A Functional riboSNitch in the 3' Untranslated Region of

Sarah D. Linnstaedt
Kyle D. Riker
Cathleen A. Rueckeis
Katrina M. Kutchko
Lela Lackey

See next page for additional authors

Follow this and additional works at: https://scholarlycommons.henryford.com/emergencymedicine_articles

Recommended Citation
Authors
Sarah D. Linnstaedt, Kyle D. Riker, Cathleen A. Rueckeis, Katrina M. Kutchko, Lela Lackey, Kathleen R. McCarthy, Yi-Hsuan Tsai, Joel S. Parker, Michael C. Kurz, Phyllis L. Hendry, Christopher A. Lewandowski, Elizabeth Datner, Claire Pearson, Brian O'Neil, Robert Domeier, Sangeeta Kaushik, Alain Laederach, and Samuel A. McLean

This article is available at Henry Ford Health System Scholarly Commons: https://scholarlycommons.henryford.com/emergencymedicine_articles/32
A Functional riboSNitch in the 3′ Untranslated Region of FKBP5 Alters MicroRNA-320a Binding Efficiency and Mediates Vulnerability to Chronic Post-Traumatic Pain

Sarah D. Linnstaedt, Kyle D. Riker, Cathleen A. Rueckeis, Katrina M. Kutchko, Lela Lackey, Kathleen R. McCarthy, Yi-Hsuan Tsai, Joel S. Parker, Michael C. Kurz, Phyllis L. Hendry, Christopher Lewandowski, Elizabeth Datner, Claire Pearson, Brian O’Neil, Robert Domeier, Sangeeta Kaushik, Alain Laederach, and Samuel A. McLean

1Institute for Trauma Recovery, 2Department of Anesthesiology, 3Department of Emergency Medicine, The University of North Carolina, Chapel Hill, North Carolina 27516, 4Department of Biology, The University of North Carolina, Chapel Hill, North Carolina 27599, 5Lineberger Comprehensive Cancer Center and Department of Genetics, The University of North Carolina, Chapel Hill, North Carolina 27514, 6Department of Emergency Medicine, University of Alabama School of Medicine, Birmingham, Alabama 35233, 7Department of Emergency Medicine, University of Florida College of Medicine, Jacksonville, Florida 32209, 8Department of Emergency Medicine, Henry Ford Hospital, Detroit, Michigan 48202, 9Department of Emergency Medicine, Albert Einstein Medical Center, Philadelphia, Pennsylvania 19141, 10Department of Emergency Medicine, Detroit Receiving, Detroit, Michigan 48201, 11Department of Emergency Medicine, 12The Cardiovascular Research Institute, School of Medicine, Wayne State University, Detroit, Michigan 48201, 13Department of Emergency Medicine, St. Joseph Mercy Health System, Ypsilanti, Michigan 48197, and 14Department of Emergency Medicine, MedStar Washington Hospital Center, Washington, DC 20010

Previous studies have shown that common variants of the gene coding for FK506-binding protein 51 (FKBP5), a critical regulator of glucocorticoid sensitivity, affect vulnerability to stress-related disorders. In a previous report, FKBP5 rs1360780 was identified as a functional variant because of its effect on gene methylation. Here we report evidence for a novel functional FKBP5 allele, rs3800373. This study assessed the association between rs3800373 and post-traumatic chronic pain in 1607 women and men from two ethnically diverse human cohorts. The molecular mechanism through which rs3800373 affects adverse outcomes was established via in silico, in vivo, and in vitro analyses. The rs3800373 minor allele predicted worse adverse outcomes after trauma exposure, such that individuals with the minor (risk) allele developed more severe post-traumatic chronic musculoskeletal pain. Among these individuals, peritraumatic circulating FKBP5 expression levels increased as cortisol and glucocorticoid receptor (NR3C1) mRNA levels increased, consistent with increased glucocorticoid resistance. Bioinformatic, in vitro, and mutational analyses indicate that the rs3800373 minor allele reduces the binding of a stress- and pain-associated microRNA, miR-320a, to FKBP5 via altering the FKBP5 mRNA 3′UTR secondary structure (i.e., is a riboSNitch). This results in relatively greater FKBP5 translation, unchecked by miR-320a. Overall, these results identify an important gene–miRNA interaction influencing chronic pain risk in vulnerable individuals and suggest that exogenous methods to achieve targeted reduction in poststress FKBP5 mRNA expression may constitute useful therapeutic strategies.

Key words: chronic pain; FKBP5; functional genetics; microRNA; post-traumatic stress; RNA structure

Significance Statement

FKBP5 is a critical regulator of the stress response. Previous studies have shown that dysregulation of the expression of this gene plays a role in the pathogenesis of chronic pain development as well as a number of comorbid neuropsychiatric disorders. In the current study, we identified a functional allele (rs3800373) in the 3′ UTR of FKBP5 that influences vulnerability to chronic post-traumatic pain in two ethnic cohorts. Using multiple complementary experimental approaches, we show that the FKBP5 rs3800373 minor allele alters the secondary structure of FKBP5 mRNA, decreasing the binding of a stress- and pain-associated microRNA, miR-320a. This results in relatively greater FKBP5 translation, unchecked by miR-320a, increasing glucocorticoid resistance and increasing vulnerability to post-traumatic pain.
Introduction

Post-traumatic chronic musculoskeletal pain (MSP) is common, morbid, and a major public health problem (Carroll et al., 2008; McLean et al., 2014; Ulirsch et al., 2014). As with other stress-related disorders, the pathogenesis of chronic poststress MSP remains poorly understood. This lack of knowledge is a barrier to the development of improved preventive/treatment interventions.

Increasing evidence suggests that individual differences in the post-traumatic expression of FK506-binding protein 51 (FKBP5) may influence poststress MSP outcomes. FKBP5 is a critical protein within the hypothalamic–pituitary–adrenal (HPA) axis that regulates glucocorticoid receptor (GR) sensitivity (Denny et al., 2000; Zhang et al., 2008). Among European Americans (EAs) experiencing two common traumatic stress exposures, motor vehicle collision (MVC) and sexual assault, FKBP5 genetic variants, including rs3800373, have been found to predict poststress MSP severity (Bortsov et al., 2013). Consistent with these human data, recent animal data indicate that FKBP5 plays an important role in pain processing (Maiarù et al., 2016).

Although studies regarding FKBP5 variants and MSP outcomes are increasing, to date a far larger set of literature has evaluated the influence of FKBP5 variants on post-traumatic psychological sequelae (Zannas et al., 2016), which are commonly comorbid with post-traumatic MSP (Asmundson et al., 2002; Bair et al., 2003; Liu and Chen, 2014). In these studies, three FKBP5 single nucleotide polymorphisms (SNPs) in high linkage disequilibrium (rs3800373, rs9296158, and rs1360780) have been identified as most likely to be functional (Binder et al., 2004; Koenen et al., 2005; Roy et al., 2010). One of these SNPs, rs1360780, has been shown to be functional and to affect FKBP5 transcription via DNA methylation (Kengel et al., 2013).

Highly influential genes such as FKBP5 can have multiple functional alleles (Hormozdiari et al., 2017). Identifying additional functional variants in this lynchpin protein, if present, would be valuable to gain further insight into pathophysiologic mechanisms and inform potential preventive/treatment interventions. In the current study, we present evidence that rs3800373, in the 3′ UTR of FKBP5, is a second FKBP5 functional allele affecting individual vulnerability to post-traumatic MSP and related stress disorders. We demonstrate a stress-dependent association between the rs3800373 allele and chronic MSP in two different ethnic cohorts and show that, among distressed trauma survivors with the rs3800373 risk allele, circulating FKBP5 mRNA levels are positively correlated with cortisol and glucocorticoid receptor (NR3C1) mRNA levels. In silico, in vitro, and in vivo human data suggest that the rs3800373 risk allele reduces the binding of a stress- and pain-associated microRNA, miR-320a, to FKBP5 via altering the RNA secondary structure. Together, these data identify a specific molecular mechanism by which a common genetic variant affects individual vulnerability to chronic MSP development after traumatic stress and novel molecular targets for potential future intervention.

Materials and Methods

Study design, setting, and eligibility criteria. Two prospective longitudinal studies enrolling male and female European or African American (AA) individuals (18–65 years of age) presenting to the emergency department (ED) within 24 h of MVC were used to study chronic post-traumatic MSP outcomes. The details of these sister studies have been described previously (Platts-Mills et al., 2011; Linnaestd et al., 2016c).

The studies were approved by the institutional review boards at the data coordinating center (The University of North Carolina at Chapel Hill) and at all participating hospitals. Each study participant provided written informed consent before enrollment.

Eligible and consenting participants provided blood samples in the ED and completed an ED interview evaluation. Interview evaluations were performed by research assistants at the time of the ED visit using a web-based survey with explicit definitions of variables. Injury characteristics and medications administered in the ED were obtained by data extraction from the ED medical record. Six weeks after the MVC, participants completed a follow-up interview by telephone, online, or via mail. Participant demographic characteristics (including age, gender, income, height, weight, and educational attainment) were obtained from the ED medical record and from participant self-report.

Assessments and outcome definitions. MVC-related overall MSP in the past week was assessed 6 weeks after MVC using the modified Regional Pain Scale (Wolfe, 2003). MSP intensity in each region and overall pain was evaluated via a 0 (no MSP) to 10 (maximum possible MSP) numeric rating scale (Farrar et al., 2001).

MVC-related post-traumatic stress (PTS) symptoms were assessed 6 months after MVC using the Impact of Event Scale: Revised (Weiss, 2007). This 22-item questionnaire includes avoidance, intrusion, and hyperarousal subscales. Scores range from 22 to 110.

Distress in the ED was measured using the Peritraumatic Distress Inventory, a 13-item questionnaire assessing the level of distress experienced immediately after a traumatic event (Brunet et al., 2001). Each item on the questionnaire was evaluated via a numeric rating scale from 0 (no distress) to 4 (high distress). A median cutoff score of 18 and 23 was used to identify those with substantial distress in the European American and African American populations, respectively. [Previous studies have demonstrated increased peritraumatic distress in African Americans vs European Americans (Clark et al., 1999; Roberts et al., 2011)].

Life trauma before MVC was assessed using the Life Events Checklist for DSM-5 (LEC-5; Gray et al., 2004). The LEC-5 assesses exposure to 16 events known to potentially result in distress and includes one additional item addressing any other extraordinarily stressful event. A composite score for each participant was generated by tallying the total number of reported life events occurring to the individual.

Litigants were classified based on whether they said yes to following the question at the 6 week follow-up assessment: “Have you hired a lawyer, or are you working with a lawyer, because of injuries or other health problems that were related to your motor vehicle accident?”

DNA collection and genotyping. European American samples were genotyped as described previously (Bortsov et al., 2013). For African American samples, study personnel collected blood samples at the time of enrollment using PAXgene DNA tubes. After DNA purification (PAXgene blood DNA kit, QIAGEN), genotyping using the Infinium Multi-Ethnic Global Array (Illumina) was performed. DNA from an individual with a known genotype (NA19819, 1000 genomes) and two repeat samples were included in each genotyping batch (96 samples) to ensure genotypic accuracy and reliability. SNP rs3800373 was in the Hardy–Weinberg equilibrium (p > 0.05) and had an excellent call rate (>99%).

Experimental design and statistical analysis. Sociodemographic characteristics of the sample were summarized using standard descriptive statistics. The relationship between rs3800373 and chronic MSP outcomes in European Americans and African Americans after MVC were assessed using general linear models. In these models, β coefficients denote the
magnitude of change in MSP severity occurring with each unit increase (positive $\beta$) or decrease (negative $\beta$) in the independent variable. A dominant genetic model (homozygous for the major allele vs heterozygous and homozygous for the minor allele) was used to match analyses leading to the main outcomes from our previous study (Bortsov et al., 2013). Based on the results of previous studies, participant age, sex, and study site were included in the model as covariates, and interactions between rs3800373 and both peritraumatic distress and participant sex were assessed by including corresponding product terms in the model (McLean et al., 2011, 2014; Bortsov et al., 2013; Linnstaedt et al., 2015a, 2015b). Marginal means corresponding to overall MSP levels were derived from the full general linear models. Associations between FKBP5 mRNA and cortisol levels, NR3C1 mRNA, or miR-320a were evaluated using Pearson correlation coefficients. All analyses were performed using R (R Project for Statistical Computing, RRID:SCR_001905) or SPSS software (SPSS, RRID:SCR_002865), and all graphs were made for publication using GraphPad Prism (GraphPad Software, RRID:SCR_002798).

RNA collection and sequencing. For RNA sample collection, research assistants collected blood samples in the ED at the time of enrollment using PAXgene blood tubes. Total RNA (including miRNA) was isolated using the PAXgene blood miRNA kit (Qiagen) and stored at −80°C until use. RNA concentration and purity were measured using NanoDrop 1000 (Nanodrop Technologies).

For small RNA sequencing, template libraries for miRNA Next Generation Sequencing were produced from 1.0 mg of total RNA using two similar protocols. An initial set of 82 samples (randomly selected from 907 participant cohort) were prepped using an adaptation of published protocols as described previously (Pfeffer et al., 2005; Linnstaedt et al., 2015b). A second set of 96 samples (also randomly selected) were prepped using TruSeq Small RNA library prep kits according to the manufacturer’s specifications (Illumina). Raw sequence reads were processed using a custom bioinformatics pipeline as described previously (Linnstaedt et al., 2015b) and were normalized using upper-quartile normalization. To normalize potential technical biases between the two methods of library preparation, the sequencing reads were adjusted using the methodology described by Johnson et al. (2007). Of the 172 samples with miRNA sequencing data, 66 samples also had total RNA sequencing data and were used for analyses in this study.

For total RNA (excluding miRNA) sequencing, template libraries were produced from 600 ng of total RNA using the Ovation Human Blood RNA-Seq Library Systems kit (NuGen) according to the manufacturer’s specifications. Libraries were multiplexed in groups of six and sequenced on a HiSeq 2000 at The University of North Carolina at Chapel Hill High Throughput Sequencing Facility. Raw sequencing reads were aligned using a custom bioinformatics pipeline as described previously (Linnstaedt et al., 2015b) and were normalized using upper-quartile normalization. To normalize potential technical biases between the two methods of library preparation, the sequencing reads were adjusted using the methodology described by Johnson et al. (2007). The 172 samples with miRNA sequencing data, 66 samples also had total RNA sequencing data and were used for analyses in this study.

For total RNA (excluding miRNA) sequencing, template libraries were produced from 600 ng of total RNA using the Ovation Human Blood RNA-Seq Library Systems kit (NuGen) according to the manufacturer’s specifications. Libraries were multiplexed in groups of six and sequenced on a HiSeq 2000 at The University of North Carolina at Chapel Hill High Throughput Sequencing Facility. Raw sequencing reads were aligned using a custom bioinformatics pipeline as described previously (Linnstaedt et al., 2015b) and were normalized using upper-quartile normalization. To normalize potential technical biases between the two methods of library preparation, the sequencing reads were adjusted using the methodology described by Johnson et al. (2007). Of the 172 samples with miRNA sequencing data, 66 samples also had total RNA sequencing data and were used for analyses in this study.

For total RNA (excluding miRNA) sequencing, template libraries were produced from 600 ng of total RNA using the Ovation Human Blood RNA-Seq Library Systems kit (NuGen) according to the manufacturer’s specifications. Libraries were multiplexed in groups of six and sequenced on a HiSeq 2000 at The University of North Carolina at Chapel Hill High Throughput Sequencing Facility. Raw sequencing reads were aligned using a custom bioinformatics pipeline as described previously (Linnstaedt et al., 2015b) and were normalized using upper-quartile normalization. To normalize potential technical biases between the two methods of library preparation, the sequencing reads were adjusted using the methodology described by Johnson et al. (2007). Of the 172 samples with miRNA sequencing data, 66 samples also had total RNA sequencing data and were used for analyses in this study.

Linnstaedt et al. (2015a) used miRDeep RNA online database (http://mirdeep.ccr.buffalo.edu/) to assess whether rs3800373 is predicted to directly affect miRNA binding and to determine miRNAs predicted to bind 300 nucleotides upstream or downstream of rs3800373. The RNAseq RNA folding algorithm (http://rth.dk/resources/masnps/) was used to determine whether the presence of the major versus minor allele of rs3800373 was likely to have an effect on the RNA secondary structure within the SNP-related binding region. To follow up on the RNAseq results, the partition and Fold programs from the RNAstructure suite (Mathews, 2006; Reuter and Mathews, 2010) were used to find the base-pairing probabilities and the minimum free energy (MFE) structures, respectively, of the 3′ UTR for the region containing selective 2′-hydroxyl acylation analyzed by primer extension (SHAPE) data. SHAPE reactivities were incorporated as a pseudo-free energy term in the nearest neighbor prediction model (Deigan et al., 2009). For both prediction algorithms, the maximum base-pairing distance was set at 200 nucleotides, and otherwise standard parameters were used for prediction and the SHAPE pseudo-free energy term.

**DNA constructs.** Lentiviral constructs containing either a firefly luciferase gene (pL-SV40-GL3) or a renilla luciferase gene (pL-SV40-RLUC) were used for dual luciferase assays (Gottwein and Cullen, 2010).

The 3′ UTR of FKBP5 was amplified from HEK293T cells using primers: ATGATGCCTGAGGTTGACCTCGGCCCTCTCCTAATGG and ATG ATGAAATCCGTGACCTGGCAATCATGTCAG. The resulting 2125 bp product was cloned downstream of the firefly luciferase gene in pL-SV40-GL3 using Xhol and EcoR1 restriction enzyme sites. This newly created construct, pL-GL3-FKBP5-maj, was sequenced to confirm the major allele, T, at position rs3800373 in the FKBP5 3′ UTR and was then used as a template to mutate the major allele to the minor allele, G, using the QuickChange II Site-Directed Mutagenesis kit (Promega) and primers GCTTAAAATTTTTAAAAAATCACTGGTAGAAGTTAATGTGATTCGTCTACT and GTAGAAGGACCAACTATATTGGTC AACCCCTAGATGGTTGTTTTAATTAAGC. This new construct, pL-GL3-FKBP5-min, was then sequenced to confirm the presence of the minor allele and the absence of additional introduced mutations.

A shortened version of the FKBP5 3′ UTR, FKBP5-truncated, was amplified from the full-length 3′ UTR using primers ATCATCCCTGGAGCACAGUACUUCUCGCAGC and ATCATCGAATTCGGTGTCCCCGAAAAAGTGCATTCC. This shortened version is 588 nucleotides and contains only the genomic region of the 3′ UTR used to predict structural changes using RNAsemp. Mutations in three nucleotide positions that were predicted to disrupt complementarity between miR-320a and the FKBP5 3′ UTR seed-binding region were engineered into FKBP5-truncated using primers CCAUGGCCGCUUUUUGUCUUUAAAGCGTTTGACATGGC and pL-GL3-FKBP5-truncated. This newly created construct pL-GL3-FKBP5-truncated was am-

A shortened version of the FKBP5 3′ UTR, FKBP5-truncated, was amplified from the full-length 3′ UTR using primers ATCATCCCTGGAGCACAGUACUUCUCGCAGC and ATCATCGAATTCGGTGTCCCCGAAAAAGTGCATTCC. This shortened version is 588 nucleotides and contains only the genomic region of the 3′ UTR used to predict structural changes using RNAsemp. Mutations in three nucleotide positions that were predicted to disrupt complementarity between miR-320a and the FKBP5 3′ UTR seed-binding region were engineered into FKBP5-truncated using primers CCAUGGCCGCUUUUUGUCUUUAAAGCGTTTGACATGGC and pL-GL3-FKBP5-truncated. This newly created construct pL-GL3-FKBP5-truncated was am-

Additionally, mutations were made to the FKBP5-truncated construct to increase or decrease nucleotide accessibility (i.e., create double-stranded regions vs single-stranded regions) in the miR-320a-binding region. We first used the online algorithms mFold (Zuker, 2003) and RNAstructure (Reuter and Mathews, 2010) to monitor structural changes in response to nucleotide mutations in the region of the miR-320a-binding site (but that did not change the sequence of the exact binding region). To the 3′ UTR with the major allele, we changed 31 nucleotides between sequence coordinates 35574855 and 35574832 on 6p21.31 from CTATTTGATTCATGAGCAGCTTTC to CCAACAAATT TAGATGCCTGAGCAGCTTTCAACACAAUAUAUGAAUAGCU AACT. To the 3′ UTR with the minor allele, we changed 20 nucleotides between sequence coordinates 35574818 and 35574793 on 6p21.31 from ATATTGAGCTCATAAGCATGAGTATA to ACAAGAAAAACGCTGCA TGGATCCTCAATTG. These FKBPs 3′ UTR sequences were synthesized and ligated into the EcoR1/XhoI restriction sites in pL-SV40-GL3 (catalog #U7355DC190, GenScript) to generate plL-GL3-FKBP5-basePaired and plL-GL3-FKBP5-Accessible. For the predicted structures resulting from the above mutations, see Figure 6A.

The genomic sequences for miR-99a, miR-122, and miR-320a were amplified from HEK293T cells using primers ATCATCGAATTCGGTGTCCCCGAAAAAGTGCATTCC.
To knock down miR-320a expression in SK-N-AS cells, we stably transduced the cells with pLCE-s320, a miR-320 sponge construct. Such “sponge” constructs have been described previously (Hajdin et al., 2013). To compare FKBP5 protein levels, protein was isolated from SK-N-AS cells using RIPA buffer with added protease inhibitors (Thermo Fisher Scientific). The total protein concentration was measured with a BCA protein assay (Pierce), and equal amounts of protein (5 μg per lane) were loaded onto a 4–12% Bis-Tris gel (Invitrogen) and analyzed by Western blotting. Primary rabbit anti-FKBP5 (catalog #82455; RRID:AB_10831198) and primary rabbit anti-β-actin (catalog #4970; RRID:AB_2223172) were obtained from Cell Signaling Technology. Secondary anti-rabbit IgG HRP was obtained from Cell Signaling Technology (catalog #7074; RRID:AB_2099233). Signals were developed using the ECL Western Blotting Substrate (Pierce), and signal intensities were quantified using ImageJ (RRID:SCR_003070).

SHAPE. Data were obtained in vivo using the EBV immortalized lymphoblastoid cell line generated from Yoruban male 19098 (1000 Genomes–Coriell Institute for Medical Research), which is heterozygous for rs3800373 (Genomes Project Consortium et al., 2015). These cells were grown in RPMI 1640 with 2 mM l-glutamine and 15% FBS. Approximately 50 million cells were grown, spun down, and resuspended in 1 mL of folding buffer (100 mM Na-HEPES, pH 8.0, 100 mM NaCl, and 10 mM MgCl2) supplemented with 400 U of RNase inhibitor (NEB). Cells were kept on ice and sonicated at 10% power for three 10 s intervals (Model 500 Sonic Dismembrator, Thermo Fisher Scientific). The lysate was incubated at 37°C for 10 min. SHAPE treatment was performed over 5 min with the addition of DMSO or three separate additions of 1-methyl-7-nitroisatoic anhydride (1M7) with a final concentration of 30 μM 1M7 and 10% DMSO. The DMSO alone provides a background control. RNA was extracted from the lysate and depleted of ribosomal RNA (Thermo Fisher Scientific Trizol LS, 5 PRIME PhaseLock Heavy, Invitrogen Purelink RNA columns, and Thermo Fisher Scientific Ribominus Eukaryote System version 2 from Invitrogen). SHAPE-Map was described previously (Siegfried et al., 2014; Smola et al., 2015). Briefly, reverse transcription was performed with SuperScript II (Thermo Fisher Scientific) under buffering conditions (Mn+2 buffer) to convert adducts into mutations (NEB randomers). Primers were designed to be specific to the 3’ region of the mRNA containing rs3800373 (CCTACAC GACGCTCTTCCGATCTNNNNTCTCCTCCAGCATTTGCTACTG and GACCTGAGATTCAAGCAGTGCTCTCCATCTNNNTGTTC TAACTCTTTTACCGT, which was amplified by PCR (NEB Q5 Hot-Start Polymerase). Secondary PCR was performed to add TruSeq barcodes. An Illumina MiSeq Sequencing Platform was used to sequence the treated and background samples as a paired-end, 2 × 300 multiplex run. The MiSeq sequencing reads were aligned to the FKBP5 3’UTR using Bowtie2 version 2.2.9 (Langmead and Salzberg, 2012). The aligned reads were then split into separate FASTQ files by the allele at the rs3800373 SNP position from cell lines heterozygous at this allele. For each allele, the SHAPE profile of the amplified region was derived from the allele-specific sorted sequencing reads using the ShapeMapper pipeline version 1.2 (Siegfried et al., 2014). The SHAPE reactivity at each position corresponds to the difference between the mutation rate in the treatment condition and the mutation rate in the background control, normalizing the mutation rates by a multiplier so that the distribution of SHAPE reactivities matched that of reference mRNA.

SHAPE reactivities were used as a pseudo-free energy term in the nearest-neighbor thermodynamic model of RNA folding. This approach significantly improves the accuracy of structure prediction from positive predictive values of ~0.5, on average, in the absence of experimental data to around 0.9 when SHAPE data are included (Deigan et al., 2009; Washietl et al., 2012; Hajdin et al., 2013; Sukosd et al., 2013; Siegfried et al., 2014). The base-pairing probabilities provide a representation of the structural ensemble of the 3'UTR and the average accessibility of each nucleotide is important and used throughout. Sequencing reads were aligned to the FKBP5 3’UTR using Bowtie2 version 2.2.9 (Langmead and Salzberg, 2012). The aligned reads were then split into separate FASTQ files by the allele at the rs3800373 SNP position from cell lines heterozygous at this allele. For each allele, the SHAPE profile of the amplified region was derived from the allele-specific sorted sequencing reads using the ShapeMapper pipeline version 1.2 (Siegfried et al., 2014). The SHAPE reactivity at each position corresponds to the difference between the mutation rate in the treatment condition and the mutation rate in the background control, normalizing the mutation rates by a multiplier so that the distribution of SHAPE reactivities matched that of reference mRNA.
Results
Participants
Baseline characteristics of participants in the AA MVC study (Linnstaedt et al., 2016c; n = 930) are shown in Table 1. Within the cohort, 763 participants provided DNA, were genotyped, and completed 6 week pain questionnaires. The miRNA sequencing was performed in another subset of 172 of 763 participants, total RNA sequencing was performed in a subset of 96 of 763 participants, and plasma cortisol assays were performed in a subset of 80 of 163 participants. Cortisol, miRNA, and total RNA data did not always overlap because plasma was obtained from only a subset of study participants and because RNA samples were selected for sequencing before planning these specific analyses. (RNA samples were selected for sequencing from individuals with relatively high or low levels of chronic MSP and RNA integrity scores of seven or greater.) Baseline characteristics of participants in the EA MVC study (Platts-Mills et al., 2011; n = 948) are also shown in Table 1.

Relationship between FKBP5 allele rs3800373 and chronic MSP in EAs after MVC
In EA individuals, we previously identified a main effect of rs3800373 genotype [minor allele frequency (MAF), 29%] on chronic MSP severity 6 weeks after MVC (Bortsov et al., 2013). In subsequent studies, we and others have found that the influence of genetic variants on vulnerability to post-traumatic MSP are often sex and/or stress dependent (Linnstaedt et al., 2016a,b; Meloto et al., 2016). We therefore performed additional analyses of EA cohort data to assess for potential interactions between sex and/or participant peritraumatic distress and the influence of rs3800373 on 6 week post-MVC MSP severity. No interaction with sex was present ($\beta = 0.052$, $p = 0.892$), but the influence of rs3800373 on chronic MSP severity was stress dependent ($\beta = 0.787$, $p = 0.035$).

Relationship between FKBP5 allele rs3800373 and chronic MSP in AAs after MVC
To determine whether this stress-dependent effect of rs3800373 on post-MVC MSP vulnerability replicated across ethnicity, we repeated these analyses in our AA MVC cohort (MAF, 44%). Consistent with EA MVC cohort findings, no interaction with sex was present ($\beta = 0.208$, $p = 0.661$), but the influence of rs3800373 on chronic MSP severity was stress dependent ($\beta = 1.36$, $p = 0.002$). These associations persisted after adjusting for opioid administration in the ED and/or use of opioids at 6 weeks.

Influence of peritraumatic distress on MSP outcome is allele dependent
Among individuals with the rs3800373 major allele, peritraumatic distress severity had relatively little impact on chronic MSP development (Fig. 1). In contrast, in both the AA and EA cohorts, individuals with increased subjective distress in the immediate aftermath of MVC and one or more copies of the minor allele developed more severe chronic MSP 6 weeks after MVC than nondistressed individuals with one or more copies of the minor allele (EA: 4.76 vs 3.43, $p < 0.001$; AA: 6.70 vs 5.29, $p < 0.001$; Fig. 1). (The presence or absence of one or more copies of the rs3800373 minor allele did not directly influence peritraumatic distress in either cohort; data not shown.) In the EA cohort, distressed individuals with the rs3800373 minor allele also developed more severe chronic post-MVC MSP than distressed individuals with the major allele (4.76 vs 3.85, $p = 0.001$). This

---

**Table 1.** Baseline characteristics of participants in the European American and African American MVC studies

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>European American</th>
<th>African American</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genotyping</td>
<td>mRNA Micro RNA</td>
<td>Cortisol</td>
</tr>
<tr>
<td>Enrolled, n</td>
<td>948</td>
<td>930</td>
</tr>
<tr>
<td>Age, years, mean (SD)</td>
<td>35.6 (13.3)</td>
<td>35.1 (12.7)</td>
</tr>
<tr>
<td>Females, n (%)</td>
<td>575 (60.7)</td>
<td>570 (62.2)</td>
</tr>
<tr>
<td>Education, n (%)</td>
<td>8–11 years</td>
<td>42 (4.4)</td>
</tr>
<tr>
<td>High school</td>
<td>184 (19.4)</td>
<td>290 (31.2)</td>
</tr>
<tr>
<td>Post-high school</td>
<td>57 (6.0)</td>
<td>42 (4.5)</td>
</tr>
<tr>
<td>Some college</td>
<td>312 (32.9)</td>
<td>338 (36.3)</td>
</tr>
<tr>
<td>College graduate</td>
<td>238 (25.1)</td>
<td>137 (14.7)</td>
</tr>
<tr>
<td>Post-graduate studies</td>
<td>113 (11.9)</td>
<td>36 (3.9)</td>
</tr>
<tr>
<td>Overall pain severity, 0–10 NRS, mean (SD)</td>
<td>19.2 (9.9)</td>
<td>22.2 (11.6)</td>
</tr>
</tbody>
</table>

NRS, Numeric rating scale.

---

**Figure 1.** FKBP5 x stress interaction on chronic pain severity after motor vehicle collision in EA (plain bars) and AA (striped bars) individuals. Shown is the interaction between the FKBP5 SNP rs3800373 allele and ED peritraumatic distress (light bars, low levels of distress; dark bars, high levels of distress) on pain severity measured 6 weeks after MVC. Individuals with increased peritraumatic distress and at least one copy of the minor allele (TG/GG, blue shading) reported more severe pain relative to individuals with less peritraumatic distress (**$p < 0.001$**) and relative to individuals with two copies of the major allele (TT, orange shading; # $p < 0.05$). Similar effects of FKBP5 x stress interactions were seen in both EAs (n = 844, left) and AAs (n = 765, right).
difference was also present at the trend level in the AA cohort (6.70 vs 6.11, \( p = 0.061 \); Fig. 1). In the AA cohort, increased peritraumatic distress also only predicted increased PTS symptoms at 6 weeks among individuals with the rs3800373 minor allele. Point estimates for the above findings did not significantly change when adjusting for previous life trauma (assessed in AA cohort only), opioid use, or litigation status (both cohorts).

Allele-dependent relationship between circulating cortisol levels and FKBP5 mRNA expression

Cortisol induces the expression of FKBP5 (Vermeer et al., 2003), and FKBP5 reduces the nuclear transport of cortisol required for negative feedback inhibition, resulting in relatively increased cortisol levels (Tatro et al., 2009). Both animal and human data indicate that increased FKBP5 and cortisol levels influence the development of chronic pain (Khasar et al., 2008; Bortsov et al., 2013; Maiarù et al., 2016, 2018). To evaluate whether the FKBP5 rs1360780 allele affects negative feedback inhibition, we assessed the relationship between circulating cortisol and FKBP5 mRNA levels in the immediate aftermath of MVC among individuals with the major versus minor allele. Among AA MVC cohort participants with the major allele (\( n = 80 \)), there was no correlation between circulating cortisol and FKBP5 mRNA expression (\( r = 0.253, p = 0.202 \); Fig. 2A). In contrast, among individuals with the rs3800373 minor allele, there was a strong positive correlation between cortisol levels and FKBP5 mRNA expression (\( r = 0.512, p = 1.2 \times 10^{-4} \); Fig. 2B). (Of note, low allele-specific subgroup sizes did not permit us to further subgroup these relationships according to distress level.) Increasing levels of FKBP5 in response to increased cortisol levels among individuals with the minor allele may contribute to chronic pain development, both via direct effects (Maiarù et al., 2016, 2018) and/or via elevated cortisol levels, which can promote chronic pain via the sensitization of primary afferents (Khasar et al., 2008).

Allele-dependent relationship between circulating FKBP5 mRNA and NR3C1 mRNA expression

Because translocation of cortisol into the nucleus is also known to downregulate GR expression (Silva et al., 1994), we also evaluated whether the FKBP5 rs1360780 allele affects the relationship between FKBP5 mRNA levels and GR receptor (NR3C1) mRNA levels. Among individuals with two copies of the major allele, there was no correlation between FKBP5 and NR3C1 mRNA levels (\( r = 0.091, p = 0.645 \); Fig. 2C). However, in individuals with one or more copies of the minor allele, FKBP5 and NR3C1 mRNA levels exhibited a strong positive correlation (\( r = 0.560, p = 8.3 \times 10^{-7} \); Fig. 2D). As with the data presented above, these results are consistent with the expected molecular consequences of reduced HPA axis negative feedback inhibition.

rs3800373-dependent miR-320a-binding efficiency

The rs3800373 is located in the 3’UTR of FKBP5 (Fig. 3A). To evaluate potential molecular mechanisms through which the rs3800373 allele might influence post-MVC MSP development, we first used web-based bioinformatics algorithms, including two databases for general regulatory function, RegulomeDB and
SNPInfo. In addition, we also used a database specific to miRNA binding, miRdSNP, because rs3800373 is located in the 3’ UTR where microRNAs primarily bind (Xu and Taylor, 2009; Boyle et al., 2012; Bruno et al., 2012). The RegulomeDB algorithm, which identifies regions with DNase hypersensitivity, binding sites for transcription factors, and biochemically characterized promoter regions, found no regulatory elements associated with rs3800373. The SNPInfo database (using the Function Prediction module) indicated that rs3800373 did not affect RNA splicing, transcription factor-binding sites, or other queried regulatory elements. However, the miRdSNP online algorithm indicated that three miRNA, miR-320a, miR-99a, and miR-122, are predicted to bind FKBP5 mRNA within 300 nucleotides upstream or downstream of rs3800373 (Fig. 3A).

To assess miRNA binding to the 3’ UTR of FKBP5, we created luciferase reporter constructs. In *in vitro* analyses, all three miRNA could bind to the FKBP5 3’ UTR in the presence of either the major or minor allele (Fig. 3B). However, for miR-320a, there was a statistically significant decrease in binding efficiency in the presence of the minor allele (*p* = 0.025; Fig. 3B). Shortening the

---

**Figure 3.** A, miR-320a binds and regulates the FKBP5 3’ UTR and does so in an allele-dependent manner. The rs3800373 is located in the 3’ UTR of FKBP5. The three closest predicted microRNA-binding sites are miR-320a, miR-99a, and miR-122, which are 134, 66, and 234 nucleotides from rs3800373, respectively. B, *in vitro* dual luciferase assays assessing miRNA binding to the FKBP5 3’ UTR in the presence of the major allele (checkered bars), the minor allele (striped bars), and the control (plain bars). Error bars (SD) are derived from at least three independent experiments performed in duplicate, and the difference in binding between the major and minor allele constructs for miR-320a was determined using a Mann–Whitney U test (*p* = 0.025). C, miR-320a binding to the FKBP5 3’ UTR in the presence of a 3’ UTR construct containing 2125 nucleotides of the FKBP5 3’ UTR (full length), 588 nucleotides of the FKBP5 3’ UTR surrounding the risk allele (truncated), and mutation of the seed-binding region for miR-320a (miR-320 mut) that conserves the predicted RNA secondary structure of the 3’ UTR. D, Nucleotide conservation among mammals at the predicted miR-320a-binding site in FKBP5. The miR-320a seed region is indicated by dark gray nucleotides, and conserved nucleotides outside of the seed region are indicated by light gray nucleotides. E, FKBP5 mRNA expression in the SK-N-AS neuroblastoma cell line knocked down for miR-320a (s320). mRNA expression levels are represented relative to two controls, a vector-only control (vector) and a nonrelated sponge sequence (control). Error bars (SD) are derived from two independently sorted cell lines for each condition measured in triplicate. F, FKBP5 protein expression in the SK-N-AS neuroblastoma cell line for the two sponge controls (vector and control) and the miR-320a sponge (s320). Western Blots were performed for each of the independently sorted cell lines. Protein expression quantitation was measured using ImageJ software, and the values represent the average band intensity calculated for each Western blot, adjusted for background signal intensity. *p* < 0.05.
size of the 3’UTR surrounding rs3800373 had no effect on miR-320a-binding efficiency, but mutation of the predicted miR-320a seed-binding region abolished binding activity (Fig. 3D). Together, these in silico and in vitro data indicate that the rs3800373 minor allele reduces the ability of miR-320a to bind FKBP5, resulting in increased FKBP5 levels. These results are consistent with previous reports indicating that increased expression of FKBP5 mRNA is associated with glucocorticoid resistance and adverse neuropsychiatric outcomes (Denny et al., 2000; Scammell et al., 2001; Binder et al., 2004; Segman et al., 2005; Klengel et al., 2013) and could at least partially account for the observed allele-dependent relationships between FKBP5 mRNA and NR3C1 mRNA and cortisol levels reported above.

Expression of miR-320a, FKBP5, and miR-320a regulation of FKBP5

To evaluate whether miR-320a regulates FKBP5 expression in an endogenous setting, we examined whether miR-320a regulates FKBP5 mRNA and protein levels in a neuroblastoma cell line. To do so, we knocked down miR-320a levels using lentiviral sponge constructs in SK-N-AS cells. Compared with cells expressing the control sponge, cells knocked down for miR-320a (s320) exhibited higher FKBP5 mRNA (Fig. 3E) and protein expression (Fig. 3F) levels.

rs3800373-dependent influence of miR-320a on chronic MSP development after MVC

In a previous pilot study using our AA MVC cohort (n = 69), we found that miR-320a expression in the hours after MVC predicts adverse MSP outcomes (Linnae et al., 2016d). Using an expanded cohort (n = 159), we evaluated whether miR-320a predicts post-MVC MSP severity in a manner consistent with FKBP5 rs3800373 allele-dependent miR-320a regulation. If an allele-dependent regulation was occurring, then a statistical interaction between the FKBP5 rs3800373 allele and miR-320a would be expected. In general linear modeling, a significant interaction between the rs3800373 allele and miR-320a was observed (t = −2.51, p = 0.013; Table 2). In stratified analyses, reduced circulating miR-320a expression in the hours after MVC predicted increased chronic MSP after MVC (standardized β = −0.233, p = 0.014) among individuals with one or more copies of the minor allele, but not among individuals who were homozygous for the FKBP5 rs3800373 major allele (standardized β = 0.185, p = 0.211). These results provide further support for the hypothesis that among individuals with the rs3800373 minor allele, there is less efficient miR-320a regulation of FKBP5 mRNA.

Table 2. Linear regression model examining the relationship between candidate predictors and chronic pain severity 6 weeks after MVC in African American individuals (n = 159)

<table>
<thead>
<tr>
<th>Variable</th>
<th>β</th>
<th>SE</th>
<th>t</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>0.05</td>
<td>0.024</td>
<td>2.25</td>
<td>0.025</td>
</tr>
<tr>
<td>Sex</td>
<td>−0.085</td>
<td>0.591</td>
<td>−0.14</td>
<td>0.885</td>
</tr>
<tr>
<td>Peritraumatic distress</td>
<td>0.06</td>
<td>0.024</td>
<td>2.58</td>
<td>0.011</td>
</tr>
<tr>
<td>rs3800373</td>
<td>2.39</td>
<td>1.25</td>
<td>1.92</td>
<td>0.056</td>
</tr>
<tr>
<td>miR-320a</td>
<td>0.01</td>
<td>0.001</td>
<td>0.17</td>
<td>0.195</td>
</tr>
<tr>
<td>rs3800373*miR-320a</td>
<td>−0.01</td>
<td>0.001</td>
<td>−2.51</td>
<td>0.013</td>
</tr>
</tbody>
</table>

*Study site and education level were also included as a categorical variables.

**Distress was assessed in the emergency department using the Peritraumatic Distress Inventory (Brunet et al., 2001).**

* A dominant genetic model was used for rs3800373.

Allele-dependent relationship between miR-320a and FKBP5 following MVC

Consistent with in vitro data (Fig. 3A–E), RNA expression levels in blood obtained from AAs in the hours after MVC also support the hypothesis that miR-320a regulation of FKBP5 is rs3800373 allele dependent (Fig. 4). Among individuals with the FKBP5 rs3800373 major allele, miR-320a and FKBP5 mRNA levels were negatively correlated (r = −0.475, p = 0.026; Fig. 4A). In contrast, among those with one or more copies of the minor allele, no correlation was observed (r = 0.144, p = 0.349; Fig. 4B). These data suggest that miR-320a is only able to bind and reduce FKBP5 mRNA levels among individuals with the major allele.

Effect of rs3800373 on FKBP5 mRNA 3’UTR secondary structure

As shown in Figure 3A, rs3800373 and miR-320a are distally located in the FKBP5 3’UTR. Therefore, rs3800373 cannot directly affect miR-320a-binding efficiency. However, genetic variants in the 3’UTR can also affect miRNA binding by altering the RNA secondary structure (Arnold et al., 2012). We evaluated whether rs3800373 might affect the RNA folding/secondary structure using in silico analyses (RNAspn). The algorithm predicted a statistically significant difference in RNA structure depending on the rs3800373 allele (p = 0.0136). We used SHAPE (Wilkinson et al., 2006; Siegfried et al., 2014) to experimentally compare RNA structural folding in RNA transcripts from each allele. SHAPE is an established method for chemically probing the RNA secondary structure in vivo, based on the selective chemical reactivity of the 2’-hydroxyl groups of flexible bases compared with bases involved in pair bonding or other interactions (Wilkinson et al., 2006; Siegfried et al., 2014). Yoruban cell line 19098 is heterozygous for rs3800373 and thus was selected for SHAPE analyses; lysis of these cells was performed using non-denaturing conditions that preserve the secondary structure of the RNA. Allele-specific preprocessing of sequencing reads was performed before SHAPE reactivity calculation to allow for controlled comparison of the allele-specific RNA structure (Siegfried et al., 2014). Results indicated allele-specific differences in RNA structure, both immediately surrounding rs3800373 and extending throughout the assayed region (Fig. 5A).

Because the mRNA structure can dramatically affect the accessibility of a 3’UTR to microRNA binding (Kertesz et al., 2007), we next evaluated whether the miR-320a-binding site in the FKBP5 3’UTR was affected by the presence of the rs3800373 allele. SHAPE reagents act by probing the relative flexibility of the mRNA structure using in silico -hydroxyl groups of flexible bases compared with bases involved in pair bonding or other interactions (Kuchko and Laederach, 2017). Given that our SHAPE experiments relied on next-generation sequencing, we were able to accurately estimate the error on each nucleotide’s reactivity as a function of sequencing depth (Smola et al., 2015). We therefore determined whether a nucleotide’s reactivity was significantly different based on the allele at rs3800373. Of the 21 nucleotides in the miR-320a-binding site, 16 nucleotides showed higher reactivity in the context of the major allele (10 of these nucleotides showed a statistically significant difference, p < 0.01; Fig. 5B). In comparison, only five nucleotides showed more reactivity in the context of the minor allele, with three of these showing a statistically significant difference (p < 0.01; Fig. 5B). Overall, this analysis of SHAPE reactivity data indicates that in the context of the rs3800373 major allele, the miR-320a-binding site is likely to be more accessible to miR-320a binding (i.e., less base paired and having a more open, single-stranded structure in the key binding region). This result is consistent with the in vitro
The above results indicate that rs3800373 likely affects structure on miR-320a-binding efficiency changes in the context of the minor allele, MFE modeling indicated that the FKBP5 3′ UTR was more compact and more sterically hindered by proximate base-paired stem loop structures (Fig. 5C). Overall, these modeling data suggest that rs3800373 alters base pairing in the miR-320a-binding site by shifting the RNA secondary structure in the context of the major allele to a more open/accessible conformation.

Together, the above results suggest that rs3800373 acts as a functional riboSNitch (Solem et al., 2015) by affecting the FKBP5 3′ UTR RNA secondary structure and the resultant efficiency of miR-320a binding to the FKBP5 3′ UTR. Furthermore, these results suggest that in individuals with the rs3800373 risk allele, the FKBP5 3′ UTR is less accessible to repression by miR-320a, leading to increased expression of FKBP5 mRNA, elevated glucocorticoid levels, and reduced negative feedback inhibition.

**Effect of mutations that alter the FKBP5 3′ UTR secondary structure on miR-320a-binding efficiency**

The above results indicate that rs3800373 likely affects FKBP5 mRNA expression via alterations to the 3′ UTR secondary structure and, more specifically, via alterations to a miR-320a-binding site. Therefore, we next sought to better understand the effects of site accessibility (as determined by base-pairing interactions within the mRNA; Kertesz et al., 2007) on miR-320a binding in the context of the FKBP5 3′ UTR. To do this, we made nucleotide changes in the FKBP5 3′ UTR in the vicinity of the miR-320a-binding site that either force the RNA to base pair at the miR-320a-binding site (Fig. 6A, base paired) or force the RNA to be single stranded at the miR-320a binding-site (Fig. 6A, accessible).

Using *in vitro* luciferase reporter assays, we measured miR-320a binding to both RNA structural variants shown in Figure 6A. Consistent with our results showing decreased miR-320a binding in the context of the minor allele 3′ UTR (that was shown via SHAPE analysis to exhibit increased base pairing in the miR-320a-binding site), we observed little to no binding when the RNA structure was fully base paired (Fig. 6B, base paired). In contrast, when the miR-320a-binding site was made more accessible through disruption of sequence complementarity, we observed increased miR-320a binding relative to either native major or minor allele structure (Fig. 6B, accessible). Together, these results indicate that miR-320a binding is sensitive to RNA structural changes in the FKBP5 3′ UTR and support the hypothesis that rs3800373 reduces miR-320a binding to FKBP5 mRNA, resulting in relatively greater FKBP5 translation unchecked by miR-320a.

**Discussion**

The FKBP5 protein has an important influence on vulnerability to a number of post-traumatic neuropsychiatric disorders, including chronic pain (Binder, 2009; Bortsov et al., 2013; Maiaru et al., 2016, 2018; Zannas et al., 2016). In this study, we identified a novel microRNA-dependent mechanism by which a common genetic variant in the 3′ UTR of FKBP5 affects chronic pain vulnerability after MVC. Building on previous work, we first identified an allele (rs3800373) in the 3′ UTR of FKBP5 that influences vulnerability to chronic post-traumatic pain in two ethnic cohorts. Then, using complementary experimental approaches, including *in silico*, *in vivo*, and mutational analyses, we showed that the FKBP5 rs3800373 minor allele reduces the ability of microRNA miR-320a to bind FKBP5 and decreases its expression by altering the RNA secondary structure of the FKBP5 3′ UTR. We show that, consistent with an inability of miR-320a binding to act as a counterbalancing regulatory mechanism restraining FKBP5 expression, among individuals with the minor allele, increasing cortisol or NR3C1 mRNA levels were associated with increasing FKBP5 mRNA levels.

The *in silico* analyses, SHAPE analyses and corresponding structural models, and mutational experiments described above support the hypothesis that the rs3800373 SNP alters the FKBP5 3′ UTR secondary structure. Such a polymorphism has previously been termed a “riboSNitch” (Halvorsen et al., 2010; Ritz et al., 2012). However, this is the first study to demonstrate that a riboSNitch affects the efficiency of microRNA binding in the 3′ UTR of a highly influential gene. Of the three microRNA identified to bind to FKBP5 in this study, only one microRNA, miR-320a, showed differential binding based on this riboSNitch. These data are consistent with previous evidence suggesting that miR-320a may be an important moderator of stress responses and the development of chronic post-traumatic pain. We previously found that peritraumatic miR-320a levels predict post-MVC pain outcomes in distressed individuals and that miR-320a...
binds multiple stress- and pain-associated transcripts. Circulating levels of miR-320a have also been associated with multiple other musculoskeletal pain conditions (Orlova et al., 2011; Bjer- sing et al., 2015; Devaux et al., 2015; Qureshi et al., 2015) and shown to be modulated by stress (Li et al., 2014). Importantly, previous studies have shown that miR-320a is expressed in nervous tissues that express FKBP5 and that are involved in chronic MSP pathogenesis (Landgraf et al., 2007; Madathil et al., 2011). Notably, it is possible that other miRNA known to bind FKBP5 and affect stress-related outcomes, such as miR-15 (Volk et al., 2016), might also be affected by alterations in the FKBP5 3'UTR RNA secondary structure induced by the rs3800373 minor allele.

The functional allele identified in this study, rs3800373, is now the second FKBP5 allele shown to influence vulnerability to post-traumatic sequelae. Kengel et al. (2013) previously demonstrated that rs1360780, in intron 2 of FKBP5, affects the methylation status of FKBP5 in intron 7. The rs1360780 and rs3800373 risk alleles are in high linkage disequilibrium ($D' = 0.89, r^2 = 0.78$), indicating that the effect of the risk alleles at each SNP generally occur in concert. The relative influence of each allele/mechanism on FKBP5 mRNA regulation and protein levels in different tissues, at different timepoints, and on different post-traumatic neuropsychiatric sequelae (e.g., pain, post-traumatic stress, depression, somatic symptoms) should be explored in fu-

Figure 5. The rs3800373 affects the RNA secondary structure of the FKBP5 3'UTR. A, Top, SHAPE data for a ~500 nt region of the FKBP5 3'UTR encompassing rs3800373 and the miR-320-binding site. Gold, Major (protective) allele; blue, minor (risk) allele; gray box, miR-320a-binding site; red box, miR-320a seed site; dotted line, position of rs3800373. RNA SHAPE reactivities indicate widespread structural differences throughout the assayed FKBP5 3'UTR transcript based on the allele at rs3800373. Bottom, Magnified SHAPE reactivity plots for the miR-320a-binding site. SHAPE reactivity is slightly higher for the major allele in the miR-320a seed site (left), indicating reduced base pairing. The thickness of the lines indicates the SE on the measurements of reactivity. B, Raw difference in SHAPE reactivity data from A for the 21 individual nucleotides (black dots) in the miR-320a-binding region. These values were computed by comparing SHAPE reactivity data in the major allele structure versus SHAPE reactivity data in the minor allele structure. Higher SHAPE reactivity values indicate a greater degree of accessibility (i.e., less base pairing). Therefore, nucleotides with a more open structure in the context of the major allele ($n = 16$) are represented by positive values, and nucleotides with a more open structure in the context of the minor allele are represented by negative values ($n = 5$). Raw differences are shown along with confidence intervals based on four separate assessments of SHAPE reactivity in this genomic region. C, SHAPE-informed minimum free energy structures for the rs3800373 major (top) and minor (bottom) alleles, with SNP and miR-320a seed sites annotated. Nucleotide colors represent measured SHAPE reactivity as indicated by the color bar.
with greater stress/distress experience greater stress-system activation that not all those with a risk factor (in this case, peritraumatic distress) develop the adverse outcome (chronic MSP). These data are consistent with the hypothesis that individuals who are carriers of the risk allele experienced worse post-traumatic pain outcomes. These mediators may promote allodynia and hyperalgesia by sensitizing peripheral and central afferents directly (Ferreira, 1993; Maier et al., 1993; Fukuoka et al., 1994) and/or by sensitizing CNS neurons via an afferent feedback mechanism (Ferreira, 1993; Maier et al., 1993; Fukuoka et al., 1994; Watkins et al., 1994, 1995a, b). In addition to influencing inflammatory mediators that elicit pain responses, increased FKB5p levels enhance circulating glucocorticoid levels, which in concert with elevated catecholamine levels cause widespread hyperalgesia, in animal models by sensitizing primary afferents (Khasar et al., 2008). FKB5p may also be a critical factor in shifting glucocorticoid receptor activation after stress exposure from antinociceptive to pronociceptive (Maiaru et al., 2016).

Several limitations should be noted when interpreting the results of this study. First, to avoid confounding by population stratification, our studies only enrolled European American or African American individuals. The generalizability of our findings to other race/ethnic groups is unknown. However, because of population heterogeneity in allele frequencies and linkage disequilibrium patterns in the two cohorts differ (Morris, 2011; Marigorta and Navarro, 2013; Hormozdari et al., 2014; Wen et al., 2015), the consistent association between rs3800373 and pain outcomes across both cohorts increases the likelihood that the allele is indeed functional. Second, we did not perform DNA methylation studies on samples from our two cohorts. Therefore, we were not able to assess the relative contribution of rs1360780 and rs3800373 on methylation and microRNA regulation of FKB5p in these samples. (We hope to obtain funding to do this in the future.) Third, different cutoffs of peritraumatic distress were used in the European and African American populations since these cutoffs were based on median scores and the distribution of distress levels in the two cohorts varied substantially. However, while applying the median distress level cutoff used in European Americans to the African American cohort greatly reduced subsample sizes, it did not significantly influence effect size estimates observed in general linear modeling. Fourth, mRNA and miRNA expression levels reported in this study were measured in blood

Figure 6. The RNA secondary structure in the FKB5p 3′UTR influences miR-320a-binding efficiency. A, Schematics of SHAPE-informed RNA secondary structures for the FKB5p 3′UTR in the presence of the major allele (top left) or the minor allele (bottom left) and schematics of predicted RNA secondary structures for the FKB5p 3′UTR with nucleotide changes that either increase base pairing in the vicinity of the miR-320a-binding site (base paired, top right) or decrease nucleotide complementarity (accessible, bottom right). The miR-320a-binding site is indicated by a red line on each schematic, and the seed region of miR-320a is indicated by an orange line. B, In vitro dual luciferase assays assessing miR-320a binding to the FKB5p 3′UTR in the presence of each construct represented by images in A. Error bars (SD) are derived from three independent experiments performed in duplicate.
tissue (vs neuronal tissues that might be more relevant to chronic pain physiology). However, RNA expression patterns in the blood and CNS overlap significantly (Sullivan et al., 2006; Liu et al., 2010; Daskalakis et al., 2014; Hensman Moss et al., 2017), a number of previous studies have linked RNA expression in the blood (including expression of FKBP5) with neurological disease outcomes (Binder et al., 2004; Segman et al., 2005; Lai et al., 2011; Brenn et al., 2018), and the stress response that appears to be involved in the pathogenesis of post-MVC MSP (McLean et al., 2005; McLean, 2011; Linnstaedt et al., 2016b) is primarily systemic and involves circulating stress and immune factors that communicate via the blood.

In conclusion, the findings of the present study indicate that, in addition to regulation via methylation levels, FKBP5 expression is regulated by miR-320a in a rs3800373 allele-dependent fashion. Identification of this additional functional SNP in FKBP5 increases understanding of genetic risk factors for post-traumatic MSP, uncovers an important gene–miRNA interaction influencing chronic pain risk, identifies the specific mechanism by which this genetic risk allele alters miRNA regulation, and suggests potential therapeutic approaches (e.g., exogenous methods to achieve targeted reduction in poststress FKBP5 mRNA expression via miRNA mimics or siRNA administration).

References
Hormozidi F, Zhu A, Kichaev G, Ju CJ, Segrè AV, Joo JWJ, Won H, Sanka-


