Discovering and characterizing the first non-coding RNA that regulates gene expression, *micF* RNA: A historical perspective

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**Abstract**

The first evidence that RNA can function as a regulator of gene expression came from experiments with prokaryotes in the 1980s. It was shown that *Escherichia coli* *micF* is an independent gene, has its own promoter, and encodes a small non-coding RNA that base pairs with and inhibits translation of a target messenger RNA in response to environmental stress conditions. The *micF* RNA was isolated, sequenced and shown to be a primary transcript. In vitro experiments showed binding to the target *ompF* mRNA. Secondary structure probing revealed an imperfect *micF* RNA/*ompF* RNA duplex interaction and the presence of a non-canonical base pair. Several transcription factors, including OmpR, regulate *micF* transcription in response to environmental factors. *micF* has also been found in other bacterial species, however, recently Gerhart Wagner and Jörg Vogel showed pleiotropic effects and found *micF* inhibits expression of multiple target mRNAs; importantly, one is the global regulatory gene *lrp*. In addition, *micF* RNA was found to interact with its targets in different ways; it either inhibits ribosome binding or induces degradation of the message. Thus the concept and initial experimental evidence that RNA can regulate gene expression was born with prokaryotes.

**Key words:** Non-coding RNAs; RNA/RNA interaction; Regulation of gene expression; *micF* RNA; Trans-acting RNA gene

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processing, but the basic principle of an RNA gene locus encoding a regulatory RNA that targets gene expression in trans via RNA/target RNA duplex formation is similar. Thus the concept and discovery of regulatory non-coding RNAs and their functions in messenger RNA inhibition originated with prokaryotes.

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**INTRODUCTION**

It is now recognized that regulation of gene expression by non-coding RNAs via RNA/mRNA interactions is a vastly widespread phenomena that occurs in all biological domains, including viruses, and it has become a basic principle in biology. Current research on non-coding RNAs has essentially “exploded”[1-7]. Yet before the 1980s, RNAs were thought of as macromolecules that primarily supported the protein synthesis machinery, were considered inert, and the concept of RNA as a regulator was unheard of.

In this review we focus on early history of the experimental work that showed that RNA is a regulator of gene expression, and this occurred approximately 30 years ago in the 1980s. micF RNA was the first regulatory RNA discovered[9-11]. This preceded the discovery of regulation of gene expression by RNAs in eukaryotes, which was in the 1990s[12]. Prokaryotic non-coding RNAs that regulate gene expression are termed sRNAs; the eukaryotic RNAs are termed microRNAs (miRNAs).

The second bacterial regulatory RNA discovered was DsrA. This RNA transcript was found to mediate rpoS expression in 1995[12] but its mechanism of action via RNA/RNA binding was not determined until 1999[14,15].

**ESCHERICHIA COLI 6S RNA, SPOT 42, EUKARYOTIC 7SK RNA AND CRISPRS**

The discovery that RNA can serve a regulatory role was in the 1980s, however, three regulatory RNAs were found before that but were uncharacterized: *Escherichia coli* (E. coli) 6S RNA, Spot 42 and the eukaryotic 7SK RNA. These RNAs were discovered and sequenced about 40 years ago but their functions were not elucidated until decades later. The 6S RNA was first detected in 1967[16] and was sequenced by George Brownlee in 1971[17]. Its function was determined approximately 30 years later in 2000 by Wassarman et al[18] who showed that 6S RNA binds the RNA polymerase-sigma70 complex and inhibits sigma factor-dependent gene transcription.

The second non-coding RNA found and also unchar-
acterized until decades later was the transcript termed Spot 42 encoded by the *E. coli* spf gene. It was first found in 1973 as a transcript on two-dimensional gel electrophoresis by Ikemura et al[19], but its function as a regulatory non-coding RNA was not determined until 2002 when Valentine-Hansen’s lab showed that Spot 42 binds the galK mRNA and inhibits the galactose operon[20]; however, more recently it has been shown to also target fourteen other operons[21].

As to eukaryotic RNAs, in 1976 Gary Zieve and Sheldon Penman found several small RNAs in HeLa cells, one was the 7SK RNA, but its function and the function of the other RNAs were unknown at the time[22]. Almost 30 years later it was shown that 7SK RNA binds to a HEXIM1 protein complex, which then binds to the transcription elongation factor P-TEFb and inhibits transcription[23,24].

There are parallels between the prokaryotic 6S RNA and the eukaryotic 7SK RNA - both were found decades before any functional roles were determined and both bind proteins resulting in inhibition of transcription. The majority of small non-coding RNAs regulate post-transcriptionally by binding target mRNAs.

Clustered regularly interspersed short palindromic repeats (CRISPRs) were discovered in *E. coli* in 1987 by Ishino et al[25]. CRISPRs are an array of genomic repeat sequences, which are separated by spacer sequences that originate from viral or plasmid DNA. They represent an acquired bacterial immune system. Similar to the RNAs discussed above, functions and mechanism of regulation of the CRISPR system as small RNA/target DNA inhibitors were not elucidated until about two to three decades later[26-29] (references shown represent only a partial list of contributors).

The bacterial CRISPR-specific RNA processing and targeting mechanism has been compared to the eukaryotic RNAi mechanism and they display striking similarities, although they are not homologous[30]. The CRISPR system currently represents one of the fastest moving fields in molecular biology, primarily because of its potential to alter gene structure and induce chromosomal rearrangements. On the other hand, Morange points out that some earlier pioneer work with the CRISPR system went under-appreciated[31].

**COLE1 RNAI**

In 1981 two labs showed that antisense RNAs can inhibit plasmid replication in *E. coli*[32,33]. These are milestone experiments as they were the first to demonstrate a regulatory function for RNA. In addition, Tomizawa[34] working with ColE1 plasmid replication, demonstrated that antisense RNA I binds to and inhibits the primer RNA II that is involved in initiating DNA replication.

Tomizawa[34] presented a model of antisense RNA/primer RNA recognition by the so-called “kissing interaction”. This involves a two-step process, whereby initially there is a loop-loop interaction via Watson-Crick base-pairing between the short stem loops of
RNA I and RNA II, followed by pairing of unstructured single-stranded segments of the two RNAs and eventual melting of the stem loops and formation of an antisense/sense RNA/RNA duplex (Figure 1).

The kissing interaction was another pioneer proposal by Tomizawa [34] whereby we now know there is board significance to the initial recognition of two RNAs via stem loop interactions [35-39]. The loop-loop interaction has also been predicted to occur in both the prokaryotic and eukaryotic non-coding RNA/target RNA recognition process [40-42].

There were also other significant plasmid-related experiments at that time. In 1981 Rosen et al [43] found three RNA transcripts encoded by plasmids R100 and R1, one a counter transcript, but RNA functions were not fully elucidated. Additionally, Simons et al [44] and Kittle et al [45] showed that an antisense counter transcript from the insertion sequence of transposon IS10 inhibits transposase expression via RNA/RNA interactions and predicting an initial loop interaction.

**MICF RNA**

In 1984, Mizuno et al [8] were the first to present the concept of a regulatory RNA gene that controls expression of another gene via RNA/RNA base-pairing. This is the E. coli micF gene whose transcript inhibits the expression of the target gene ompF. This was based on multicopy plasmid repression of OmpF protein from a sequence upstream of the ompC gene. This sequence has complementarity to ompF mRNA [8]. OmpF is an outer membrane protein, a porin protein that allows small molecules to diffuse passively through the cell. Thus it is an important protein to regulate in terms of protecting the cell from deleterious molecules.

At that time it was a rather bold and innovative proposal that an RNA can regulate gene expression, There were no role models for such a function, and RNA was for the most part still considered a passive macromolecule that participates in the protein synthesis process and formed the scaffolding for ribosomal proteins, notwithstanding the previous work on antisense RNA repression of plasmid replication [32,33].

Dr. Inouye should be credited for his creativity in first proposing the existence of a regulatory RNA gene. But his lab had only multicopy plasmid effects and had not isolated the RNA transcript. An RNA molecular biologist was needed and I was asked to contribute to the work. Subsequently my lab isolated and sequenced the chromosomal-encoded micF RNA, found that micF is an independent gene with its own promoter, determined the regulatory RNA/target RNA base-pairing by structure probing, and determined its function in terms of regulation of target gene in response to environmental stress conditions [9,10].

By using *in vivo* P32 labeling, isolating low molecular weight RNAs and separation on gels, we found a 4.5S RNA transcript. Its sequence showed that it was micF RNA and that it was 93 nt long with a rho independent termination site [9]. To characterize the micF promoter
strain (SM3001). The findings revealed that \( \text{micF} \) RNA plays a major role in the thermal regulation of \( \text{ompF} \) mRNA and OmpF protein. However, the mechanism of thermal regulation of \( \text{micF} \) expression is still an open question, but temperature has been shown to regulate DNA supercoiling that is associated with the induction of stress related genes\[46-49\]. \( \text{micF} \) expression was also found to respond to other environmental stress conditions such as osmolarity change and exposure to ethanol\[10,50\].

The upstream \( \text{micF} \) regulatory region is complex in that it contains binding sites for a number of transcription factors; these regulate \( \text{micF} \) expression in response to different environmental stress factors\[51\]. Five transcription factors are known to bind in the upstream regulatory region (Figure 3). With respect to osmolarity change, there are three binding sites (C1-C3) for transcription factor OmpR that activates expression of \( \text{micF} \) in response to stress conditions, \( \text{lacZ} \) was fused at different sites upstream of the \( \text{micF} \) gene and \( \text{micF} \) was found to have a strong promoter based on beta galactosidase activity.

**MICF RESPONSE TO STRESS CONDITIONS**

A search for function was initiated by looking at the response of \( \text{micF} \) expression to various environmental factors. A major effect was found with temperature change and other factors. Levels of \( \text{micF} \) RNA increased dramatically in response to cell growth at high temperature\[10\]. The levels of \( \text{ompF} \) mRNA and the OmpF protein were also measured and found to decrease under these conditions. Figure 2 shows a marked decrease in \( \text{ompF} \) mRNA levels with temperature increase in the wild type strain, but no significant change in the \( \text{micF} \) deletion strain (SM3001). The findings revealed that \( \text{micF} \) RNA plays a major role in the thermal regulation of \( \text{ompF} \) mRNA and OmpF protein. However, the mechanism of thermal regulation of \( \text{micF} \) expression is still an open question, but temperature has been shown to regulate DNA supercoiling that is associated with the induction of stress related genes\[46-49\]. \( \text{micF} \) expression was also found to respond to other environmental stress conditions such as osmolarity change and exposure to ethanol\[10,50\].

![Figure 2 ompF mRNA levels after temperature shift from 24 °C to 42 °C. Lanes marked a-k correspond to time 0-120 min. Left, RNA from strain MC4100 that has the \( \text{micF} \) gene; right, strain SM3001 that is a \( \text{micF} \) deletion strain. Data from Andersen et al\[10\]. Reproduced with permission.](image1)

![Figure 3 Schematic of \( \text{micF} \) gene, upstream P-10, P-35 promoter region and transcription factor binding sites. Diagram modified from Delihas et al\[51\].](image2)
to osmolarity increase\textsuperscript{[60]}. MarA responds to weak acids\textsuperscript{[52]}, SoxS to oxidative stress\textsuperscript{[53]}, Rob to peptide antibiotics\textsuperscript{[54,55]} and Lrp to nutritionally poor media\textsuperscript{[56]}. These four transcription factors share the same binding site on the micF promoter region (Figure 3). MarA, SoxS and Rob are related proteins that activate micF. Rowena Matthews’ lab showed that Lrp represses micF transcription\textsuperscript{[57]}; Lrp is part of the nucleoid-associated protein group\textsuperscript{[57]}. The crystal structure of transcription factor Rob bound to the micF promoter region has been elucidated (by Kwon et al\textsuperscript{[57]}). The model shows one protein helix-turn-helix motif bound to the major groove of micF DNA. Additional biochemical studies showed a high affinity of binding micF\textsuperscript{[58]}.

micF is also regulated at the post-translational level when cells are grown in a nutrient poor medium\textsuperscript{[59]}. Dorman and co-workers hypothesized that Stp induces a conformational change in micF RNA that makes it susceptible to degradation by nucleases\textsuperscript{[59]}. Stp is also a nucleoid-associated protein and a parologue of H-NS\textsuperscript{[60,61]}. Thus micF gene expression is regulated at both the transcriptional and post-transcriptional levels in response to different environmental conditions.

**MICF RNA/TARGET ompF mRNA DUPLEX**

It was demonstrated that a RNA/RNA duplex could be formed \textit{in vitro} between micF RNA and the target ompF mRNA\textsuperscript{[62]}. Full length micF RNA and a 150 nt 5’ end fragment of ompF mRNA were synthesized \textit{in vitro} and the RNA/RNA duplex was formed by annealing at 55 °C and 37 °C. Subsequently, \textit{in vitro} formed duplexes were used for secondary structure probing\textsuperscript{[63]}. Single and double stranded specific RNAs and chemical modification with a NiCR complex that is single stranded G-specific\textsuperscript{[64]} were used for probing. As nuclease probes can be sensitive to steric hindrance, chemical modification was performed using the NiCR reagent to try to gain additional information\textsuperscript{[63-65]}. A schematic of the deduced micF RNA/ompF mRNA duplex base-pairing is in Figure 4.

The RNA/RNA interaction shows an imperfect duplex, and a non-canonical G\textsuperscript{45}-G\textsuperscript{49} base-pair that was determined from the absence of RNase T1 cleavage and NiCR reaction, but also the presence of double stranded specific RNase V1 cleavages\textsuperscript{[63,65]}. The Shine-Dalgarno (S-D) ribosome binding site is blocked, which implies that micF RNA inhibits ribosome binding. \textit{In vivo} experiments show that ompF mRNA levels decrease with temperature increase in an \textit{E. coli} strain carrying micF (Figure 2); however, micF RNA has not been shown to directly participate in degradation of the message, but to block ribosome binding.

Long-range pairing based on the Maximum Weighted Matching computational program of Tabaska et al\textsuperscript{[66]} was predicted to also contribute to the RNA/RNA interaction (Figure 4). The pairing is supported by phylogenetic comparisons and for the most part, by structure probing. Long-range pairings should contribute to the three-dimensional structure of the interacting RNAs.

**MICF RNA HAS MULTIPLE TARGETS AND PARTICIPATES IN GLOBAL GENE REGULATION**

Recently it has been shown that the functions of micF RNA are multifaceted and extend far beyond regulation of ompF expression. Gerhart Wagner’s lab\textsuperscript{[67]} showed that micF is part of a global regulatory network involving the leucine responsive protein (Lrp), and Jörg Vogel’s lab\textsuperscript{[68]} at the University of Würzburg in Germany showed that micF targets different mRNAs and base-pairs with these RNAs in different ways.

Approximately 10% of all genes in \textit{E. coli} are controlled by Lrp, a transcription factor which responds to nutrient availability. Wagner’s group\textsuperscript{[67]} showed participation of micF RNA in a circular regulatory pathway, \textit{i.e.}, Lrp regulates transcription of micF RNA and micF RNA regulates Lrp expression post-transcriptionally, depending on the nutritional content of the cell growth media (Figure 5). Both Lrp and micF RNA function as repressors. micF RNA participates in this global regulatory network by regulating \textit{lrp} mRNA; thus this greatly expands its role in regulation of gene expression and cell metabolism.

On the other hand, using \textit{Salmonella} as a model, Vogel et al\textsuperscript{[68]} demonstrated that micF RNA targets multiple mRNAs in addition to ompF mRNA and \textit{lrp} mRNA (Figure 5). Interestingly, its mode of binding to different mRNAs is multifaceted. On the one hand, micF RNA can induce
destabilization of the \( \text{yahO} \) mRNA by unfolding a stem-loop structure located at the 5′-terminus, and thus make the mRNA accessible to exonuclease action. With \( \text{lpXR} \) mRNA, \( \text{micF} \) RNA binds at two sites. One site is within the coding region of the message, and when \( \text{micF} \) RNA binds at this site, it induces a conformational change exposing an AU region that can be targeted by the endonuclease RNase E, which then degrades the message \[68\].

\( \text{yahO} \) encodes a periplasmic protein and \( \text{lpXR} \) encodes an outer membrane lipid A-modifying enzyme.

**HFQ PROTEIN**

*In vitro* studies showed that \( \text{micF} \) RNA binds to a protein based on mobility shifts of protein-RNA complexes on non-denaturing gels\[62\]. UV-cross-crosslinking experiments suggested that the protein was 80 kDa, however the protein was not further characterized. It is well known that many sRNAs bind the Hfq protein and that Hfq facilitates the binding of sRNAs to their target mRNAs, including \( \text{micF} \) RNA\[70\]. The molecular weight of Hfq is 11.2 KDa\[71\], but the 80 kDa protein found to bind \( \text{micF} \) RNA\[62\] is inconsistent with this and there is a need for further investigation.

Hfq is a central component of the pairing of bacterial non-coding RNAs with their target messenger RNAs. The multifaceted ways that Hfq, together with sRNAs can participate in the inhibition of translation and/or mRNA degradation has been outlined\[72\]. Hfq also interacts with another protein, catalase HPII. The crystal structure of Hfq bound to catalase HPII has been solved\[71\], but the crystal structure of an Hfq-sRNA complex has not been determined.

**OTHER NON-CODING RNA FUNCTIONS**

In this paper we focused on initial findings involving the regulation of gene expression by RNA, however, there is a wealth of discoveries with other functions of non-coding RNAs that also occurred during the 1980s, and it is important to mention this. Table 1 lists several initial findings that include enzymatic RNA, catalytic RNA and RNA functions in protein translocation. The work on regulation of gene expression by RNA and the studies outlined in Table 1 provide a breakthrough on understanding functions of RNAs whereby before the 1980s, RNAs were largely considered inert with no dynamic functions.

**CONCLUSION**

The initial discovery that RNA can function as a regulatory molecule occurred in the 1980s. Table 2 summarizes the chronology. Bacterial plasmid RNAs were first shown by two labs to regulate DNA replication via sense/antisense RNA/RNA base-pairing\[32,33\] and the *E. coli* \( \text{micF} \) gene was the first found to regulate expression of another gene in trans via imperfect RNA/RNA base-pairing, also by two labs\[8-10\]. These finding were major breakthroughs that came approximately 5-10 years before the discovery of eukaryotic microRNAs and their functions. Subsequently, numerous labs added to the molecular genetics of \( \text{micF} \) and to functional properties of the transcript that greatly advanced our knowledge of the role of this gene in cell survival. So it was essentially work with prokaryotes that first opened the door to a new form of regulation of gene expression by RNA.
that is now found in all biological kingdoms, including viruses. However, there are many different types of regulatory RNAs that are found only in eukaryotes (e.g., piRNA, siRNA, IncRNA), and the prospects of finding new and unique functions of RNAs may lie primarily with eukaryotic RNAs. Looking towards the future, there are tens of thousands of IncRNAs that have been detected, and for the most part are uncharacterized. But the few that have been characterized display very diverse and intricate functions.[78-82]

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