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# MicroRNA signatures in genetic frontotemporal dementia and amyotrophic lateral sclerosis

Virgilio Kmetzsch¹ ², Morwena Latouche³, Dario Saracino¹ ⁴ ⁵, Daisy Rinaldi³ ⁴ ⁵, Agnès Camuzat³ ⁶, Thomas Gareau³, the French Research Network on FTD/ALS, Isabelle Le Ber³ ⁴ ⁵ ⁷, Olivier Colliot¹ & Emmanuelle Becker²

¹Sorbonne Université, Institut du Cerveau – Paris Brain Institute – ICM, CNRS, Inria, Inserm, AP-HP, Hôpital de la Pitié Salpêtrière, F-75013, Paris, France
²Univ Rennes, Inria, CNRS, IRISA, F-35000, Rennes, France
³Sorbonne Université, Institut du Cerveau – Paris Brain Institute – ICM, CNRS, Inserm, AP-HP, Hôpital de la Pitié Salpêtrière, F-75013, Paris, France
⁴Centre de référence des démences rares ou précoces, IM2A, Département de Neurologie, AP-HP - Hôpital Pitié-Salpêtrière, Paris, France
⁵Département de Neurologie, AP-HP - Hôpital Pitié-Salpêtrière, Paris, France
⁶EPHE, PSL Research University, Paris, France
⁷Paris Brain Institute – Institut du Cerveau – ICM, FrontLab, Paris, France

## Abstract

**Objective:** MicroRNAs are promising biomarkers of frontotemporal dementia (FTD) and amyotrophic lateral sclerosis (ALS), but discrepant results between studies have so far hampered their use in clinical trials. We aim to assess all previously identified circulating microRNA signatures as potential biomarkers of genetic FTD and/or ALS, using homogeneous, independent validation cohorts of C9orf72 and GRN mutation carriers.

**Methods:** 104 individuals carrying a C9orf72 or a GRN mutation, along with 31 controls, were recruited through the French research network on FTD/ALS. All subjects underwent blood sampling, from which circulating microRNAs were extracted. We measured differences in the expression levels of 65 microRNAs, selected from 15 published studies about FTD or ALS, between 31 controls, 17 C9orf72 presymptomatic subjects, and 29 C9orf72 patients. We also assessed differences in the expression levels of 30 microRNAs, selected from five studies about FTD, between 31 controls, 30 GRN presymptomatic subjects, and 28 GRN patients.

**Results:** More than half (35/65) of the selected microRNAs were differentially expressed in the C9orf72 cohort, while only a small proportion (5/30) of microRNAs were differentially expressed in the GRN cohort. In multivariate analyses, only individuals in the C9orf72 cohort could be adequately classified (ROC AUC up to 0.98 for controls versus presymptomatic subjects, 0.94 for controls versus patients, and 0.77 for presymptomatic subjects versus patients) with some of the signatures.

**Interpretation:** Our results suggest that previously identified microRNAs using sporadic or mixed cohorts of FTD and ALS patients could potentially serve as biomarkers of C9orf72-associated disease, but not GRN-associated disease.

## Introduction

Frontotemporal dementia (FTD) is a neurodegenerative disease characterized by brain atrophy in the frontal and temporal lobes, causing severe changes in personality and social behavior. The most prevalent genetic causes of FTD are GGGGCC repeat expansions in the C9orf72 gene and mutations in the GRN gene. FTD shares disease...
pathways with amyotrophic lateral sclerosis (ALS), a debilitating motor neuron disease that causes progressive motor deficit and muscle wasting. The $C9orf72$ hexanucleotide repeat expansion has been identified as the most common genetic cause of both familial FTD and ALS, as well as of their sporadic counterparts.2

There are currently no disease-modifying treatments that can stop the course of FTD or ALS. New therapeutic trials depend on robust progression biomarkers to assess treatment outcomes. The study of FTD/ALS genetic forms is particularly important, since asymptomatic mutation carriers may provide insights about the early disease stages, before any irreversible neuronal damage.5

Among the potential noninvasive biomarkers of neurodegenerative diseases, circulating microRNAs (miRNAs) constitute a promising approach.6 MiRNAs are short noncoding RNAs that negatively regulate gene expression.7 There is increasing evidence of a link between miRNA expression levels and the diagnosis of FTD8–12 and ALS.11–22 However, there are strong inconsistencies between the identified miRNA signatures in different studies. The examined cohorts are highly heterogeneous, most of them being sporadic or mixed cohorts of sporadic and genetic forms. Importantly, it is unclear which miRNAs are specific to a particular genetic mutation or might serve as biomarkers for several genetic forms. It is also uncertain whether miRNAs found in sporadic forms are differentially expressed in genetic forms. Furthermore, several of the published articles lacked an independent validation cohort, which also might have caused disparity between results. Finally, differences in lifestyle factors (e.g., diet, exercise, cognitive training) across the studied cohorts may contribute to non-reproducible results.3,4 This absence of convergence among different studies so far hinders the use of miRNAs in clinical trials.

The present work aims at testing circulating miRNA signatures identified in the literature, using two independent homogeneous cohorts of patients and presymptomatic carriers: one focused on $C9orf72$ expansion carriers and another comprising $GRN$ mutation carriers. For that purpose, we selected all published studies that identified specific miRNAs isolated from plasma or serum as potential biomarkers of FTD and/or ALS. With a preregistered study design, we investigated whether (1) miRNAs revealed in cohorts of sporadic patients (or in mixed cohorts with sporadic and genetic forms) may be biomarkers in $C9orf72$ and/or $GRN$ genetic forms, (2) miRNAs identified in a $C9orf72$ cohort are validated in an independent $C9orf72$ cohort, and (3) miRNAs discovered in a $C9orf72$ cohort may be relevant in a $GRN$ cohort.

We hypothesize that if a miRNA is a potential biomarker in a particular genetic form, it will be differentially expressed (adjusted $p$ value below 0.05) between controls and presymptomatic subjects, controls and patients, or presymptomatic subjects and patients in an independent cohort of subjects carrying that mutation. Moreover, we consider that a miRNA signature will constitute an acceptable biomarker if a logistic regression model (using these miRNAs as features) classifies subjects between clinical groups with an area under the ROC curve greater than 0.70.25

Materials and Methods

This research was conducted according to the preregistration available in https://osf.io/4pw8f.

Participants of the validation cohorts

Between 2011 and 2021, 135 individuals were recruited through the French research network on FTD/ALS (Inserm RBM02-59) and investigated with the same protocol, as previously described in detail.26 All participants signed written informed consents. This study was approved by the Comité de Protection des Personnes CPP Ile-De-France VI (CPP 36–09/ID RCB 2008-A01376-49 and CPP 68–15/ID RCB 2015-A00856-43).

Two cohorts were studied. One cohort was focused on $C9orf72$ mutation carriers, including 29 patients (20 FTD, 6 FTD/ALS and 3 ALS) and 17 carriers in the presymptomatic phase. Another cohort was focused on $GRN$ mutation carriers, comprising 28 FTD patients and 30 presymptomatic carriers. The control group, shared between the two cohorts, was made up of 31 neurologically healthy individuals that did not carry any of these mutations. Table 1 displays the demographic characteristics of the studied cohorts.

Standardized interviews with family members, full neurological examinations, quantitative motor testing, and extensive neuropsychological tests measuring all cognitive domains were used to assess each participant’s cognitive and clinical conditions. All subjects underwent blood tests, and collected samples were stored in the Paris Brain Institute (ICM) DNA and cell bank.

Plasma preparation, miRNA sequencing and computation pipeline

Blood samples from all participants were collected on EDTA following standardized collection and handling procedures. The mean disease duration at sampling was 4.9 (SD 3.8) years in the $C9orf72$ patients’ group and 3.2 (SD 1.4) years in the $GRN$ patients’ group. All participants were in fasted state. At the ICM DNA and cell bank, all samples were centralized and processed in
conformity with the same procedure. Blood samples were centrifuged at 2500 rpm for 10 min before plasma was extracted at room temperature. At a temperature of −80°C, 1 ml aliquots were stored in polypropylene tubes. Following the instructions provided by the manufacturer, miRNA extraction was carried out using a miRNeasy Serum/Plasma Kit (Qiagen). We used 200 μl of plasma that was progressively melted at 4°C and added directly to 1 ml of QIAzol solution. Using the QIAseq miRNA Library Kit (Qiagen) in accordance with the manufacturer’s protocol, miRNAs were eluted in 14 μl of water; 5 μl were utilized to prepare the miRNA sequencing library. Targeting a minimum of 10 million mapped reads per sample, two independent batches of miRNA sequencing were performed on the Illumina NovaSeq 6000.

The quantification of miRNAs was carried out according to recommendations by Potla et al. The quality of reads was assessed with FastQC (Andrews S. 2010, http://www.bioinformatics.babraham.ac.uk/projects/fastqc/).

Next, UMI-tools and Cutadapt were used to clean sequences and extract unique molecular identifiers (UMIs). Then, the resulting reads were aligned to the mature miRNA sequences from the miRBase (https://www.mirbase.org) database version 22.1, using Bowtie.

After that, the PCR duplicates were removed with UMI-tools. Finally, miRNA count tables were created with Samtools idxstats.

Selected studies

We aimed to find all papers that identified specific miRNAs extracted from human plasma or serum as potential biomarkers of FTD and/or ALS, excluding reviews and meta-analyses. We thus conducted the following search in PubMed (https://pubmed.ncbi.nlm.nih.gov/), on March 10, 2022:

(microRNA[Title] OR microRNAs[Title] OR miR[Title] OR miRNA[Title]) AND (serum[Title] OR circulating[Title] OR plasma[Title]) AND (ALS[Title] OR FTD[Title] OR amyotrophic[Title] OR frontotemporal[Title] OR (neurodegenerative[Title] AND (frontotemporal[Title/Abstract] OR amyotrophic[Title/Abstract]))) NOT mice[Title/Abstract] NOT mouse[Title/Abstract] NOT extracellular vesicles[Title] NOT review[PT] NOT meta-analysis[PT] NOT (comment[PT])

This search resulted in 19 journal articles. Two papers were excluded because they were review studies, one was discarded because it was focused on protein levels, and one was excluded because it was focused on one microRNA from serum exosomes.

Our final selection therefore contained 15 articles. These selected papers, along with the studied diseases (FTD, ALS, or both), cohort types (sporadic, genetic, or mixed), cohort sizes, methods of analyses (qRT-PCR, microarrays, RNA-sequencing, or a combination), and the identified miRNA signatures are displayed in Table 2.
### Table 2. Selected studies investigating circulating microRNA expression (from serum or plasma) of patients with FTD or ALS. Columns indicate each reference, studied disease (FTD, ALS, or both), type of the analyzed cohort (sporadic, genetic, or mixed), number of patients in the discovery and replication (if available) cohorts, number of presymptomatic carriers included in the study, method of analysis (qRT-PCR, microarrays, RNA-sequencing, or a combination), and the identified miRNA signature.

| Article                     | Disease                  | Cohort                        | Patients, No. (discovery/replication) | Presymptomatic carriers, No. | Method of analysis | MiRNA signature                          |
|-----------------------------|--------------------------|-------------------------------|--------------------------------------|-----------------------------|-------------------|------------------------------------------|
| Grasso et al., 2019         | FTD                      | Sporadic                      | 10/48 split of same cohort            | –                           | qRT-PCR of 752 miRNAs                      | miR-663a, miR-502-3p, miR-206               |
| Piscopo et al., 2018        | FTD                      | Sporadic                      | 54                                   | –                           | qRT-PCR of 9 miRNAs linked with apoptosis | miR-127-3p                                |
| Denk et al., 2018           | FTD                      | Sporadic                      | 48                                   | –                           | qRT-PCR of 96 miRNAs identified in preliminary study | let-7b-5p, let-7 g-5p, miR-106a-5p, miR-106b-5p, miR-18b-5p, miR-223-3p, miR-26a-5p, miR-26b-5p, miR-301a-3p, miR-30b-5p, miR-146a-5p, miR-15a-5p, miR-22-3p, miR-320a, miR-320b, miR-92a-3p, miR-1246 |
| Kmetzsch et al., 2021       | FTD, ALS                 | Genetic (C9orf72)             | 22                                   | 45                          | RNA-sequencing of 2576 miRNAs               | miR-34a-5p, miR-345-5p, miR-200c-3p, miR-10a-3p |
| Sheinerman et al., 2017     | FTD, ALS                 | Unspecified                   | For each disease, 25/25 split of same cohort | –                           | qRT-PCR of 37 brain-enriched miRNAs         | miR-9/let-7e, miR-7/miR-451, miR-335-5p/let-7e (FTD) and miR-206/miR-338-3p, miR-9/miR-129-3p, miR-335-5p/miR-338-3p (ALS) |
| Magen et al., 2021          | ALS                      | Mixed sporadic and genetic (C9orf72) | 126/122 split of same cohort          | –                           | RNA-sequencing of 125 miRNAs identified in longitudinal study | miR-181a-5p, miR-181b-5p |
| Soliman et al., 2021        | ALS                      | Mixed sporadic and genetic (unspecified mutation) | 30                                   | –                           | qRT-PCR of 7 miRNAs involved in ALS         | miR-206, miR-143-3p, miR-142-3p |
| Dobrowolny et al., 2021     | ALS                      | Mixed sporadic and genetic (unspecified mutation) | 13/23                                | –                           | RNA-sequencing followed by qRT-PCR           | miR-151a-5p, miR-199a-5p, miR-423-3p |
| Raheja et al., 2018         | ALS                      | Mixed sporadic and genetic (C9orf72, SOD1) | 23                                   | –                           | qRT-PCR of 191 miRNAs identified on prior study | miR-29b-3p, miR-320c, miR-34a-5p, miR-29c-3p, miR-320a, miR-22-3p, miR-1, miR-133a-3p, miR-191-5p, miR-144-5p, miR-320b, miR-423-3p, miR-192-5p, miR-133b, miR-194-5p, miR-7-1-3p, miR-19a-3p, miR-425-5p, miR-145-5p, miR-144-3p |
| Waller et al., 2017         | ALS                      | Sporadic                      | 27/23                                | –                           | qRT-PCR of 750 miRNAs                      | miR-206, miR-143-3p, miR-374b-5p |
| Tasca et al., 2016          | ALS                      | Sporadic                      | 14                                   | –                           | qRT-PCR of 9 muscle-specific,              | miR-206, miR-133a, miR-133b, miR-27a |

(Continued)
Table 2 Continued.

| Article                        | Disease | Cohort               | Patients, No. (discovery/replication) | Presymptomatic carriers, No. | Method of analysis | MiRNA signature                     |
|-------------------------------|---------|----------------------|--------------------------------------|-----------------------------|--------------------|-------------------------------------|
| Takahashi et al., 2015\(^{19}\) | ALS     | Sporadic             | 16/48 split of same cohort            | –                           | Microarrays, followed by qRT-PCR of 9 miRNAs | miR-4649-5p, miR-4299         |
| Freischmidt et al., 2015\(^{20}\) | ALS     | Sporadic             | 18/20                                | –                           | Microarrays of 1733 miRNAs, followed by qRT-PCR of 2 miRNAs | miR-1234-3p, miR-1825         |
| Freischmidt et al., 2014\(^{21}\) | ALS     | Separate sporadic and genetic (SOD1, FUS, C9orf72) | 9/13 (genetic), 14 (sporadic)         | 18                          | Microarrays of 1733 miRNAs and qRT-PCR of 4 miRNAs | miR-4745-5p, miR-3665, miR-1915-3p, miR-4530 |
| De Felice et al., 2014\(^{22}\) | ALS     | Sporadic             | 10                                   | -                           | qRT-PCR of 1 miRNA  | miR-338-3p                          |

Differential expression

Differential expression analyses were performed using the R package EdgeR.\(^{35}\) After microRNA extraction, sequencing and quality control steps, our dataset contained the expression levels of 2656 miRNAs (denoted by \(i\), corresponding to all miRNA sequences mapped in miRBase version 22.1) for each of the 135 subjects (represented by \(j\)). First, we created two count matrices: one containing the miRNA counts from the C9orf72 patients, presymptomatic subjects and controls, and another containing the miRNA counts from the GRN patients, presymptomatic individuals, and controls. Second, for each count matrix, we used generalized linear models (GLM) to fit a log-linear model to each miRNA, following a negative binomial distribution with mean \(\mu_{ij}\) and dispersion \(\phi_i\):

\[
\log_2\mu_{ij} = x_j^T \beta_i
\]

where \(x_j\) denotes the covariates describing sample \(j\) and \(\beta_i\) denotes the coefficients to be fitted for miRNA \(i\). To control for possible age, sex, center and batch effects, we included them as covariates in the models, in addition to the clinical group (control, presymptomatic or patient). A trimmed mean of \(M\)-values\(^{36}\) was used to normalize raw counts. Finally, after the log-linear models were fitted,
quasi-likelihood (QL) F-tests were used to identify the differentially expressed miRNAs.

Concretely, we tested each of the 65 miRNAs associated with either FTD or ALS in the literature, to identify which were differentially expressed between (a) controls versus C9orf72 presymptomatic subjects, (b) controls versus C9orf72 patients, and (c) C9orf72 presymptomatic subjects versus C9orf72 patients. Additionally, we tested the 30 miRNAs associated with only FTD in the literature, to highlight which were differentially expressed between (d) controls versus GRN presymptomatic subjects, (e) controls versus GRN patients, and (f) GRN presymptomatic subjects versus GRN patients.

All p values were 2-tailed, and the level of statistical significance was set at 0.05. The Benjamini-Hochberg procedure was used to adjust p values for multiple testing. Additionally, we considered as suggestive, but not statistically significant, miRNAs with adjusted p values between 0.05 and 0.1. Our differential expression analyses resulted in two meta-signatures for each cohort: one meta-signature including miRNAs with adjusted p values below 0.05 (thus including only statistically significant miRNAs), and one containing miRNAs with adjusted p values below 0.1 (thus including both statistically significant and suggestive miRNAs).

**Binary classification**

To test if the miRNA signatures described in the literature could discriminate between clinical groups, we trained L2-regularized logistic regression classifiers, using Python 3.8.5 with scikit-learn 0.23.2. We first organized the miRNA expression data into six datasets, one for each relevant pairwise comparison: (a) controls versus C9orf72 presymptomatic subjects, (b) controls versus C9orf72 patients, (c) C9orf72 presymptomatic subjects versus C9orf72 patients, (d) controls versus GRN presymptomatic subjects, (e) controls versus GRN patients, and (f) GRN presymptomatic subjects versus GRN patients. A total of 18 classifiers were trained for each of the comparisons (a), (b) and (c): 16 classifiers used as features each of the miRNA signatures identified in the literature, and two were trained with meta-signatures containing the differentially expressed miRNAs identified in the univariate analyses (a), (b) and (c), respectively with adjusted p values lower than 0.05 and 0.1. In addition, seven classifiers were built for each of the comparisons (d), (e) and (f): five of them used as features each of the miRNA signatures associated with FTD in the literature, and two were trained with meta-signatures containing the differentially expressed miRNAs identified in the univariate analyses (d), (e) and (f), respectively with adjusted p values lower than 0.05 and 0.1.

Each logistic regression model was trained with a stratified nested 5-fold cross-validation strategy followed by bootstrapping to compute confidence intervals (CIs), as previously detailed. The inner cross-validation loop was used for hyperparameter (L2 regularization coefficient) search. The outer cross-validation loop was used to assess each classifier’s performance by computing the area under the ROC curve. Since a k-fold cross-validation does not provide an unbiased estimator of the variance, it cannot be used to compute CIs. Therefore, we used 2000 bootstrap samples to compute empirical 90% CIs for the ROC AUC scores, by considering the 5th and 95th percentiles of the bootstrap distribution. A miRNA signature was considered an acceptable biomarker for a given comparison if the corresponding ROC AUC was above 0.70.

**Results**

**Differential expression in the C9orf72 cohort**

The first analysis consisted of testing which of the 65 miRNAs identified in the literature as potential biomarkers of FTD and/or ALS were differentially expressed in our C9orf72 cohort. For this analysis, we considered the miRNA counts obtained from sequencing plasma samples from the C9orf72 patients, C9orf72 presymptomatic subjects, and controls. After negative binomial generalized linear models were fitted for each miRNA, we thus performed 65 quasi-likelihood F-tests per pairwise comparison (controls versus C9orf72 presymptomatic subjects, controls versus C9orf72 patients, and C9orf72 presymptomatic subjects versus C9orf72 patients), adjusting for multiple comparisons using the Benjamini-Hochberg method.

All differentially expressed miRNAs identified in this analysis are displayed in Table 3 (second to fourth columns). We can see that a considerable amount of miRNAs (35 of the 65 miRNAs identified in the literature) were significantly differentially expressed (adjusted p values smaller than 0.05) in at least one comparison: miR-34a-5p, miR-338-3p, miR-142-3p, miR-320a, miR-145-5p, miR-92a-3p, let-7 g-5p, miR-199a-5p, miR-206, miR-30b-5p, miR-101-5p, miR-27a, miR-320b, miR-143-3p, miR-1246, miR-223-3p, miR-144-3p, miR-451, miR-194-5p, miR-144-5p, miR-29b-3p, miR-29c-3p, miR-192-5p, miR-19a-3p, miR-502-3p, miR-15a-5p, miR-374b-5p, miR-7-1-3p, miR-320c, miR-106b-5p, miR-146a-5p, miR-133b, let-7b-5p, miR-345-5p, and miR-22-3p. Moreover, the following 9 miRNAs had a p value between 0.05 and 0.1, close to significance value: miR-151a-5p, miR-1234-3p, miR-26a-5p, miR-301a-3p, let-7e, miR-18b-5p, miR-106a-5p, miR-1915-3p, and miR-9.
The complete output from the differential expression analyses in the C9orf72 cohort, including log-fold changes indicating the intensity of underexpression or overexpression, as well as computed p values, are displayed in Table S1. Expression heatmaps of the differentially expressed miRNAs are shown in Figure S1.


**Differential expression in the GRN cohort**

The second analysis focused on identifying which of the 30 miRNAs linked with FTD in the literature were differentially expressed in our GRN cohort. For this experiment, we used the miRNA counts acquired by sequencing plasma samples from the GRN patients, GRN presymptomatic individuals, and controls. Once negative binomial generalized linear models were fitted for each miRNA, we conducted 30 quasi-likelihood F-tests per pairwise comparison (controls versus GRN presymptomatic subjects, controls versus GRN patients, and GRN presymptomatic subjects versus GRN patients), adjusting for multiple comparisons using the Benjamini-Hochberg method.

Table 3 (fifth to seventh columns) shows all differentially expressed miRNAs identified in this experiment. Contrary to what was observed with the C9orf72 cohort, we note that only a small proportion of miRNAs (5 of the 30 miRNAs identified in the literature) were significantly differentially expressed (adjusted p values lower than 0.05), all of them when comparing controls and GRN patients: miR-451, miR-15a-5p, miR-502-3p, miR-7, and miR-129-5p. Additionally, 4 miRNAs had a p value close to significance value, between 0.05 and 0.1: miR-106a-5p, miR-92a-3p, miR-106b-5p, and let-7b-5p.

Table S2 summarizes the complete results of the differential expression experiments in the GRN cohort, including log-fold changes reflecting the degree of underexpression or overexpression of each miRNA in each pairwise comparison, and the calculated p values. Figure S1 displays expression heatmaps of the differentially expressed miRNAs.

Finally, Table 3 also allows comparing the results obtained with the C9orf72 and the GRN cohorts. Remarkably, the three comparisons involving the C9orf72 cohort revealed significantly differentially expressed miRNAs, but that was the case for only one comparison involving the GRN cohort (controls versus GRN patients). We also note that only a small minority of miRNAs (3) was significantly differentially expressed in both cohorts.

Taken together, these results offer evidence for the potential contribution of miRNAs identified in previous studies as biomarkers of C9orf72-associated disease, but not GRN-associated disease.

**Binary classification in the C9orf72 cohort**

The first set of binary classification experiments focused on the C9orf72 cohort. We trained 18 logistic regression classifiers for each pairwise comparison between clinical groups (controls versus C9orf72 presymptomatic subjects, controls versus C9orf72 patients, and C9orf72 presymptomatic subjects versus C9orf72 patients). For each of the 18 classifiers, we used as features the expression levels of distinct sets of miRNAs: the 16 miRNA signatures identified in the previously published studies about FTD and ALS, and two meta-signatures obtained from our differential expression analyses with the C9orf72 cohort (one containing miRNAs with adjusted p value <0.05, and another including miRNAs with adjusted p value <0.1).

Figure 1 displays the areas under the ROC curves obtained by each of the 18 logistic regression classifiers in the three pairwise comparisons, as well as the empirical 90% confidence intervals. We observe that more than half of the classifiers (10 of the 18) achieved a ROC AUC greater than 0.70 in at least one comparison: those using the miRNA signatures from Kmetzsch et al., 2021,11 Sheinerman et al., 201712 (FTD), Sheinerman et al., 201712 (ALS), Soliman et al., 2021,13 Dobrowolsky et al., 2021,15 Raheja et al., 2018,16 Waller et al., 2017,17 Tasca et al., 2016,18 and the two meta-signatures from our differential expression analyses. The miRNA signatures with the largest ROC AUC were from Kmetzsch et al., 202111 (0.98 for controls versus presymptomatic subjects), Raheja et al., 201816 (0.94 for controls versus patients), and the meta-signature with p < 0.1 (0.77 for presymptomatic subjects versus patients).

As well as in the differential expression analyses, these findings provide support for the potential use of several miRNAs identified in previous studies as biomarkers of C9orf72-associated FTD and ALS.

**Binary classification in the GRN cohort**

The second set of binary classification experiments consisted of training seven logistic regression classifiers for each pairwise comparison in the GRN cohort (controls versus GRN presymptomatic subjects, controls versus GRN patients, and GRN presymptomatic subjects versus GRN patients). Each of the seven classifiers was trained with a different set of features: the expression levels of the five miRNA signatures linked with FTD in previously published studies, and two meta-signatures obtained in our differential expression analyses with the GRN cohort (one consisting of miRNAs with an adjusted p value smaller than 0.05, and another comprising miRNAs with an adjusted p value smaller than 0.1).

The areas under the ROC curves and empirical 90% confidence intervals for each of the seven logistic regression classifiers, in the three pairwise comparison involving the GRN cohort, are shown in Figure 2. Strikingly, only one ROC AUC was (slightly) greater than 0.70: when classifying GRN presymptomatic subjects and GRN patients, using the meta-signature from our differential
Figure 1. Area under the ROC curve results when classifying groups from the C9orf72 cohort. The solid circles indicate the areas under the ROC curves obtained for each pairwise comparison using 18 different miRNA signatures. The whiskers denote empirical 90% confidence intervals obtained with 2000 bootstrap samples.
expression analysis comprising miRNAs with $p$ value lower than 0.1. The miRNA signatures with the largest ROC AUC were from Grasso et al., 2019\textsuperscript{8} (0.53 for controls versus presymptomatic subjects), and the meta-signature with $p < 0.1$ (0.63 for controls versus patients, and 0.72 for presymptomatic subjects versus patients).

**Figure 2.** Area under the ROC curve results when classifying groups from the GRN cohort. The solid circles indicate the areas under the ROC curves obtained for each pairwise comparison using seven different miRNA signatures. The whiskers denote empirical 90% confidence intervals obtained with 2000 bootstrap samples.
It is noteworthy that these results are consistent with our differential expression analyses with the GRN cohort, offering evidence that most miRNAs identified in previous studies about FTD are not useful biomarkers of GRN-associated disease.

Discussion

The goal of this study was to assess all circulating miRNA signatures previously published in the literature as possible biomarkers of FTD and/or ALS, by testing them in two separate homogenous cohorts of C9orf72 and GRN mutation carriers, comprising patients and presymptomatic subjects. The results of this work demonstrate that (1) several miRNAs identified in sporadic or mixed FTD/ALS cohorts could potentially be used as biomarkers of C9orf72 disease; (2) some miRNAs revealed in a C9orf72 cohort are validated in an independent C9orf72 cohort; and (3) most miRNAs associated with FTD in sporadic or mixed cohorts, or in a cohort of C9orf72 mutation carriers, are not relevant biomarkers of GRN disease.

First, differential expression results (Table 3) showed that more than half (35/65) of the miRNAs linked with FTD and/or ALS in the literature were significantly differentially expressed in the C9orf72 cohort. Remarkably, only four of the 15 selected studies included C9orf72 mutation carriers,11,13,16,21 three of which focused exclusively on ALS.13,16,21 Therefore, these outcomes reveal similarities in miRNA dysregulation between individuals with sporadic forms of FTD/ALS and C9orf72-associated disease. Classification results with the C9orf72 cohort (Fig. 1) also corroborate these findings, since half of the examined miRNA signatures (8/16) yielded at least one pairwise comparison with acceptable performance, and all comparisons employing the meta-signatures had acceptable performance. We considered as an acceptable biomarker any signature with a ROC AUC above 0.70, in accordance with the recommendation by Man-drekar.23 This means that such a signature has some discriminatory power and is worthy of further exploration. It does not mean that the signature is suitable for clinical use.

Next, we observed that a miRNA signature previously identified in a homogeneous C9orf72 cohort11 and another one revealed in a mixed cohort of sporadic and familial ALS16 displayed an outstanding result (ROC AUC above 0.90) when classifying controls versus C9orf72 presymptomatic subjects and controls versus C9orf72 patients (Fig. 1). These two signatures have in common the presence of miR-34a-5p, which has the smallest adjusted p value in the differential expression analyses regarding these comparisons (Table S1, respectively $p = 2.42E-08$ and $p = 5.06E-06$). In contrast, the performance of both of these signatures classifying C9orf72 presymptomatic individuals from patients was unsatisfactory. Indeed, neither of them contained miR-206, which is the most differentially expressed miRNA in this comparison (Table S1, p = 9.04E-05). The overexpression of miR-206 in ALS patients had already been evidenced,40 and the results of the present work extend this association also to C9orf72-disease. Nevertheless, even using the expression levels of miR-206, the classification of C9orf72 presymptomatic subjects versus patients led to lower performances than comparisons involving the control group: the highest ROC AUC was 0.77, using the meta-signature with $p < 0.1$.

Finally, our results with the GRN cohort suggest that previously identified miRNAs have a weaker correlation with disease diagnosis and progression in this genetic form. Only a small proportion (5/30) of the miRNAs associated with FTD in previous studies was significantly differentially expressed in the GRN cohort (Table 3), and not a single miRNA was differentially expressed between controls and presymptomatic GRN carriers. Regarding the classification experiments, none of the studied miRNA signatures in the GRN cohort exhibited an acceptable performance (Fig. 2), and the only ROC AUC slightly above 0.70 was obtained when classifying GRN presymptomatic carriers and patients using the largest meta-signature (miRNAs with $p$ value <0.1). One should note that none of the previous studies included GRN participants. Thus, our results demonstrate that miRNAs associated with sporadic FTD or genetic FTD due to C9orf72 are not relevant for GRN-associated disease. Further studies are needed to determine if other miRNAs, not analyzed in the present paper, are useful in GRN-associated disease.

Validation studies using independent datasets, such as this one, are crucial to assess the utility of biomarker candidates, fostering research rigor and reproducibility. Notably, we carefully defined our research questions and analysis plan before data analysis, and preregistered our study. Preregistration has the strong benefit of leaving no flexibility for changes in analytical decisions after observing the data, which has been highlighted as a major source of false discoveries and replication failure.41

The main limitation of this work is the size of the studied cohorts, particularly the small group of C9orf72 presymptomatic carriers (17) in comparison with the other groups, due to the rarity of genetic FTD. Additionally, due to the low number of C9orf72 patients with different phenotypes (20 FTD, 6 FTD/ALS and 3 ALS), no conclusions can be drawn concerning the relationship between miRNAs and different disease manifestations. Moreover, this study did not investigate the influence of
lifestyle factors in microRNA levels. Future work will explore the combination of circulating microRNAs with other biomarkers, such as gray matter volume, white matter integrity, and neurofilament light chain level. Multimodality will be crucial to accurately assess progression in GRN-associated FTD, and will likely improve the understanding of C9orf72-associated disease.

In summary, the present work revealed that most miRNAs previously identified in sporadic or mixed FTD/ALS cohorts are potential biomarkers of C9orf72-associated FTD/ALS, but not of GRN-associated FTD. Longitudinal studies are needed to confirm our findings and to determine miRNAs expression levels changes throughout disease progression, before circulating miRNAs can be used to assess treatment outcomes in C9orf72-associated disease clinical trials.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Virgilio Kmetzsch had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Conception and design of the study: all authors. Data acquisition, analysis and interpretation: all authors. Statistical analysis: VK. Drafting of the manuscript: VK. Revising the manuscript: all authors. The French research network on FTD/ALS contributed to data acquisition: Sophie Auriacombe (CHU Pellegrin, Bordeaux), Serge Belliard (CHU Rennes), Frédéric Blanc (Hôpitaux Civils, Strasbourg), Claire Boutouleau-Bretonnière (CHU Laennec, Nantes), Alexis Brice (Hôpital Pitié-Salpêtrière, Paris), Agnès Camuzat (ICM, Paris), Mathieu Ceccaldi (CHU La Timone, Marseille), Philippe Couratier (CHU Limoges), Vincent Deramecourt (CHU Roger Salengro, Lille), Mira Didic (CHU La Timone, Marseille), Charles Duyckaerts (Hôpital Pitié-Salpêtrière, Paris), Frédérique Etcherry-Bouyx (CHU Angers), Maïté Formaglio (CHU Lyon), Véronique Golfer (CHU Rennes), Didier Hannequin (CHU Charles Nicolle, Rouen), Lucette Lacombel (Hôpital Pitié-Salpêtrière, Paris), Isabelle Le Ber (Hôpital Pitié-Salpêtrière, Paris), Bernard-François Michel (CH Sainte-Marguerite, Marseille), Jérémie Pariente (CHU Rangueil, Toulouse), Florence Pasquier (CHU Lille), Daisy Rinaldi (CHU Pitié-Salpêtrière, Paris), Adeline Rollin-Sillaume (CHU Roger Salengro, Lille), Mathilde Sauvée (CHU Grenoble Alpes), François Sellal (CH Colmar), Christel Thauvin-Robinet (CHU Dijon), Catherine Thomas-Anterion (CH Plein-Ciel, Lyon), Martine Vercelletto (CHU Laennec, Nantes) and David Wallon (CHU Charles Nicolle Rouen).

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Supporting Information

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Figure S1 Expression heatmaps of differentially expressed microRNAs. Rows represent microRNAs and columns represent individuals ordered by clinical status (control, presymptomatic, and patient). The log2 expression values of microRNAs are standardized (mean of 0 and standard deviation of 1), and z-scores are indicated by colors (blue indicates underexpression and red indicates overexpression). (A) All 35 differentially expressed microRNAs identified in the C9orf72 cohort. (B) Zoom over five of the most differentially expressed microRNAs identified in the C9orf72 cohort. (C) All five differentially expressed microRNAs identified in the GRN cohort.

Table S1 Complete output from differential expression analyses in the C9orf72 cohort, for each pairwise comparison between the clinical groups. The columns show the 30 studied miRNAs, the log-fold change when comparing the clinical groups, the unadjusted p values, and finally the adjusted p values after Benjamini-Hochberg. For each pairwise comparison, a positive log-fold change means that the miRNA is overexpressed in the first group. Controls (n = 31), C9orf72 presymptomatic subjects (n = 17), and C9orf72 patients (n = 29). Adjusted p values lower than 0.05 are shown in bold.

Table S2 Complete output from differential expression analyses in the GRN cohort, for each pairwise comparison between clinical groups. The columns show the 30 studied miRNAs, the log-fold change when comparing the clinical groups, the unadjusted p values, and finally the adjusted p values after Benjamini-Hochberg. For each pairwise comparison, a positive log-fold change means that the miRNA is overexpressed in the first group. Controls (n = 31), GRN presymptomatic subjects (n = 30), GRN patients (n = 28). Adjusted p values lower than 0.05 are shown in bold.