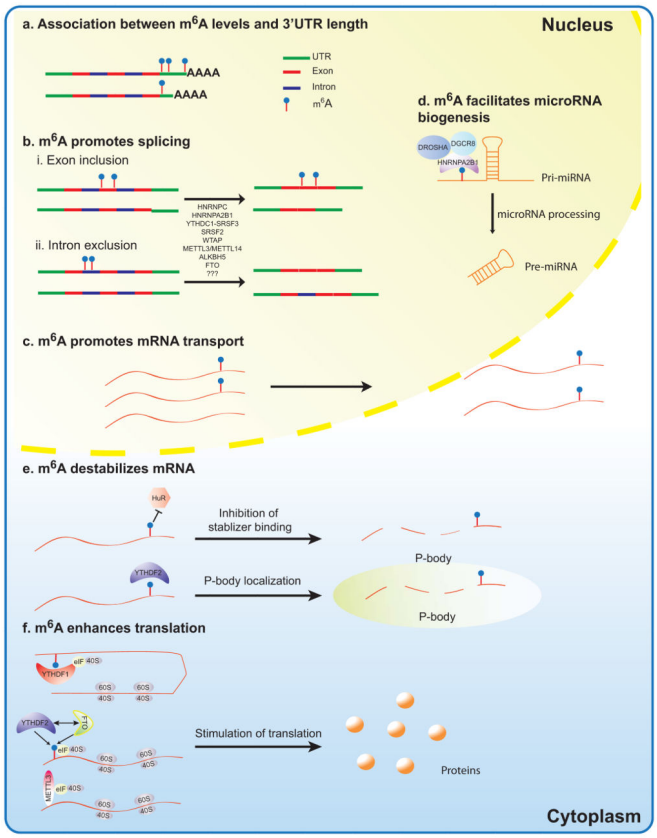


Figure 1. Formation, removal, and recognition of m^{6}A

METTL3/METTL14 were identified as core components of an *N*^{6}-methyladenosine methyltransferase complex. Both form a heterodimer catalyzing m^{6}A formation. WTAP has been identified as a METTL3- and METTL14-interacting protein. The presence of WTAP does not alter METTL3/METTL14 methyltransferase activity *in vitro,* but WTAP has a critical role in m^{6}A formation *in vivo* through an unknown mechanism. Other METTL3/METTL14-interacting proteins have been identified, but their activities remain to be determined. Two Alkb family members, FTO and ALKBH5, reportedly serve as m^{6}A demethylases and remove m^{6}A in an oxidative manner, although additional unknown m^{6}A demethylases may also serve this function. Several m^{6}A binding proteins are reported, including multiple YTH family members (YTHDF1–3 and YTHDC1), heterogeneous ribonucleoprotein HNRNPA2B1, and eIF3.



Key Figure Figure 2.

Diverse molecular mechanisms of m^6**A.**

(a) Association between m^{6}A levels and 3′UTR length, (b) m^{6}A promotes splicing, (c) m^{6}A promotes mRNA transport, (d) m^{6}A facilitates microRNA biogenesis, (e) m^{6}A destabilizes mRNA, and (f) m^{6}A enhances translation. As indicated, these activities occur in the nucleus, cytoplasm, or both.

Table 1

Methods used to detect and map m^6A modification of polyadenylated RNA.

Method	Purpose	Pros	Cons
2D-TLC [17, 24]	Measure overall m^6A levels	Well-established protocol; Quantitative; High sensitivity.	Requires radioactivity; Does not cover all A sites due to specificity of ribonucleases used for 5′ end labeling.
LC-MS/MS [25]		Quantitative; Covers all A sites; Very high sensitivity.	Requires special equipment and expertise; High cost.
Dot blot [25]		Low cost; No radioactivity required.	Nonspecific antibody binding; Low sensitivity.
Ligation assay [55]	Measure m^6A levels at a specific site	Easy to set up.	Not applicable to endogenous m^6A sites; Requires radioactivity.
Primer extension [53]		Easy to set up.	Relies on specific RTase; Cannot detect low abundant m^6A sites.
SMRT [54]		Single-molecule, real time detection.	Requires special equipment; Quantification not reported.
SCARLET [56]		Precise locations mapped; Highly quantitative.	Requires radioactivity and sophisticated methodology.
m^6A- meRIP-Seq [29, 30]	Map m^6A locations genome-wide	Well established protocol; High sensitivity.	IP/antibody can yield false- positives; Low resolution.
PA-m^6A- RIP-Seq [36]		Higher resolution than meRIP-seq.	Need to use living cells to incorporate 4-SU; thus cannot be applied to tissue or clinical samples. IP/antibody can yield false- positives.
miCLIP-Seq [37, 38]		Single-nucleotide resolution.	High reliance on specific antibody to generate a signature at m^6A sites.
m^6A-LAIC- seq [39]		Only method to quantify percentage of methylated vs. unmethylated RNAs.	Cannot detect specific m^6A sites.
Two-color microarray [47]		Antibody not required.	Low sensitivity.