Identification of novel post-transcriptional features in olfactory receptor family mRNAs

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ABSTRACT

Olfactory receptor (Olfr) genes comprise the largest gene family in mice. Despite their importance in olfaction, how most Olfr mRNAs are regulated remains unexplored. Using RNA-seq analysis coupled with analysis of pre-existing databases, we found that Olfr mRNAs have several atypical features suggesting that post-transcriptional regulation impacts their expression. First, Olfr mRNAs, as a group, have dramatically higher average AU-content and lower predicted secondary structure than do control mRNAs. Second, Olfr mRNAs have a higher density of AU-rich elements (AREs) in their 3′UTR and upstream open reading frames (uORFs) in their 5 UTR than do control mRNAs. Third, Olfr mRNAs have shorter 3′ UTR regions and with fewer predicted miRNA-binding sites. All of these novel properties correlated with higher Olfr expression. We also identified striking differences in the post-transcriptional features of the mRNAs from the two major classes of Olfr genes, a finding consistent with their independent evolutionary origin. Together, our results suggest that the Olfr gene family has encountered unusual selective forces in neural cells that have driven them to acquire unique post-transcriptional regulatory features. In support of this possibility, we found that while Olfr mRNAs are degraded by a deadenylation-dependent mechanism, they are largely protected from this decay in neural lineage cells.

INTRODUCTION

Olfactory receptors (OLFRs) are G protein-coupled receptors (GPCRs) essential for odor detection in olfactory sensory neurons (OSNs). These receptors are encoded by the largest gene family in mice, occupying ∼2% of the protein-coding genome (1–3). Olfr genes are divided into 2 classes, each of which has a different evolutionary origin: class-I receptors are thought to be derived from ancestral fish and evidence suggests that class-II receptors evolved from ancestral amphibians (3). These two Olfr gene classes are responsible for generating receptors that detect different odorants; e.g. it has been shown that class-I OLFRs preferentially detect predator-related odorants (4).

Olfr genes are regulated in a unique manner. Only a single Olfr gene allele from ∼1000 Olfr gene choices is selected to be expressed in a given OSN (5–8). The Olfr gene selected by each OSN is not only responsible for detecting odorants in the olfactory epithelium (OE), but it also directs the axons of OSNs that express the same Olfr gene to converge into the same glomerulus in the olfactory bulb (9,10). By controlling both axon guidance and receptor expression, this ‘1-receptor, 1-cell’ rule provides the foundation by which the olfactory system distinguishes different odorants (1,3,11). How precisely this 1-receptor, 1-cell rule is implemented at the molecular level remains enigmatic. In principal, it appears to be largely dictated by a selective transcriptional mechanism in which one Olfr gene is transcriptionally activated and all other Olfr genes are transcriptionally repressed in a given OSN. Likely to be involved are transcription factors that regulate Olfr gene expression, including the LHX2 LIM/homeobox transcription factor and members of the OLF-1/EBF (O/E) helix-loop-helix (HLH) family (12–14). The regulation of Olfr gene choice may also be dictated by epigenetic signatures that correlate with transcriptional activity (15,16).

While considerable progress has been defining transcriptional mechanisms acting on Olfr genes, little is known about post-transcriptional mechanisms regulating Olfr mRNAs. This is a large gap in the field given that post-transcriptional regulation has the potential to be critical for regulation of OLFR expression. For example, selective RNA decay mechanisms could contribute to the ‘1-receptor, 1-cell rule’ by degrading non-selected Olfr mRNAs that are expressed from incompletely silenced Olfr genes. Post-transcriptional mechanisms also have the potential to control Olfr mRNA levels during OSN development, as well as in response to acute exposure to odorants.

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Post-transcriptional regulation is typically directed toward the 5′ and 3′ untranslated regions (UTRs) of mRNAs, as they house a plethora of cis elements that impact mRNA stability and translation. For example, UTRs harbor sequence motifs and secondary structures that recruit ribosomes and RNA-binding proteins (RBPs) to govern rates of mRNA decay and translation (17–19). Also recruited to UTRs, particularly to 3′ UTRs, are microRNAs (miRNAs), which are short RNAs that elicit translational repression, mRNA destabilization, or both (20). None of these features have been investigated in Olfr mRNAs.

To address post-transcriptional regulatory mechanisms that regulate Olfr transcripts, it is critical to first define Olfr mRNA sequences. Zhang et al. and Shiao et al. detected the expression of ~800–1200 Olfr mRNAs in the OE using a custom microarray and RNA-seq, respectively, but they did not define the 5′ and 3′ termini of these transcripts or identifying alternative isoforms (21,22). Other studies have used transcription start-site mapping to identify the 5′ UTR and promoter regions of ~200 Olfr mRNAs (23–26) and one study screened cDNA libraries to identify promoter and 5′ UTR sequences of ~400 Olfr mRNAs (27). In our study, we employed RNA-seq analysis to analyze Olfr mRNAs with respect to their post-transcriptional features. Our analysis revealed that Olfr mRNAs tend to have several unique features, including a short 3′ UTR, high AU-content, and a high density of AREs and uORFs. After our manuscript describing this work was submitted, another paper was published that characterized Olfr mRNAs using RNA-seq analysis (28). While this Ibarra-Soria et al. paper did not focus on post-transcriptional features, it provided us an opportunity to examine such features using another Olfr data set. As described herein, the data sets from this paper corroborated what we determined with our Olfr data sets. In summary, we have uncovered unusual post-transcriptional features that are unique to the Olfr gene family, thereby shining light into how these genes are potentially regulated in OSNs.

In support, we provide in vitro evidence that Olfr mRNAs are post-transcriptionally regulated in a neuronal-specific manner.

MATERIALS AND METHODS

Compiling the Olfr mRNA transcriptome

RNA-seq analysis was performed on two 8 week-old C57BL/6 female OE littermates, who were housed in accordance with UCSD IACUC policies. In brief, dissected OE RNA was isolated using TriZOL (Life Technologies), followed by a secondary purification step using RNeasy columns (Qiagen). RNA-seq was performed at the UCSD Biogem Core. Total RNA was assessed for quality using an Agilent Bioanalyzer, and samples determined to have an RNA Integrity Number (RIN) of at least 8 or greater were used to generate RNA libraries using Illumina’s TrueSeq RNA Sample Prep Kit following manufacturer specifications, with the RNA fragmentation time adjusted to 5 min. 1 ug of total RNA was used per sample. RNA libraries were multiplexed and sequenced at 10 PM with 50 basepair (bp) single end reads to a depth of approximately 40 million reads per sample on an Illumina HiSeq2000. The OE transcriptome was extracted using the Tuxedo suite, encompassing Bowtie2, Tophat2 and Cufflinks programs (29,30) using the ‘novel gene discovery mode’ as outlined in the Tuxedo suite program manuals (30). Specifically using the CuffCompare program, we extracted information such as the nearest Ensembl reference ID, exon start/end positions, chromosome, gene direction and gene symbol from each gene entry. Next, we fetched the CDS of all entries using the nearest reference IDs from the UCSC Table Browser from the mm9 genome. Using the exon start/end positions for each reference ID entry, we extracted the exon sequences from the mm9 genome, and ligated them together in silico for each transcript. For each entry, the entire transcript sequence is subtracted from the known CDS sequence obtained above to identify the 5′ and 3′ UTRs. If a 30-nucleotide sequence was matched for the 5′ and 3′ peripheral regions of the nearest reference coding sequence with the corresponding in silico spliced transcript then the transcript was considered complete. For the complete transcripts, the 5′ and 3′ regions flanking the coding sequence were considered 5′ and 3′ UTRs, respectively. Intron sequences were extracted by using the regions between the exon junctions for each transcript. The second set of Olfr transcripts were provided by the supplemental data sets provided by Ibarra-Soria et al. (28). Only transcripts with both a detectable 5′ UTR and 3′ UTR were considered in subsequent analysis.

GC-content, ARE and miRNA site search

Once extracted, the lengths and GC-content were calculated for 5′/3′ UTRs, coding sequences and introns. To calculate global GC-content for Olfr, control and GPCR groups we created sets for each position, ranging from −50 to +50, flanking the splice-site of each intron. The GC-content was calculated for each of these positions to construct a general global GC analysis for each group of transcripts. To construct sequence logos, we used all sequences flanking splice-sites, ranging from −15 to +15, in UCBS WebLogo application (http://weblogo.berkeley.edu/) (31). The 3′ UTR sequences generated during the annotation were used to scan for AREs. We scanned the 3′ UTR sequences for the following n-mers identified by AREsite (http://rna.tbi.univie.ac.at/cgi-bin/AREsite.cgi) (32): AUUUA and WWAUU-UAWW. W indicates either an adenine or uracil nucleotide. miRNA sites were discovered using TargetScan 6.0 (33–36). In brief, 9 miRNA mature and whole sequences were scanned along all genes from the three gene groups to find putative miRNA binding sites.

Secondary structure minimum free energy

To select the minimum free energy of the 5′UTR sequences, we used University of Vienna’s RNAfold Web Server (http://rna.tbi.univie.ac.at/cgi-bin/RNAfold.cgi) (37) to calculate the folding energy. The 5′ UTR sequences used were generated from the RNA-seq reads, Ensembl reference IDs, and the annotation algorithms described above.

3′UTR cloning, cell culture and luciferase assay

The 3′ UTRs of Olfr212, Olfr1226 and Olfr1242 were amplified by PCR from adult OE cDNA and cloned by guest on 29 July 2018.
downstream of the Firefly luciferase ORF (at the SpeI and HindIII restriction enzyme sites) in the pMIR-REPORT vector (Ambion). These reporter constructs were transfected by Lipofectamine 2000 reagent (Life Technologies) into P19 and Neuro2A cells. The P19 cells were cultured in 10% fetal calf serum (Stem Cell Technologies) and MEMα media (Invitrogen); Neuro2A cells were cultured in 10% fetal calf serum (Stem Cell Technologies) and DMEM media (Invitrogen). Also transfected into these cells was the CCR4-6 expression vector (kindly provided by Jens Lykke-Andersen [UCSD]) and the Ccr4-6 siRNA and the ONTARGETplus siRNA control (ThermoScientific). The Firefly Renilla luciferase reporter was co-transfected as an internal control. Luciferase activity was assayed as previously described (38) using the Dual Luciferase Assay System (Promega). Cellular RNA was harvested using TriZOL (Invitrogen), followed by iScript Reverse Transcription Kit and SYBR Green qPCR Reagent (BioRad), all according to manufacturer’s protocol. The level of Ccr4-6 mRNA was measured using the following qPCR primers: UCSD8023: TGCGAGTGCTGCTCAAGTGTG and UCSD8024: GTGCAGTGCTGTCAAGTGTG. The endogenous RNA control Rpl19 was used and was amplified using the following qPCR primers: UCSD4667: CTTGAACTCTATGTGATCTC. Results and Discussion

RESULTS AND DISCUSSION

Genome-wide identification of class I and II Olfr transcripts

Olfr transcripts were defined using RNA-seq data from adult mice OE as outlined in Figure 1A. We detected reads from 1101 Olfr genes, but there were insufficient reads from some of these Olfr genes to accurately determine their 5’ and 3’ termini (data not shown). To exclusively annotate Olfr mRNAs that encode functional proteins, we only analyzed transcripts with RNA-seq reads matching the coding sequence (CDS) of known OLFR proteins, as defined in the Ensembl database. Using this criterion, we identified 805 full-length mRNAs encoded by 554 Olfr genes (Supplementary Table S1). The alternative isoforms included those with different 5’ and 3’ UTR regions and those generated by alternative splicing (Supplementary Table S2). The Olfr transcripts we identified emanate from Olfr genes distributed on the various chromosomes known to have Olfr gene clusters (Figure 1B; 27), suggesting that our analysis was not biased for a particular sector of the genome. Analysis of the reads corresponding to individual Olfr genes showed they exhibited considerable heterogeneity in expression (Figure 1C and D), confirming findings from other studies on Olfr mRNAs (27,28).

We observed that class-I Olfr genes tend to be expressed at strikingly lower level than most class-II Olfr genes (Figure 1C–E). A likely explanation is that class-I Olfr genes are selected to be expressed less often than are class-II Olfr genes in individual OSNs, as class-I Olfr genes comprise only ~10% of all Olfr genes (40). In further support of this possibility, class-I OLFR-expressing OSNs are only found in the dorsal zone of the OE, whereas class-II OLFR-expressing OSNs are present in virtually all regions of the OE (41,42). A non-mutually exclusive explanation for the lower levels of class-I Olfr mRNAs in the OE is that class-I Olfr genes are transcribed at a lower rate per OSN than are class-II Olfr genes. Since class-I Olfr genes have a distinct evolutionary origin to that of class-II Olfr genes (3), they may have distinct promoters that support lower levels of transcription than do class-II promoters. Finally, it is also possible that class-I Olfr mRNAs are intrinsically less stable than are class-II Olfr mRNAs.

Olfr mRNAs tend to have short 3’ UTRs

To understand how Olfr mRNA characteristics potentially impact their expression, we analyzed Olfr mRNAs as defined by RNA-seq (Figure 2, Supplementary Figure S1A–B, Supplementary Table S3), as Olfr transcripts on publicly available databases such as Ensembl and RefSeq have inaccuracies. Unless otherwise noted, all data analysis below was performed in Olfr mRNAs we identified through our RNA-seq analysis. As a basis of comparison, we examined two other gene groups: (i) Gpcr genes encoding 92 non-OLFR GPCR proteins defined by the International Union of Basic and Clinical Pharmacology Database [IUPHAR-DB] (43) that we found were significantly expressed in the OE, based on our RNA-seq analysis, and (ii) Ctr1 genes, a randomly selected group of 587 non-Gpcr genes expressed in the OE.

This analysis revealed unique features of Olfr mRNAs as a group. One unusual feature of Olfr mRNAs is 3’ UTR length. The average 3’ UTR length of Olfr mRNAs in our data set (‘Olfr A’, 1094 nt) is dramatically shorter than that of the Ctr1 (1895 nt) and Gpcr (1800 nt) group mRNAs (Figure 2A; P < 0.0001). Olfr mRNAs defined by Ibarra-Soria et al. (28) (‘Olfr-B’) also had a shorter 3’ UTR length (1439
Figure 1. RNA-seq analysis of Olfr mRNAs in the mouse adult OE. (A) Schematic of workflow used to assemble the Olfr transcriptome. (B) Full-length Olfr mRNA transcripts detected by our RNA-seq analysis versus all known Olfr genes in each mouse chromosome. (C) Bar graph of the expression level of individual Olfr genes plotted sequentially along all mouse chromosomes, expressed as Fragments Per Kilobase of transcript per Million mapped reads (FPKM). (D) Bar graph displaying the expression level of individual Olfr genes along chromosome 7. (E) Boxplot of average expression level of class-I versus -II Olfr transcripts. **** P < 0.0001.

The finding that Olfr 3′ UTRs tend to be shorter than control 3′ UTRs (Figure 2A, Supplementary Figure S1C) raised the possibility that there has been strong selection pressure on Olfr genes to evade post-transcriptional regulation pathways that target the 3′ UTR. For example, previous work has suggested that polyadenylation site selection shifts during development and cancer progression to differentially expose recognition sites for RNA-binding proteins (RBPs) or miRNAs for regulatory purposes (44–49). Both RBPs and miRNAs dictate translation efficiency and RNA decay rates, and thus mechanisms that control their ability to be recruited to an mRNA are critical for the fate of an mRNA (50). Below, we consider how the unique characteristics of Olfr 3′ UTRs, including their short length, might shape the post-transcriptional fate of Olfr transcripts.

We also found that there is considerably heterogeneity in the length in Olfr mRNAs encoded by different Olfr genes (Supplementary Figure S1D). This is largely attributable to the heterogeneity of 3′ UTR length, since the coding region (CDS) length of Olfr mRNAs are nearly invariant (Supplementary Figure S1E) and the 5′ UTR region does not
contribute much to the variation in Olfr mRNAs (Supplementary Figure S1F). Another contributing factor to Olfr mRNA length heterogeneity is the difference in the average length of class-I and-II Olfr mRNAs; we found that class-I mRNAs are modestly, but significantly shorter than class-II mRNAs (Supplementary Figure S1G).

In contrast to the 3′ UTR, the 5′ UTR was not significantly different in median length in Olfr mRNAs (223 nt in Olfr-A, 241 nt in Olfr-B) as compared to either Ctrl (212 nt) or GPCR (242 nt) mRNAs (Figure 2C). However, we found that Olfr 5′ UTRs were quite heterogeneous in length, in large part because class-I Olfr 5′ UTRs (129 nt) are, on average, half the length of Class-II Olfr 5′ UTRs (240 nt, Figure 2D; P < 0.01, Supplementary Table S3). Thus, Class-I Olfr 5′ UTRs tend to be much shorter than the average length of 5′ UTRs in mRNAs in general. We suggest that this likely reflects the different evolutionary origins and/or unique selection pressures exerted on class-I Olfr genes (3). 5′ UTR regions are known to be major sites for regulation of translation efficiency and RNA decay rate (19) and thus class-I Olfrs may have been selected to have short 5′ UTR regions over evolutionary time for regulatory purposes.

**Olfr mRNAs have few predicted binding sites for OE-expressed miRNAs**

We first considered the possibility that Olfr mRNAs have short 3′ UTRs to avoid repression by miRNAs. miRNAs are short (18-22 nucleotides) RNAs that bind by complementarity with their mRNA targets and recruit RBPs that lead to mRNA stabilization and/or translational repression (51). miRNAs typically bind to the 3′ UTR region of their target mRNAs and thus there has been considerable interest in identifying mechanisms that dictate which 3′ UTR regions are accessible to miRNA-mediated regulation (44,47,52). In the case of Olfr mRNAs, we hypothesized that they were selected to harbor short 3′ UTRs to escape repression mediated by miRNAs.

To test this possibility, we used the miRNA target-prediction program, TargetScan, to screen for miRNA-binding seed sequences in the Olfr mRNAs we defined as well as the data set from Ibarra-Soria et al. In particular, we used this in silico screen to examine the following miRNAs: miR-200a/miR-141a, the only miRNA known to have a role in olfactory neurogenesis (53), and eight well-studied neurally expressed miRNAs: miR-7, -7-9, -124, -128, -132, -134, -138 and let-7 (38,54–61). We found that at least 2 of these miRNAs—miR-9 and -128—are expressed in the OSN layer of the OE (Figure 3A). We functionally tested one of the Olfr 3′ UTRs (Olfr1226) with a predicted miR-9 target site. In support of the accuracy of the TargetScan algorithm, we found that the Olfr1226 3′ UTR conferred repression in response to exogenously expressed miR-9 (Figure 3B).

Analysis of predicted target sites revealed less predicted binding sites for 8 out of the 9 miRNAs in Olfr transcripts compared to the GPCR and Ctrl transcript groups (Figure 3C–D, Supplementary Table S4). As another means to analyze miRNA-regulatory potential, we examined the percentage of miRNAs in a given group predicted to be targeted by the nine neurally expressed miRNAs. We found that a significantly lower percentage of Olfr miRNAs had predicted target sites for these nine miRNAs than did the other mRNA groups (P < 0.0001; Figure 3C).

We considered the possibility that the only reason that Olfr mRNAs have fewer miRNA-target sites than control mRNAs is because their 3′ UTRs are shorter. If this was the case, then the density of miRNA-target sites should be similar between the three groups. Instead, we found that Olfr mRNAs had significantly lower density of predicted binding sites for the nine miRNAs than the control groups (Figure 3E). Thus, the low number of predicted miRNA-target sites in Olfr mRNAs is not only because they tend to have short 3′ UTRs. Together, these data are consistent with a model in which Olfr genes evolved to reduce miRNA-mediated repression by both shortening their 3′ UTRs and reducing the number of miRNA-target sites by mutation. During the course of this analysis, we noted that a relatively large percentage of GPCR genes (>15%) contain predicted miR-7 and -128 binding sites (Figure 3C), suggesting that miR-7, -200a, -9 and -128, in particular, may be broad regulators of GPCR mRNAs.

**Olfr mRNAs are AU-rich**

Previous studies have demonstrated that the average AU-content of mammalian mRNAs is ~45% (18). In contrast, we found that most Olfr mRNAs have an AU-content of greater than 50%. This characteristic was evident throughout the length of Olfr mRNAs, including both UTRs and the CDS, and even the splice junction region (Figure 4A–B, Supplementary Figure S2A–C). Particularly striking was the Olfr 5′ UTR region, which had ~60% average AU-content versus the ~40% average AU-content of the 5′ UTR region in the Ctrl and GPCR mRNAs (Figure 4B, P < 0.0001, Supplementary Table S5). Of note, both class-I and –II Olfr mRNAs tended to be AU-rich (Supplementary Fig.
Figure 3. Olfr mRNAs tend to have few predicted target sites for neurally expressed miRNAs. (A) In situ hybridization of neurally expressed miRNAs in the OE. (B) Dual luciferase analysis of the effect of the Olfr1226 3′ UTR in response to ectopic expression of miR-9 in Neuro2A cells. (C) The percentage of mRNAs from the indicated gene groups with predicted miRNA-binding site defined using the TargetScan algorithm. (D) Boxplot representation of the average percentage of miRNA-binding sites determined across all 9 miRNAs, determined from the data in panel C. (E) Average frequency of miRNA sites per kb of 3′UTR in each gene group. *P < 0.05; ****P < 0.0001.

The discovery that Olfr mRNAs have a high AU-content suggests that this feature is important for Olfr post-transcriptional regulation. One possibility is that this reduces secondary structure that would otherwise reduce translation efficiency or lead to steric hindrance of interaction with RNA-binding proteins (19). To assess whether Olfr mRNAs have reduced secondary structure relative to control mRNAs, we utilized the RNAFold algorithm (37), which calculates minimum free energy (mfe), a measure of the difficulty to linearize a given sequence. Since 5′ UTR length contributes to mfe calculations, we selected 50 5′ UTRs from each mRNA group that have similar 5′ UTR length. This analysis revealed that Olfr mRNAs have a strikingly higher average mfe compared to Gpcr and Ctrl transcripts (Figure 4C).

mRNAs with low GC-content and secondary structure are thought to be more efficiently translated than those with a high GC-content (19). This is supported by genome-wide studies observing a significant correlation between 5′ UTR secondary structure folding free energy and protein abundance (62). While the molecular mechanism for this is not known, a likely possibility is that less structured 5′ UTRs permit more efficient scanning of the 40S ribosomal subunit as it traverses from the 5′ cap to the start AUG codon of the main ORF (63). This raises the possibility that Olfr genes have been selected to have low GC-content over evolutionary time so that they can translate high levels of Olfr proteins. Because translation can protect mRNAs from decay (64), this also predicts that Olfr mRNAs harboring 5′ UTRs with low GC-content would be more stable than those without. In agreement with this prediction, we found a negative correlation between Olfr expression level and the 5′ UTR GC-content of Olfr mRNAs (Figure 4D). In contrast, we observed a statistically significant positive correlation be-
Figure 4. Olfr mRNAs are AU-rich. (A) GC-content along exon-intron junctions (top) and intron-exon junctions (bottom). (B) Boxplot of % of AU-content in the 5′ UTR. (C) Boxplot of minimal free energy (mfe) in the 5′ UTR. (D) Scatterplot and linear regression analysis of expression level versus 5′ UTR % GC-content. * $P < 0.05$; ** $P < 0.01$; **** $P < 0.0001$; n.s., not statistically significant.
between the GC-content of Gpcr mRNAs and their expression. While we do not know the underlying mechanism for this, one possibility is higher GC-content alters the spectrum of ribonucleoprotein complexes that form on the 3′ UTR of Gpcr mRNAs in a manner that favors the stability of these mRNAs. No correlation was observed for the Ctrl mRNAs, possibly because they represent a broad group of genes with confounding variables. While there are several explanations for these findings, we suggest that the most parsimonious interpretation is that Olfr mRNAs evolved to have unstructured 5′ UTRs as a means to increase their translation efficiency, which in turn increased the stability of their mRNAs.

Olfr mRNAs tend to be enriched for ARE motifs

Our finding that Olfr mRNAs tend to be AU-rich (Figure 4 and Supplementary Figure S2) raised the possibility that they are enriched for AU-rich binding elements (AREs). AREs are typically permutations of the core sequence AUUUA (or, more rarely, short stretches of U) that serve as cis elements to promote the degradation of mRNAs through a deadenylation-dependent mechanism called ARE-mediated RNA decay (AMD) (65,66).

AREs have been computationally defined in mammalian transcriptomes and deposited in several databases, including ARED and AREsite (32,67). However, these databases do not contain most Olfr mRNAs, including those annotated recently (28). Our annotation of Olfr genes expressed in the mouse OE together with another dataset provided an opportunity to fill this gap. We analyzed the average ARE density in Olfr mRNAs and found it is twice as high as in the Gpcr and Ctrl mRNA groups (Figure 5A, Supplementary Table S6). We found this to also be the case when we analyzed the recently defined Olfr mRNA data set from Ibarra-Soria et al. (28) (‘Olfr-B’ in Figure 5A). Given that Olfr mRNAs have much shorter average 3′ UTR length than these other groups (see below), this is consistent with the possibility that there has been strong selection pressure for enrichment of AREs to maintain regulation by ARE-binding proteins. The net result is that AREs are as prevalent in Olfr mRNAs as in the other gene groups (Figure 5B).

To assess the possible impact of AREs on Olfr expression, we asked whether there is an association between ARE density and expression level. We found a strong positive correlation between AUUUA pentamer density and expression level, as assessed by RNA-seq reads (Figure 5C). Linear regression analysis demonstrated that this was highly statistically significant (P < 0.0001). In contrast, there was a negative correlation between ARE density and expression for the Ctrl group and no significant correlation for the Gpcr group (Figure 5C). To extend this analysis, we evaluated the density of another functional ARE motif: the WWAUUAAW nonamer (32). As with AUUUA pentamer density, WWAUUAAW density was higher in Olfr mRNAs than in the other groups (Supplementary Figure S3A). The frequency of these nonomers per transcript positively correlated with Olfr mRNA expression level (Supplementary Figure S3B).

Our finding that Olfr 3′ UTRs are both enriched in AREs and expressed in a pattern that positively correlates with ARE density raises the possibility that Olfr mRNAs are a new class of transcripts that are positively regulated by ARE-binding proteins. While AREs are normally associated with decay, they can also promote mRNA stabilization. Some ARE-binding proteins serve as mRNAs stabilizers, including members of the embryonic lethal abnormal vision (ELAV) family member (68). At least one member of this family, HuC, is expressed in the developing OE and other neuronal tissues (69). Another family member, HuD, is neuron-specific in its expression and is responsible for regulating Gap43 mRNA, which encodes a neuron-specific protein critical for neurogenesis (70,71). This raised the possibility that AREs promote the expression of transcripts in a neuronal setting.

Olfr 3′ UTRs confer stability

We examined whether the unique 3′ UTR characteristics of Olfr mRNAs confer stable expression in neural cells. To test this possibility, we cloned the 3′ UTRs of two Olfr genes—Olfr1226 and Olfr1242—downstream of the firefly luciferase ORF in the pMIR-REPORT reporter vector (Figure 5D). We transfected these constructs into a neuronal cell line, Neuro2A, together with an endogenous control containing a Renilla plasmid reporter and measured the stability of the encoded transcripts. We found that both the Olfr1226 and Olfr1242 3′ UTRs confer an extremely long RNA half-life in Neuro2A cells, as measured by treatment with the transcriptional inhibitor, Actinomycin D (> 10 h; Figure 5E). This suggests that these 3′ UTRs confer stability to Olfr mRNA in neuronal cells.

A key rate-limiting step of mRNA decay is deadenylation (65). To examine whether Olfr 3′ UTRs confer deadenylation-dependent mRNA downregulation, we measured the effect of depleting or overexpressing the core deadenylase, CCR4B, on reporter mRNAs harboring the two Olfr 3′ UTRs described above. Forced overexpression of CCR4B (Supplementary Figure S3C) downregulated Olfr 3′ UTR-dependent reporter expression and destabilized the reporter mRNA transcript in Neuro2A cells (Figure 5E–F), suggesting that, indeed, Olfr 3′ UTRs are sensitive to deadenylation-dependent decay. In contrast, siRNA-mediated knockdown of CCR4B (Supplementary Figure S3C) did not significantly affect Olfr 3′ UTR-dependent reporter expression (Figure 5F), consistent with our finding that Olfr 3′ UTRs are normally stable in neural cells (Figure 5E).

To assess the specificity of this response, we tested whether Olfr 3′ UTR responds to deadenylation-dependent decay in non-neuronal cells. We used P19 embryonal carcinoma cells for this experiment, which are stem-like cells that transfect efficiently (72). As we observed in Neuro2A cells, overexpression of CCR4B from an expression vector in P19 cells (Supplementary Figure S3D) elicited reduced reporter expression from the two Olfr 3′ UTR reporters (Supplementary Figure S3E). In striking contrast to the results obtained with Neuro2A cells, knocking down CCR4B in P19 cells (Supplementary Figure S3D) increased the expression the two Olfr 3′ UTR reporters and stabilized its mRNA half-life (Supplementary Figure S3E and F). The difference in Olfr 3′ UTR sensitivity to CCR4B depletion in neuronal
Figure 5. *Olfr* mRNAs are ARE-rich. (A) ARE pentamer density measured *in silico*. (B) Density distribution plot of the number of AUUUA ARE pentamers, assessed as in panel (A). (C) Scatterplots and linear regression analysis of expression level versus AUUUA pentamer density, assessed as in panel A. (D) Schematic of luciferase and renilla reporters used. (E,F) Two *Olfr* 3′ UTRs influence mRNA steady-state level and mRNA half-life in response to CCR4B depletion (using a siRNA targeting CCR4B [siCcr4b]) and CCR4B overexpression (using a CCR4B expression vector). Panel E is measurement of relative mRNA levels (RQ) and panel (F) is measurement of relative luciferase values (RLU). *P < 0.05; n.s. not significant.

versus non-neuronal cells suggests that the *Olfr* 3′ UTRs have evolved to permit stable mRNA expression specifically in neural cells.

### *Olfr* mRNAs are uORF-rich

Another well-studied deadenylation-dependent RNA degradation mechanism is Nonsense-mediated RNA decay (NMD). This pathway that was originally defined by virtue of its ability to degrade aberrant mRNAs containing premature stop codons as a result of mutations or biosynthetic (e.g. RNA splicing) errors (73,74). More recently, it was discovered that NMD also targets normal mRNAs that have an in-frame stop codon in a context that is recognized as premature (73,75,76). Increasing evidence indicates that the ability of NMD to degrade a subset of normal mRNAs acts as a biological switch to control biological events, including developmental pathways (38,75–80). Thus, we investigated whether *Olfr* mRNAs might be targeted for decay by NMD.

The best-characterized context that triggers NMD is the presence of an exon-exon junction (intron) at least 55 nt downstream of the stop codon defining the end of the main ORF (81). Most *Olfr* mRNAs do not have this architecture (Supplementary Figure S4). Nevertheless, we identified a small number of *Olfr* mRNAs (15 of 805) defined by RNA-seq analysis that do possess an ‘NMD-inducing’ architecture; i.e. an exon-exon junction >55 nt downstream of the stop codon (Supplementary Figure S4). Since virtually all mRNAs with this feature are targeted for decay by NMD (73,74), it is likely that this small subset of *Olfr* transcripts
Figure 6. Olf r mRNAs are uORF-rich. (A) The percentage of transcripts from the three groups with the indicated number of uORFs. (B) The average number of uORFs. (C) Box plot comparing the expression level of transcripts harboring or lacking uORFs from the three groups. (D) Scatterplot and linear regression analysis of expression level versus uORFs density. (E) Scatterplot and linear regression analysis of expression level versus average uORF length. **** P < 0.0001; n.s., not statistically significant.
is subject to rapid decay by NMD, perhaps to provide developmental regulation.

Another NMD-inducing feature is the presence of a long 3′ UTR (82,83). While no specific 3′ UTR length has been shown to trigger NMD, our finding that Olfr mRNAs tend to have considerably shorter 3′ UTRs than do control mRNAs (Figure 2A) suggests that it is unlikely that Olfr transcripts are generally degraded by this mechanism.

Additionally, it has been shown that upstream open reading frames (uORFs) can trigger NMD, perhaps by virtue of the ability of the stop codon in the uORF to trigger premature translation termination and thereby recruit mRNA decay enzymes (19,74). We found that majority of the 805 Olfr mRNAs expressed in the OE (67%) have uORFs (Figure 6A, Supplementary Table S7). This is a significantly higher proportion than in the Gpcr and Ctrl groups. Only 38% of the Ctrl mRNA group have uORFs, a value consistent with the average value recently reported for all human mRNAs (84). In addition, Olfr mRNAs from both our data set and Ibarra-Soria et al. have a significantly higher average number of uORFs per transcript than Ctrl and Gpcr group (Figure 6B) despite having a similar average 5′ UTR length as the Ctrl and Gpcr groups (Figure 2C).

Even though uORFs can trigger NMD, few uORF-containing mRNAs are likely to be subject to NMD regulation (85). This follows from the fact that while ~40% of human and rodent mRNAs have uORFs (84,86,87) (Figure 6A), at most 5% of mammalian mRNAs are targeted for decay by NMD, based on microarray and RNA-seq analyses of cells depleted of NMD factors (85). Indeed, several mRNAs have been defined that escape uORF-induced NMD (88,89). This predicts that a majority of uORFs found in Olfr mRNAs are not bona fide targets of NMD. Consistent with this prediction, we found that Olfr mRNA harboring uORFs were statistically more highly expressed, when analyzed as a group, than those without (Figure 6C). We also observed a statistically significant positive correlation between the number of uORFs per transcript and Olfr mRNA level (Figure 6D). Finally, we also observed a positive correlation between average uORF length and Olfr mRNA level (Figure 6E). As evidence for specificity, we did not observe a correlation between any of these parameters and the expression of the Gpcr or Ctrl gene groups (Figure 6C–E). Together, these results suggest that uORFs have an overall positive effect on Olfr mRNA expression. It will be interesting in the future to determine the underlying mechanism. One means by which uORF-containing mRNAs may escape uORF-induced NMD is by allowing ribosomes that terminate translation in uORFs to reinitiate downstream. In S. cerevisiae, the 5′ UTR environment surrounding uORFs has been shown to influence this. For example, it has been shown that the AU-rich region downstream of the uORF in gcn4 mRNA allows for efficient ribosome reinitiation, thereby avoiding triggering NMD (90). Given that we found that Olfr 5′ UTRs tend to be AU-rich (Figure 4), this may provide a general mechanism by which they escape uORF-induced NMD. Given that translation is generally regarded as providing a protective role from mRNA degradation (64), one explanation is that the AU-rich environment of Olfr uORFs promotes stabilization of Olfr mRNAs through their ability to promote re-initiation of translation. We note, however, that our results do not rule out that a subset of Olfr mRNAs are targeted for decay through their uORFs by NMD.

SUMMARY

A comprehensive landscape of mRNA features present in Olfr mRNAs revealed several unusual mRNA features in both the 5′ and 3′ UTR of Olfr mRNAs that we posit were selected over evolutionary time to direct the post-transcriptional regulation of Olfr genes. We provide evidence that Olfr mRNAs are extremely stable, which we posit results from one or more of these post-transcriptional features. Mechanisms potentially impacted by the unique features in Olfr mRNAs include ARE-mediated RNA decay, miRNA-mediated regulation and NMD.

SUPPLEMENTARY DATA

Supplementary Data are available at NAR Online.

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