Melanoma MicroRNA Signature Predicts Post-Recurrence Survival

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Abstract

Purpose: To identify a melanoma microRNA (miRNA) expression signature that is predictive of outcome and then evaluate its potential to improve risk stratification when added to the standard-of-care staging criteria.

Experimental Design: Total RNA was extracted from 59 formalin-fixed paraffin-embedded melanoma metastases and hybridized to miRNA arrays containing 911 probes. We then correlated miRNA expression with post-recurrence survival and other clinicopathologic criteria.

Results: We identified a signature of 18 miRNAs whose overexpression was significantly correlated with longer survival, defined as more than 18 months post-recurrence survival. Subsequent cross-validation showed that a small subset of these miRNAs can predict post-recurrence survival in metastatic melanoma with an estimated accuracy of 80.2% (95% confidence interval, 79.8–80.6%). In contrast to standard-of-care staging criteria, a six-miRNA signature significantly stratified stage III patients into “better” and “worse” prognostic categories, and a multivariate Cox regression analysis revealed the signature to be an independent predictor of survival. Furthermore, we showed that most miRNAs from the signature also showed differential expression between patients with better and worse prognoses in the corresponding paired primary melanoma.

Conclusions: MiRNA signatures have potential as clinically relevant biomarkers of prognosis in metastatic melanoma. Our data suggest that molecularly based models of risk assessment can improve the standard staging criteria and support the incorporation of miRNAs into such models.

The treatment of metastatic melanoma remains a daunting clinical challenge, and the introduction of molecularly targeted therapies has failed to make a significant impact on overall survival. In the absence of effective therapy for stage IV melanoma, the early identification of patients at highest risk for the development of aggressive disease is critical. Thickness remains the single most important predictor of survival in localized melanoma, but the morphologically based staging system only partly explains the variability in the natural history of melanoma.

With advances in our understanding of melanoma tumorigenesis, there has been heightened interest in the utility of molecular markers as evidenced by the addition of mitotic index to the 2009 American Joint Committee on Cancer (AJCC) staging criteria (1). Several immunohistochemistry-based biomarkers such as Ki-67 and matrix metalloproteinase-2 are promising in terms of their prognostic potential, but they are limited by interobserver variability and lack of standardization (2–4). Thus, none of these markers have yet been integrated into common clinical practice.

MicroRNAs (miRNA) are endogenous noncoding small RNAs that negatively regulate expression of their target genes at the posttranscriptional level via translational repression and/or cleavage (5). Recent data support the role of dysregulated miRNAs as oncogenes or tumor suppressors based on their ability to affect cell cycle regulators and mediators of apoptosis that contribute to the development of the malignant phenotype (6–8). MiRNAs possess several features that make them attractive candidates for new prognostic biomarkers. First, they are upstream regulators that can simultaneously target large numbers of protein-coding genes and multiple cancer pathways. Second, miRNAs are the direct functional product of the...
Translational Relevance

Emerging evidence suggests that microRNAs (miRNA) play an important role in melanoma tumorigenesis, but the clinical implications of these findings have not been well defined. Here, we show that a specific signature of a small set of miRNAs is predictive of post-recurrence survival in a cohort of metastatic melanoma patients. We further explored the prognostic relevance of miRNAs and found that the addition of the miRNA signature to the standard-of-care staging criteria improved risk stratification for stage III patients. Furthermore, we found that most miRNAs from the metastatic signature also showed differential expression between patients with “better” and “worse” prognosis in the corresponding primary melanoma. These data suggest that miRNA signatures may be clinically useful prognostic biomarkers for both early-stage and late-stage melanomas, and thus may have the potential to influence clinical management by identifying high-risk patients most likely to benefit from adjuvant therapy and/or heightened surveillance. Further studies of the clinical utility of miRNA-based monitoring assays are warranted.

corresponding gene. This is in contrast to mRNAs that need to be translated and often posttranslationally modified to exert their function. Third, the stability of miRNAs in archival formalin-fixed paraffin-embedded (FFPE) tissues allows them to be extracted from the initial biopsy specimen and quantified by standardized methods such as reverse transcription-PCR (RT-PCR) at any point during the patient’s clinical course (9). One of the primary limitations of miRNA-based gene expression profiling is the requirement for fresh frozen tissue, the acquisition of which is both labor intensive and time sensitive. Additionally, concerns have been raised about the possibility of compromising the accuracy of the staging when part of a frozen section from a thin melanoma is sampled for research purposes (10).

To assess the clinical significance of melanoma miRNA signatures, we first performed miRNA expression profiling on a cohort of human metastatic melanoma specimens with annotated clinical follow-up. An initial signature of miRNAs strongly associated with post-recurrence survival was identified and then further refined using supervised learning methods to a six-miRNA set predictive of survival. The miRNA signature added prognostic value to the standard-of-care staging criteria in terms of the risk stratification of stage III patients. Notably, specific components of the prognostic signature in the metastatic tissue exhibited the same pattern of differential expression in the matched pair primary melanoma, suggesting that the miRNA signature may have early prognostic potential. Our data support the addition of molecularly based models of risk assessment to the standard staging criteria and suggest that miRNA signatures hold promise as robust, clinically useful biomarkers with the ability to identify high-risk patients at both early and late stages.

Materials and Methods

Clinical specimens

Primary and metastatic melanoma specimens were collected at the time of surgery from patients enrolled from 2002 to 2009. Congenital nevi were obtained from biopsies taken from patients without a history of skin cancer. Informed consent was obtained from all patients and approval acquired by the Institutional Review Board of NYU School of Medicine (protocol nos. 10362 and 08-598). Patients enrolled in the Interdisciplinary Melanoma Cooperative Group database are prospectively followed up every 3 mo. Clinical status at last date of follow-up is recorded as “alive, no melanoma,” “alive with melanoma,” “died with melanoma,” “died, no melanoma,” or “died, cause unknown.” All patients with a follow-up of less than 20 mo were deceased. When a patient is determined to be deceased, the patient’s history and last clinical status are reviewed with the medical oncology investigator (A.P.) to determine if melanoma was the cause of death. All tumors were classified according to the AJCC staging system. Only metastatic samples with tumor content >80% were included in the study. All congenital nevi and primary melanoma tissue were sectioned on Leica PEN-membrane slides and macro- or micro-dissected.

RNA extraction

Total RNA was extracted as previously described (11). Briefly, 10 sections of 10-μm FFPE tissues were deparaffinized with xylene, washed in ethanol, and digested with proteinase K. RNA was extracted with acid phenol/chloroform followed by ethanol precipitation and DNase digestion or using the Qiagen miRNeasy FFPE kit. Total RNA quantity and quality were evaluated using a Nanodrop ND-1000 (Thermo Scientific) with an inclusion criteria of A260/A280 ≥1.8.

miRNA microarray expression profiling and data preprocessing

miRNA microarrays were prepared as described previously (11). Each RNA sample (3.5 μg) was labeled by ligatation of an RNA-linker, p-CrU-Cy/dye, to the miRNA 3’ end. Hybridization and washing of the microarray slides were done as previously described (11). Arrays were scanned using an Agilent Microarray Scanner Bundle G2565BA and analyzed using SpotReader software (Niles Scientific) to generate raw intensity data. Triplicate spots were combined into one signal by taking the logarithmic mean of the reliable spots. Quantile normalization was applied to make arrays comparable to one another (12). MiRNAs with low variance across samples (i.e., coefficient of variation <1% on the log scale) were filtered out, leaving 610 miRNAs for analysis.
The significant gene was used in SAM to identify miRNAs that were differentially expressed between these two groups. The significant gene lists resulting from the two types of analyses (survival and expression) were then compared.

Construction of a "predictor biomarker" based on miRNA expression. To develop a miRNA signature of post-recurrence survival, we used the following classification methods: nearest shrunken centroids (implemented in the Bioconductor package pamr; ref. 16), classification trees

Additional methods were used with and without preselection of input variables (i.e., miRNAs) based on an FDR criterion (i.e., FDR <5%), whenever applicable. The prediction accuracy of the classification algorithms was estimated using 1,000 cross-validation randomizations.

Comparison of the miRNA predictor with clinical predictors. We used the method of pre-validation (PV; refs. 20, 21) to compare the prediction accuracy of the miRNA signature to that of tumor-node-metastasis stage, site of metastasis, age at recurrence, and other clinical and demographic variables. PV outputs a prediction for each patient based on a classifier (e.g., nearest shrunken centroids) that is estimated without using that patient's data, thus reducing the bias that might arise from reuse of the data. The PV miRNA predictor was compared with other predictors of survival in a multivariate Cox regression analysis of post-recurrence survival. The Kaplan-Meier method was used to estimate the post-recurrence survival function (22). The log-rank test was used to compare the survival distribution between groups (23). All analyses were done using the R language for statistical computing and the Bioconductor software (13, 24). Heatmap and hierarchical clustering analyses were done using Prism 4 software v4.0 (GraphPad Software, Inc.).

Bioinformatics analysis
DAVID bioinformatics resource8 was used to conduct KEGG pathway analysis on predicted targets (according to TargetScan) of the miRNAs from the predictive signature. Most frequently represented pathways are assigned a P value calculated with a modified version of Fisher exact test (P value cutoff of <0.1) showing significance of the association as compared with a random list using the human genome as a background.

Real-time PCR
Quantitative real-time PCR analysis of hsa-miR-126, hsa-miR-145, hsa-miR-143, hsa-miR-497, hsa-miR-150, hsa-miR-155, hsa-miR-342-3p, and hsa-miR-455-3p was done by using an miRNA-specific TaqMan MicroRNA Assay Kit (Applied Biosystems) and an Applied Biosystems 7500 Sequence detection system. RNU44 small nuclear RNA was used for normalization of input RNA/cDNA levels. Each measurement was done in triplicate and no-template controls were included for each assay.

Results
miRNA signature distinguishes metastatic melanoma patients with worse prognosis. A miRNA expression profile

Table 1. Metastatic patient characteristics (n = 59)

<table>
<thead>
<tr>
<th>Variables</th>
<th>n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td></td>
</tr>
<tr>
<td>Mean (± SD)</td>
<td>59.6 ± 17.2</td>
</tr>
<tr>
<td>Median</td>
<td>59</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>38 (64.4)</td>
</tr>
<tr>
<td>Female</td>
<td>21 (35.6)</td>
</tr>
<tr>
<td>Stage</td>
<td></td>
</tr>
<tr>
<td>IIIB</td>
<td>16 (27.1)</td>
</tr>
<tr>
<td>IIIC</td>
<td>20 (33.9)</td>
</tr>
<tr>
<td>IV</td>
<td>23 (39.0)</td>
</tr>
<tr>
<td>Anatomic location</td>
<td></td>
</tr>
<tr>
<td>Soft tissue/skin</td>
<td>15 (25.4)</td>
</tr>
<tr>
<td>Regional lymph node</td>
<td>26 (44.1)</td>
</tr>
<tr>
<td>Visceral</td>
<td>7 (11.9)</td>
</tr>
<tr>
<td>Brain</td>
<td>11 (18.6)</td>
</tr>
<tr>
<td>Treatment presurgery</td>
<td></td>
</tr>
<tr>
<td>Treated</td>
<td>40 (67.8)</td>
</tr>
<tr>
<td>Not treated</td>
<td>19 (32.2)</td>
</tr>
</tbody>
</table>

NOTE: Clinical characteristics of the metastatic melanoma cohort.

http://david.abcc.ncifcrf.gov

http://www.bioconductor.org
of 911 miRNAs in 59 metastatic melanoma patients was obtained. These 59 patients were followed clinically for a median of 21 months (range, 1-69 months) after excision of the metastatic lesion. Clinicopathologic features of the 59 melanoma patients included in the study are presented in Table 1. A complete description of the stage at initial presentation, the stage at the time of tissue collection, and the metastatic site for each sample used is provided in Supplementary Table S1. The median survival of the entire cohort from the time of excision to date of last follow-up or death was 20 months. We evaluated the association between tumor miRNA expression profiles and post-recurrence survival based on the interval from metastasectomy to date of last follow-up or death. Using post-recurrence survival as the outcome variable in SAM, we identified 18 significant miRNAs (using an FDR of 5%), for which higher expression was associated with longer survival (Fig. 1A; Table 2). Similar results were obtained using a two-sample nonparametric comparison to discriminate between patients with longer survival (those who survived 18 months or longer from the date of resection of the metastatic tumor; n = 36) and shorter survival (patients who survived less than 18 months; n = 23). We chose 18 months as the threshold for longer/shorter survival based on the median survival of our own cohort (21 months), which is consistent with previous studies (25).

Of the 59 patients included in the study, 19 (32%) had treatment before surgery (55% chemotherapy, 35% immunotherapy, and 45% radiation). When we excluded patients with prior treatment from the analyses, 10 of the 18 miRNAs were still found to be significantly associated with post-recurrence survival based on the remaining 40 treatment-naïve patients using SAM and a FDR cutoff of 5%.

Validation of microarray data by quantitative RT-PCR. To validate the data obtained using the microarray platform, we quantified the expression of seven miRNAs (miR-150,
miR-126, miR-155, miR-145, miR-497, miR-143, and miR-455-3p) in 10 specimens using real-time PCR designed to detect mature miRNAs. The data were normalized to the endogenous control small nuclear RNA RNU44. Real-time PCR showed that all seven selected miRNAs display higher expression levels in the five cases with longer survival compared with the five cases with worse prognosis (Fig. 1B; Supplementary Table S2). Six of the seven miRNA gene chip expression assays were significantly correlated with the RT-PCR results, showing an average Pearson correlation coefficient of 0.82 (range, 0.73-0.97; Supplementary Table S2).

**A small set of miRNAs predicts post-recurrence survival.** To develop a miRNA signature of post-recurrence survival, we used supervised learning methods (see Materials and Methods). All miRNAs as well as significant subsets of miRNAs (i.e., FDR <5%) were used as input variables in the classification algorithms. The prediction accuracy of the classification algorithms was estimated using cross-validation. Provided in Supplementary Table S3 are training error rates as well as estimated true error rates of the classifiers along with 95% confidence intervals (95% CI) obtained from 1,000 cross-validation randomizations. The method of nearest shrunken centroids performed best with an estimated average prediction accuracy of 80.2% (95% CI, 79.8-80.6%).

Based on 1,000 cross-validation randomizations, the miRNA signatures obtained by the method of nearest shrunken centroids were most often composed of the following six miRNAs: mir-150, mir-342-3p, mir-455-3p, mir-145, mir-155, and mir-497. The median number of miRNAs used by the nearest shrunken centroids method was 2 (range, 1-10). The number of miRNAs used by the classification trees was 1 and 2. These findings suggest that a small number of miRNAs might be sufficient to accurately predict post-recurrence survival.

**miRNA signature is an independent predictor of post-recurrence survival in metastatic melanoma.** We next used the method of prevalidation (PV) to derive a miRNA predictor of post-recurrence survival. The PV miRNA predictor assigned each patient to a “better” prognosis (n = 43) or a “worse” prognosis (n = 16) group using the nearest shrunken centroids classifier. The median survival of patients in better and worse prognostic groups was 880 days (95% CI, 653-NA) and 189 days (95% CI, 111-438), respectively. The Kaplan-Meier estimated survival curves of the better prognosis and worse prognosis groups predicted by the PV miRNA signature are shown in Fig. 2C. The PV miRNA predictor was able to segregate patients into better prognosis and worse prognosis groups with significance comparable to that of stage at recurrence (log-rank P = 0.004; Fig. 2A) and the site of recurrence (log-rank P = 0.0026; Fig. 2B). Among the cohort of patients with stage IIIA melanoma, the AJCC designation of IIIB versus IIIC was unable to significantly risk-stratify the patients based on post-recurrence survival (log-rank P = 0.48; Supplementary Fig. S1A). The PV miRNA predictor, however, was able to significantly separate stage IIIB and IIIC
patients into better and worse prognosis groups based on post-recurrence survival (log-rank *P* = 0.0046; Supplementary Fig. S1B).

We next used a multivariate Cox proportional hazard regression analysis to compare the PV miRNA signature to standard clinicopathologic factors including age, sex, stage, site of metastasis, recurrence number, and time to first recurrence in their ability to predict post-recurrence survival. The miRNA predictor was significantly associated with a longer post-recurrence survival in metastatic patients [hazard ratio (HR), 3.42; 95% CI, 1.49-7.86; *P* = 0.0038] with only a designation of stage IV exhibiting a comparable predictive value (HR, 5.69; 95% CI, 1.41, 22.9; *P* = 0.0144; Table 3A). When the PV miRNA signature and stage were included in the model, other variables such as age, sex, or time to first recurrence were not significant. We did find, however, that select miRNAs from the signature were related to stage and site of metastasis (Supplementary Table S4). Specifically, all six miRNAs were significantly associated with stage at recurrence (Supplementary Table S4; Supplementary Fig. S1C) and all except for mir-342-3p were associated with site of metastasis (Supplementary Table S4). To further optimize the prediction model, we removed all variables except stage and the miRNA predictor. A new Cox hazard regression model inclusive of only stage and the miRNA predictor showed that both a designation of stage IV (HR, 3.76; *P* = 0.0072) and the PV miRNA signature (HR, 3.16; *P* = 0.0029) were significant predictors of post-recurrence survival (Table 3B). Finally, based on this Cox model, we derived an optimal predictor of post-recurrence survival that combined the PV miRNA and AJCC stage variables and segregated the patients into better prognosis and worse prognosis groups using the median HR as the cutoff point. The Kaplan-Meier estimates of survival functions of these two groups are shown in Fig. 2D (*P* < 0.0001).

These findings show the potential of specific miRNAs to provide a molecular classification model predictive of melanoma patient survival that can enhance the current morphologically based staging criteria.

**Select miRNAs retain predictive capacity in primary matched pairs.** We next sought to investigate if the miRNA prognostic signature found in metastatic melanoma tissue could also be detected in the corresponding primary tumor. We used real-time PCR to assess the expression levels of the six miRNAs that most frequently make up the prediction signature (and an endogenous control, RNU44) in a subset of 20 matched primary-metastatic cases with <1.5 years post-recurrence survival (n = 10) and ≥1.5 years post-recurrence survival (n = 10). The clinicopathologic features of these primary specimens are summarized in Supplementary Table S5. To establish the basal expression level of the six miRNAs in the "normal" melanocytic lineage, we analyzed their expression in congenital nevi (n = 5) and compared it to that of the 20 aforementioned matched pairs. Primary and metastatic expressions were positively correlated for all six miRNAs, although the strength of the correlation reached statistical significance only for miR-145 (Spearman’s *ρ* = 0.54, *P* = 0.05).
Five of the six miRNAs had higher average expression in the primary tumor of patients with longer survival (consistent with what we observed in the metastatic samples), although these differences did not reach statistical significance (Fig. 3). Additionally, miR-497, miR-155, miR-150, miR-342-3p, and miR-145 were significantly overexpressed in metastatic melanoma compared with nevi (P values < 0.02), and miR-150 and miR-155 were also significantly elevated in primary melanoma compared with nevi (P < 0.01). MiR-455-3p was significantly downregulated in patients with shorter survival in both primary and metastatic samples compared with nevi (P = 0.0027 and P = 0.14, respectively). These results suggest that miRNAs may be useful markers of prognosis before the development of metastases.

**Discussion**

In this study, we identified a miRNA signature in metastatic melanoma tissue that was predictive of post-recurrence survival such that patients with higher expression levels of the signature elements had longer survival. The miRNA signature was able to significantly stratify stage III patients into better and worse prognosis groups based on survival probability better than the standard classification of IIIB and IIIC. Some miRNAs from the signature recapitulated the differential expression between prognostic categories in the matched-pair primary tissue, suggesting that miRNA signatures may play a role in prognosis at early stages.

It is generally recognized that there are limitations in the current staging system, and it is expected that the addition of molecularly based prognostic risk stratification will ultimately result in optimized, personalized cancer treatment. A clinically useful biomarker must be reflective of melanoma biology, but more importantly, it should affect patient care. To our knowledge, no genome-wide miRNA studies defining signatures associated with survival or prognosis have been reported in cutaneous melanoma to date. One recent study, in which only 16 miRNAs were analyzed, found that elevated miR-15b was associated with worse recurrence-free survival and overall survival in primary melanoma (26). Our report, which focuses on metastatic melanoma, identifies a multimarker signature of miRNAs correlated with outcome. A number of studies have described miRNA alterations associated with melanoma progression (7, 27–31). Although these studies offer new insight into the role of miRNAs in melanoma pathogenesis, they do not address the prognostic significance of those findings.

Our miRNA signature was able to enhance the predictive potential of conventional staging for stage III patients, allowing for a significant risk stratification based on post-recurrence survival that was not attainable using the AJCC designation of IIIB or IIIC. The optimal model was one that incorporated both the miRNA signature and stage at recurrence. Primary treatment for stage III patients typically includes surgical resection of the lymph nodes, but the options for postsurgical adjuvant therapy are varied and include observation, clinical trials, radiation to the nodal basin, or IFN therapy. As shown in our patient cohort, the conventional staging system offers little guidance about which type of adjuvant therapy (if any) is indicated for stage III patients based on an appropriate assessment of risk. The addition of the miRNA signature to staging, however, was able to provide clear risk stratification based on survival. Thus, one could imagine a clinical scenario in which patients with a worse prognosis could be targeted for IFN therapy or entered into a clinical trial, whereas those with better prognosis could be observed and spared the morbidity of further therapy.

Although our miRNA signature was developed from an expression profile of tissues from stage III and IV patients, an ideal prognostic marker is one that can also risk-stratify early in the disease course. We assessed the expression pattern of our predictive miRNA signature in 20 matched pair cases to assess if the differential expression of the six select miRNAs and their association with survival were
maintained in the primary melanoma. Five of the six miRNAs in the signature showed the same expression and association with survival trends in the primary and metastatic tissues. The difference did not reach statistical significance, however, possibly because of the low sample size of the matched pair cohort. Further studies with a larger set of primary tissues are needed to adequately assess the utility of miRNAs in predicting recurrence at early melanoma stages.

An association between any of the six miRNAs from the predictive signature and melanoma outcome has not been previously reported, but several of these miRNAs have been identified as being relevant to tumorigenesis and prognosis in other malignancies (Supplementary Table S6). miR-155 has been shown to play an oncogenic role in both hematopoietic malignancies (32) and solid cancers including breast, cervical, and clear renal cell carcinomas (33–35). In our cohort, however, increased expression of miR-155 in metastatic tissue was associated with longer survival. The same result was also noted in previous studies of pancreatic cancer (36), inviting speculations about the nature of miR-155 oncogenic effect. These differences may be attributable to tumor-specific or host-specific effects given the well-established link between miR-155 and the regulation of immune function (37). It has been shown that expression of miR-155 increases on activation of immune cells by Toll-like receptors, cytokines, and other antigens (38). Thus, it is possible that although immune function is initially stimulated in early tumor development, the response and corresponding levels of miR-155 expression eventually decrease with the development of an increasingly malignant phenotype. Nonetheless, a recent study has shown antiproliferative and proapoptotic activities of miR-155 in melanoma cell lines (39), implying that miRNA-155 could be a direct negative regulator of melanoma cell proliferation and survival.

Our results show that higher expression of miR-145 in metastatic tissue is associated with longer survival. This finding is consistent with previous reports on colon, lung, breast, and prostate cancers, suggesting a tumor suppressor role for miR-145 (33). Higher expression of miR-145 in tissue from patients with longer survival might be interpreted as an attempt to impair tumor progression because it has previously been shown that p53 transcriptionally induce miR-145 to repress c-Myc (40). It is possible that elevated levels of miR-145 serve as a functional readout of
preserved p53 activity and increased efficiency of DNA damage repair or proapoptotic mechanisms. On the other hand, miR-497 has been found suppressed in colon, breast, prostate, ovarian, gastric, and lung cancers (41, 42). Similarly, mir-342-3p expression is reduced in human colorectal cancer (along with the hosting gene EVL) by means of CpG island methylation (43), and its restoration induces an apoptotic response. In a comparative genomic hybridization study on DNA copy number abnormalities of genomic regions containing known miRNA genes, mir-342 was found downregulated in a minority of melanoma cell lines (8 of 45; ref. 44). MiR-150 has been involved in the maturation of B-cells and has been found upregulated in lymphocytic leukemias, and it targets oncogenes such as c-Myc (45) and the receptor P2X7 (46). Interestingly, it has also been shown to be downregulated in chronic myeloid leukemia by BCR-ABL1 (47). Further functional analyses in melanoma would be required to establish whether these miRNA alterations represent “passenger” defects reflective of prognosis, or whether they actively participate in tumor progression.

We also identified miR-455-3p as downregulated in both primary and metastatic melanomas compared with nevi in patients with shorter survival. The mature, processed form of the miRNA (miR-455) has also been shown to be downregulated in primary melanoma cell lines compared with normal melanocytes (48). Transcription factor PAX6, a putative target of miR-455, has been shown to play a critical role in the self-renewal and differentiation of neural stem cells (49). Melanocytes are derivatives of the neural crest, and comparative genomic studies have shown an association between overexpression of genes such as NEDD9 (neural precursor cell expressed, developmentally downregulated and increased invasive potential) (50). Thus, it is possible that the loss of miR-455 and its subsequent effect on PAX6 expression may disrupt the normal progression of melanogenesis, resulting in an immature melanocyte with increased migratory capacity and enhanced metastatic potential. Again, further mechanistic studies would be needed to further explore the relationship between mir-455-3p, PAX6, cell differentiation, and metastatic potential.

Although we recognize that it is not possible to draw firm conclusions about the mechanism of action of the prognostic miRNAs identified in the signature, our preliminary pathway analyses revealed that the putative targets of the miRNAs in the signature converge on common pathways known to be altered in melanoma (e.g., Wnt, mitogen-activated protein kinase, and transforming growth factor β) and other cancers (chronic lymphocytic leukemia and colorectal, endometrial, and pancreatic cancers; Supplementary Table S7). Because miRNAs are able to simultaneously modulate multiple genes from different pathways, it is plausible that they might play a role in the complex process of melanoma progression and metastasis. Although not definitive, this analysis suggests that the set of miRNAs identified in our study not only has prognostic capacity but may also be reflective of the underlying biology. Further supporting this possibility, recent reports suggest that genomic regions frequently altered in melanoma are enriched for miRNA genes (44). Many of the miRNAs from our signature are located in genomic regions previously reported as altered in melanoma, such as loss of 9q32 (miR-455-3p) in melanoma cell lines, gain of the 5q locus (miR-145) in acral melanoma, and gain of 21q (miR-155) in uveal melanoma (Supplementary Table S8).

In conclusion, our results show the potential of miRNAs as clinically useful markers of prognosis in metastatic melanoma patients. A six-miRNA signature was able to improve risk stratification for stage III patients, suggesting that miRNAs may serve as a useful molecular adjunct to the current morphologic staging system in identifying high-risk patients who might benefit from adjuvant therapy. Differential expression of most miRNAs from the predictor signature was also observed in the matched-pair primary tissue, suggesting that the miRNA signature may also play a role in prognosis of early lesions. Further studies with a larger cohort of primary melanoma patients are needed to better define the role of the signature in predicting the development of aggressive disease.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

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