Proteomic Analysis of Rat Prefrontal Cortex after Chronic Lithium Treatment

Jaganathan Lakshmanan1,2,3, Ratnam S Seelan1,2,4, Muthusamy Thangavel1,2, Robert E Vadnal5, Anthony J Janckila4, Manuel F Casanova2, Latha K Parthasarathy1,2 and Ranga N Parthasarathy1,2,7*

1Molecular Neuroscience and Bioinformatics Laboratories, Mental Health, Behavioral Science and Research Services, Robley Rex Veterans Affairs Medical Center, USA
2Department of Psychiatry and Behavioral Sciences, University of Louisville, USA
3Price Institute of Surgical Research, Department of Surgery, School of Medicine, University of Louisville, USA
4Department of Molecular, Cellular & Craniofacial Biology, School of Dentistry, University of Louisville, USA
5Eastern Colorado Health Care System, Department of Veterans Affairs, USA
6Special Hematology Lab, Robley Rex Veterans Affairs Medical Center and Department of Microbiology and Immunology, School of Medicine, University of Louisville, USA
7Department of Biochemistry and Molecular Biology, University of Louisville, USA

Abstract

Although lithium is widely used to treat Bipolar disorder (BD), its therapeutic role in BD is unclear. To gain insights into its mechanism of action we have used proteomic analysis to identify differentially expressed proteins in rat Prefrontal cortex (PFC), a region specifically affected in BD, after six weeks of lithium treatment. Proteins from control and lithium treated rat PFCs were separated by 2 Dimensional - Differential In-Gel Electrophoresis (2D-DIGE) and identified by mass spectrometry. Of the 2198 protein spots resolved, the abundance of 19 proteins was found to be significantly altered in the lithium treated group (with the levels of 5 proteins increasing and those of 14 decreasing). The levels of two protein spots exhibiting significant alteration after chronic lithium exposure were verified by Western blot analysis of rat PFC extracts. The 19 identified proteins represent novel targets for lithium action and participate in diverse functions that converge on a biological network that is specifically related to brain cell survival, prevention of neurodegeneration, and/or suppression of hyperactivity related signaling pathways. The identification of these targets should facilitate a better understanding of lithium’s overall effect on mood control.

Keywords: 2D-DIGE; Bipolar disorder; Chronic lithium; Prefrontal cortex; Proteomics

Abbreviations: 2D-DIGE: 2-Dimensional Differential In-Gel Electrophoresis; BD: Bipolar Disorder; IEF: Isoelectric Focusing; IPA: Ingenuity Pathway Analysis; PFC: Prefrontal Cortex; PTM: Post Translational Modification

Introduction

Bipolar Disorder (BD) is a devastating psychiatric disorder affecting ~2% of the world population [1]. Lithium is the most widely used drug for the treatment of BD [2-4] but the precise mechanism of its action remains an area of intense research [5]. Much attention has been focused on lithium’s inhibition of inositol monophosphatase-1 and inositol polyphosphate1-phosphatase, both of which lead to the accumulation of inositol 1-phosphates and reduction in myo-inositol levels, thus depleting the pool of cellular inositol triphosphate, a critical second messenger generated from membrane phosphoinositides [5-8]. Apart from its effects on the brain inositol-signaling pathway, lithium affects protein kinase B (Akt)/glycogen synthase kinase 3 (Gsk3) signaling cascades [2,6,7,9-12] which may have an effect on neurotrophic factors [13,14], cellular metabolism, cytoskeletal organization, and regulation of gene expression [6,10,13-18]. Lithium also modulates a number of signaling pathways involved in neurotransmission, circadian rhythm and arachidonic acid metabolism [19-21], and may prevent neurodegeneration in animal models of Alzheimer’s disease (AD), Parkinson’s syndrome, Huntington’s disease and spinal cord injury [22,23]. These diverse functions suggest a pivotal role for lithium in neural protein regulation in the prefrontal cortex (PFC), a region linked to the pathophysiology of BD [24-27].

Many of the studies on chronic lithium treatment are based on microarray analyses which reflect changes in mRNA levels that may not necessarily reflect quantitative changes in protein levels [28-31]. In this study, we have used whole rat brain PFC to identify novel proteins employing a 2D-DIGE technique and mass spectrometry analysis, after six weeks of chronic lithium treatment under therapeutically relevant conditions. Analysis of these novel proteins and determination of their role in metabolic pathways will enhance our understanding of the therapeutic and neuroprotective actions of lithium.

Materials and Methods

Animal treatment

Male Sprague-Dawley rats (250-300 gm), three per group for 2D-DIGE analysis and four per group for Western blot analysis, were used. Rats in the lithium group were fed standard rat-chow containing 2 gm/kg of lithium carbonate and were provided 0.9% saline to minimize the electrochemical imbalance caused by the diuretic properties of lithium. All rats had free access to food and water. At the end of 6 weeks, the rats were decapitated under deep CO2 anesthesia. The brain was rapidly dissected on ice and the PFC was isolated and immediately frozen in dry ice and stored in -70°C. All methods using rats were...
approved by the VA Animal Care Committee, which follows the guidelines set forth by the National Institutes of Health, Washington, DC, USA.

2D-DIGE

Rat brain PFC samples were shipped in dry ice to Applied Biomics (Hayward, CA) for 2D-DIGE analysis. Samples were homogenized by sonication at 4°C in 2D-lysis buffer (30 mM Tris-HCl, pH 8.8, containing 7 M urea, 2 M thiourea and 4% CHAPS), followed by shaking for 30 minutes at room temperature in the dark. The samples were then centrifuged for 30 min at 10,000 × g at 4°C and the protein content in the clear homogenate was measured using Bio-Rad PCA reagent. Three similar gels were run containing controls (Cy3), lithium treated extracts (Cy5) and internal standard samples (Cy2) for reliable comparison and quantification of samples.

Cyanine dye labeling of samples

30 μg of protein from control and lithium treated samples were labeled with cyanine dyes, Cy3 and Cy5, respectively, with 1.0 μl of diluted CyDyes each and kept in dark on ice for 30 min. For internal standards, equal amounts of control and lithium treated protein samples were mixed and labeled with Cy2. To enable comparative quantification, this mixture was run on every gel to normalize gel to gel variation and to help align all protein spots across different gels. The labeling reaction was stopped by adding 1.0 μl of 10 mM Lysine to each sample, and then incubated in the dark on ice for an additional 15 min. All samples were then mixed together. The 2X 2-D Sample buffer (8 M urea, 4% CHAPS, 20 mg/ml DTT, 2% pharmalytes and trace amount of bromophenol blue), 100 μl DeStreak solution and Rehydration buffer (7 M urea, 2 M thiourea, 4% CHAPS, 20 mg/ml DTT, 1% pharmalytes and trace amount of bromophenol blue) were added to the labeling mix for a total volume of 250 μl. Samples were mixed well before loading onto the strip holder.

IEF and SDS-PAGE

After loading the samples, IEF (pH 3-10 Linear) was performed, following the protocol of Amersham BioSciences (Piscataway, NJ). Upon completion of IEF, the IPG strips (Invitrogen, Carlsbad, CA) were incubated in freshly made equilibration buffer-1 (50 mM Tris-HCl, pH 8.8, containing 6 M urea, 30% glycerol, 2% SDS, with trace amount of ammonium thiocyanate and trace amount of bromophenol blue), 100 μl DeStreak solution and Rehydration buffer (7 M urea, 2 M thiourea, 4% CHAPS, 20 mg/ml DTT, 1% pharmalytes and trace amount of bromophenol blue) were added to the labeling mix for a total volume of 250 μl. Samples were mixed well before loading onto the strip holder.

Western-blot analysis

Peptides corresponding to Synuclein A (Snca) and synaptosomal-associated 25 kDa protein (Snap25) were identified by 2D-DIGE to be significantly affected by chronic lithium treatment and exhibited increased and decreased levels, respectively. The levels of these proteins were quantified by Western blotting. PFC samples from four controls and four lithium fed rats were used. Protein was extracted with 2 volumes (wt/vol) of 4 mM HEPES buffer containing 320 mM sucrose and protease inhibitors using a glass homogenizer and motorized Teflon pestle. The samples were centrifuged at 9,000 × rpm for 15 min at 4°C in a Tomy MTX-150 centrifuge. Supernatant protein was quantified using Pierce’s BCA protein estimation kit. 50 μg of protein were loaded per well in 12% SDS-polyacrylamide gel, resolved and transferred onto a polyvinylidene difluoride (PVDF) membrane and probed with monoclonal antibodies from Abcam (Cambridge, MA, USA) against Snca (ab1903) or Snap25 (ab24737) and were visualized using ECL chemiluminescence reagents (GE Healthcare). β-Actin was used as control and was detected using the monoclonal antibody MAB1501 from Chemicon International (Temecula, CA, USA). Band intensities were determined using the ImageJ software (http://rsb.info.nih.gov/ij/) and were normalized to corresponding β-actin levels. The levels of these proteins in lithium-fed rats (mean ± S.E.) were expressed as a percentage of values relative to that observed in control rats, taken as 100%. All protein band intensities were averaged from three runs.

Protein identification

Protein spots significantly different from control derived protein spots were picked by Ettan Spot Picker (GE Healthcare) based on analysis by the DeCyder software (version 6.0). The spots of interest were washed four times with 25 mM ammonium bicarbonate in 50% acetonitrile and then digested in gel with modified porcine trypsin protease (Trypsin Gold, Promega). Tryptic peptides were desalted from Zip-tip C18 (Millipore) columns using 0.5 μl of matrix solution (5 mg/ml of cyano-4-hydroxydineamic acid in 50% acetonitrile, 0.1% trifluoroacetic acid, 25 mM ammonium bicarbonate) and spotted on AB SCIEX MALDI plate (Opti-TOF® 384 Well Insert). MALDI-TOF MS and TOF/TOF tandem MS/MS were performed on an AB SCIEX TOF/TOF™ 5800 System (AB SCIEX). MALDI-TOF mass spectra were acquired in reflectron positive ion mode, averaging 4000 laser shots per spectrum. TOF/TOF tandem MS fragmentation spectra were acquired for each sample, averaging 4000 laser shots per fragmentation spectrum on each of the 10 most abundant ions present in each sample (excluding trypsin autolytic peptides and other known background ions). Average value per spot of protein was calculated across triplicate gels and spots that demonstrated > 1.2 fold difference and p-values of < 0.05 (ANOVA) were chosen for identification by mass spectrometry. Confidence intervals and corrected p-values were calculated using a Rank Wilcoxon test. Significance was assessed using a 0.5 threshold of the false discovery rate (FDR). The protein spots were subjected to tryptic digestion followed by MALDI-TOF/TOF analysis. The peptide fragments were identified using the Mascot search engine. Searches were performed without constraining protein molecular weight or isoelectric point, with variable carbamidomethylation of cysteine and oxidation of methionine residues, and with one missed cleavage allowed in the search parameters. Both the resulting peptide masses and the associated fragmentation spectra were submitted to GPS-Explorer workstation equipped with MASCOT search engine (Matrix science) to search the National Center for Biotechnology Information non-redundant (NCBI) database. Candidates with either protein or ion scores of more than 95 % C1. (Confidence Interval) were considered significant. Detailed results of the aforementioned proteomic analyses are provided in the Supplementary File.

Citation:
Lakshmanan J, Seelan RS, Thangavel M, Vadnal RE, Janckila AJ, et al. (2012) Proteomic Analysis of Rat Prefrontal Cortex after Chronic Lithium Treatment. J Proteomics Bioinform 5: 140-146. doi:10.4172/jpb.1000226
Results

Identification of differentially expressed proteins by 2D-DIGE after chronic lithium treatment

Total proteins extracted from PFC of three control and three lithium fed rats were analyzed by 2D-DIGE. Of the 2198 protein spots resolved, 19 protein spots were identified to be significantly altered (> 1.2 fold; p < 0.05) in the lithium treated group as compared to the control group - 5 peptides exhibited increased levels whereas 14 exhibited decreased levels; the latter included two Map2 forms, one of which was phosphorylated. A representative 2-D gel with the identified protein spots is shown in Figure 1.

Identification and characterization of the differentially expressed proteins in rat PFC after lithium treatment

The 19 differentially expressed proteins, inferred from the protein spots, were analyzed using IPA (Ingenuity Pathway Analysis; Ingenuity Systems, Mountain View, CA) analysis. When grouped according to their biological function (Table 1, Figure 2), many of the 19 differentially expressed proteins were found to be involved in synaptic functions, cellular energy metabolism, signaling processes, and cytoskeletal functions. Lithium-induced changes in protein levels are shown in Table 2. Levels of Efemp2 and Snap25 were significantly reduced (> 1.7 fold) whereas those of Snca and Hk1 were significantly increased (> 1.3 fold).

Western blot analysis of Snca and Snap 25

Western blot analysis was used to verify the levels of two of the most affected proteins – Snca and Snap25 – in rat PFC. Snca levels were increased by 41% (p<0.0001; n=4), whereas Snap25 levels were decreased by 17% (p<0.0015; n=4) in lithium fed rats when compared to levels in control rats (Figure 3). These results are consistent with the 2D-DIGE findings (Table 2).

Discussion

Lithium is the drug of choice for the treatment of BD and its clinical efficacy is apparent only after chronic treatment. Little is known about the global changes occurring in brain protein levels after lithium therapy. Our present study represents a model of chronic lithium administration that is clinically and physiologically relevant. A number of studies have examined changes in mRNA levels [28-31] but not changes in protein levels. This work addresses this omission by analyzing changes in protein levels in whole rat PFC, a BD susceptible region [24,26,32], and supports an earlier study that focused specifically on the synapto-neurosomes of the PFC [27].

Using 2D-DIGE and mass spectrometry analysis, we determined the relative levels of 2198 protein spots, 19 of which were significantly different in the PFC of chronic lithium fed rats when compared to controls. Levels of five protein spots were increased and 14 were decreased (the latter included two Map2 polypeptides, one of which was phosphorylated). The 19 identified proteins classified according to their known functionality (based on IPA analysis; Table 1), are involved in biological processes that are relevant to the therapeutic action of lithium, such as triggering anti-apoptotic mechanisms, modulating synaptic function, regulating cell-cell signaling, and remodeling the cytoskeleton architecture. The changes in the levels of the above proteins, coupled with their known functions, may help explain their...
role in disease states. These proteins, therefore, represent novel targets for lithium action and are potential candidates for treatment of BD.

Altered energy metabolism due to malfunctioning of mitochondria is known to contribute to the pathophysiology of psychiatric disorders [32,33]. Brain hexokinase 1 (Hk1) was found to be significantly up-regulated in lithium fed rat PFC (Table 2). This observation establishes a potential link between the up-regulation of HK1 and the increase in brain glucose-6-phosphate concentrations, observed by Plenge [34], before lithium treatment in normal rats.

PFC SNAP25 promoter region exhibit aberrantly increased expression of SNAP25 [35]. Of relevance to this study, increased levels of SNAP25 have been observed in dorsolateral PFC of bipolar I patients from postmortem brain samples [36]. Chronic lithium treatment caused a 1.7 fold decrease in Snap25 levels suggesting a mechanism directed against glutamate-induced excitotoxicity in BD. Levels of Cltb, an integral component of the clathrin coated vesicles, were decreased against glutamate-induced excitotoxicity in BD. Levels of Cltb, an integral component of the clathrin coated vesicles, were decreased 1.35 fold by lithium treatment, likely resulting in decreased levels of neurotransmitter receptors as well as to a reduction in the rate of synaptic vesicle exocytosis/recycling. These observations strongly suggest that alterations in synaptic processes may have a potential role in disease states. These proteins, therefore, represent novel targets for lithium action and are potential candidates for treatment of BD.

| Functional classification | Protein | Location | Biological function |
|--------------------------|---------|----------|---------------------|
| **Synaptic**              | Snap25  | Cytoplasm, plasma membrane | Neurotransmitter uptake and secretion; synaptic transmission; synaptic vesicle docking during exocytosis; regulation of insulin secretion. |
|                          | CItb    | Plasma membrane | Intracellular protein/receptor transport; vesicle-mediated transport. |
|                          | Snca    | Nucleus, cytoplasm, plasma membrane | Integration of presynaptic signaling and membrane trafficking; regulation of dopamine secretion; negative regulation of mono-oxygenase activity; response to interferon gamma; negative regulation of histone acetylation. |
| **Metabolic**             | Hk1     | Mitochondria, cytoplasm | Glycolysis; anti-apoptosis; energy and glucose metabolism. |
|                          | Gapdh   | Cytoplasm, nucleus, membrane, perinuclear region | Glucose metabolism; glycolysis; oxidation reduction; apoptosis; energy metabolism. |
|                          | Psmb2   | Nucleus, cytoplasm, proteasome | Ubiquitin-dependent protein degradation. |
|                          | Vars    | Nucleus | Valine-IRNA aminoacylation. |
| **Signaling**             | Cair    | Cytoplasm | Ca** binding; regulator of transcription; regulator of apoptosis. |
|                          | Rpsa    | Cellsurface, cytoplasm, nucleus, ribosome | Translational elongation; cell adhesion; structural constituent of ribosome; receptor activity; ribosome binding. |
|                          | Gap43*  | Plasma membrane, synaptosomes | Calmodulin binding; activation of protein kinase C activity by G-protein coupled receptor protein signaling pathway; nervous system development; glial cell differentiation; axon process point recognition; growth cone guidance; actin dynamics. |
|                          | Nudt3   | Cytoplasm | Diphosphoinositol-polyphosphate diphosphatase activity; cell-cell signaling; turnover of inositol polyphosphates. |
|                          | Oas1    | 1H | Anti-viral action of interferon. |
| **Cytoskeleton**          | Basp1   | Plasma Membrane | Calmodulin binding; component of brain lipid raft; neuron-specific regulates neurite outgrowth. |
|                          | Map2**  | Cytoskeleton, cytoplasm | Negative regulation of microtubule depolymerization; calmodulin binding; structural molecule. |
|                          | Cnp     | Cytoplasm | Phosphodiesterase activity; microtubule cytoskeleton organization; synaptic transmission; axonogenesis; RNA metabolism. |
|                          | Efemp2  | Basement membrane, extracellular space | Extracellular matrix structural constituent; calcium ion binding; protein binding; transmembrane receptor activity. |
| **Transport**             | Ensa    | Cytoplasm | Transport; response to nutrient; receptor binding; ion channel inhibitor activity. |

Note: *Gap-43 is localized in the plasma membrane and is also a component of the cytoskeletal structure and synapse.

**two forms of Map2 were identified, one of which was phosphorylated.

Table 1: Functional classification of proteins that are differentially expressed in rat PFC upon chronic lithium treatment.
### Table 2: List of differentially expressed proteins in rat PFC after chronic lithium treatment.

| Spot No. | Top ranked protein name | Gene Name | NCBI Accession No. | MW (Da) (pI) | MASCOT Score | p-value | Fold change |
|----------|--------------------------|-----------|--------------------|--------------|--------------|---------|-------------|
| **Proteins with increased levels** | | | | | | | |
| 22 | Synuclein α | Snca | GI9507125 | 14506.2 (4.74) | 279 | 0.006 | 1.34 |
| 10 | Hexokinase Type I, Chain B, rat brain | Hk1 | GI5542104 | 102455.2 (6.29) | 223 | 0.00023 | 1.31 |
| 21 | Proteasome (prosome, macrpan, subunit, β type 2) | Psmb2 | GI34849630 | 22897.7 (6.96) | 176 | 0.014 | 1.27 |
| 24 | Endosulfine α | Ensα | GI9624979 | 13326.7 (6.62) | 127 | 0.016 | 1.26 |
| 11 | TNF receptor-associated protein 1 | Trap1 | GI55741837 | 8041.0 (6.56) | 99 | 0.025 | 1.26 |
| **Proteins with decreased levels** | | | | | | | |
| 25 | EGF-containing fibulin-like extracellular matrix protein 2 | Efemp2 | GI53733803 | 44820.3 (4.79) | 33 | 0.046 | -1.78 |
| 19 | Synaptosomal-associated 25kD protein | Snap25 | GI57114057 | 23300.2 (4.66) | 213 | 0.034 | -1.70 |
| 1 | 2’-5’ oligoadenylate synthetase 1H | Oas1h | GI57222310 | 42800.7 (5.38) | 39 | 0.024 | -1.49 |
| 12 | Calreticulin | Calr | GI11693172 | 47965.6 (4.33) | 343 | 0.017 | -1.47 |
| 2’ | Microtubule-associated protein 2 | Map2 | GI547890 | 202287.6 (4.77) | 103 | 0.007 | -1.45 |
| 3’ | Microtubule-associated protein 2 | Map2 | GI56625 | 198445.6 (4.76) | 226 | 0.036 | -1.38 |
| 23 | Similar to diphosphoinositol polyphosphate phosphohydrolase | Nudt3 | GI27704734 | 19083.6 (6.00) | 36 | 0.0011 | -1.38 |
| 15 | Laminin receptor 1/ Ribosomal protein SA | Rpsa | GI8393693 | 32803.4 (4.8) | 204 | 0.04 | -1.36 |
| 17 | Calrthin, light chain B | Cilb | GI15758690 | 25102.1 (4.56) | 289 | 0.015 | -1.35 |
| 13 | Growth associated protein 43 | Gap43 | GI8393145 | 203589.3 (4.61) | 40 | 0.035 | -1.35 |
| 9 | Brain abundant, membrane attached signal protein 1 | Basp1 | GI11560135 | 21777.4 (4.5) | 70 | 0.0097 | -1.32 |
| 7 | Valine t-RNA synthetase | Vars | GI484949 | 66744 (6.19) | 42 | 0.024 | -1.32 |
| 16 | 2’,3’-cyclic nucleotide 3’-phosphodiesterase | Cnp | GI294527 | 47238.6 (9.03) | 48 | 0.012 | -1.29 |
| 18 | Glyceraldehyde-3-phosphate dehydrogenase | Gapdh | GI8393418 | 35805.2 (8.14) | 152 | 0.0038 | -1.27 |

Note: *Spot 2 represents a phosphorylated form of Map2*

In regulating mood stabilization. Increased levels of Snca (1.34 fold) support this hypothesis. Snca binds to tyrosine hydroxylase, the rate limiting enzyme of dopamine synthesis [37]. Increases in Snca levels brought about by chronic lithium treatment can decrease dopamine levels by inhibiting tyrosine hydroxylase synthesis, possibly explaining the dysregulation of dopamnergic neurotransmission observed in BD [38,39].

Lithium caused a significant 1.38 fold decrease in the levels of diphosphoinositol polyphosphate phosphohydrolase (Nudt3/Dipp) which is regulated by cellular Ca\(^{2+}\) levels, as well as by receptor-mediated cyclic nucleotides [40] which act as a neurotransmitter and possible Akt suppressor [41]. This implies a potential Lithium>Dipp>lAkt signaling mechanism that may affect signaling by the Gsk3/Akt pathway. Ensa is a member of the highly conserved cAMP-regulated phosphoprotein family that interacts directly with Snca, and regulates brain G protein coupled receptors and synaptic functions [42]. Thus an increase in Ensa levels is consistent with an increase in Snca levels observed after chronic lithium treatment.

Levels of cytoskeletal proteins are often altered in schizophrenia and BD [43,44]. Our study reveals that chronic lithium treatment decreases Gap-43, Basp1 and Map2 levels. Gap-43 and Basp1 are abundantly present in the inner surface of neuronal plasma membranes and are members of the growth-associated protein family [45,46]. Basp1 stimulates neurite outgrowth [47], possibly by remodeling the actin...
The fold changes observed in the levels of the various peptides, after lithium treatment, though statistically significant, is quite small. However, small changes in protein levels can have profound effects on cellular function. In particular, post-translational modifications (PTMs) which may significantly impact protein function tend to result in small changes in protein levels [50,51]. It is also likely that various kinds of PTMs (acetylation, carbonylation, glycosylation, hydroxylation, methylation, nitration, palmitoylation, phosphorylation, sulfation, etc.) may have escaped our detection. Nevertheless, the decrease in Map2 phosphorylation after lithium administration (Table 2) is particularly interesting as Sanchez et al. [52] have observed a decrease in site-specific phosphorylation of MAP2 (Thr231/Thr235) by GSK3 with lithium treatment in short-term cultured neurons. Map2 phosphorylation appears to be quite complex involving not only Gsk3, but many protein kinases and protein phosphatases [53]. Changes in Map2 phosphorylation can affect microtubule stability affecting neuronal development. Further verification of the observation that Map2 phosphorylation is decreased after lithium treatment is warranted.

It is well known that aberrant neuronal signaling underlies BD pathophysiology and several psychiatric illnesses [54-57]. However the various interlinking mechanisms are not well known. An interaction generated by IPA analysis linking the 19 proteins whose levels were significantly altered by chronic lithium treatment identified several pathways relevant to BD pathology (data not shown). In particular, Protein kinase C (Pkc) was identified as a convergent point for some of these proteins. Activation of Pkc is one of the biochemical hallmarks of BD [58,59]. Hyperactive Pkc signaling [60] is associated with mania, of these proteins. Decreased SNAP25 levels could result from inability of Pkc to phosphorylate and stabilize SNAP25. In summary, the targets identified in this study have potential therapeutic relevance in the treatment of bipolar disorder.

References
1. Kessler RC, Chiu WT, Demler O, Merikangas KR, Walters EE (2005) Prevalence, severity, and comorbidity of 12-month DSM-IV disorders in the National Comorbidity Survey Replication. Arch Gen Psychiatry 62: 617-627.
2. Baldessarini RJ, Tondo L (2000) Does lithium treatment still work? Evidence of stable responses over three decades. Arch Gen Psychiatry 57: 187-190.
3. Tondo L, Baldessarini RJ (2009) Long-term lithium treatment in the prevention of suicidal behavior in bipolar disorder patients. Epidemiol Psychiatr Soc 18: 179-183.
4. Müller-Oerlinghausen B, Lewitzka U (2010) Lithium reduces pathological aggression and suicidality: a mini-review. Neuropsychobiology 62: 43-49.
5. Beaulieu JM, Caron MG (2008) Looking at lithium: molecular moods and complex behaviour. Mol Interv 8: 230-241.
6. Klein PS, Melton DA (1996) A molecular mechanism for the effect of lithium on development. Proc Natl Acad Sci USA 93: 8455-8459.
expression profiling of mouse brain mRNA in a model of lithium treatment. Psychiatr Genet 18: 64-72.

30. McEachin RC, Chen H, Sartor MA, Saccone SF, Keller BJ, et al. (2010) A genetic network model of cellular responses to lithium treatment and cocaine abuse in bipolar disorder. BMC Syst Biol 4:158.

31. McQuillin A, Rizig M, Gurling HM (2007) A microarray gene expression study of the molecular pharmacology of lithium carbonate on mouse brain mRNA to understand the neurobiology of mood stabilization and treatment of bipolar affective disorder. Pharmacogenet Genomics 17: 605-617.

32. Andreazza AC, Shao L, Wang JF, Young LT (2010) Mitochondrial complex I activity and oxidative damage to mitochondrial proteins in the prefrontal cortex of patients with bipolar disorder. Arch Gen Psychiatry 67: 360-366.

33. Rezin GT, Amboni G, Zugno AI, Quevedo J, Streck EL (2009) Mitochondrial dysfunction and psychiatric disorders. Neurochem Res 34: 1021-1029.

34. Plenge P (1982) Lithium effects on rat brain glucose metabolism in vivo. Effects after administration of lithium by various routes. Psychopharmacology (Berl) 77: 348-355.

35. Eltain B, Dumaine A, Mathieu F, Chevalier F, Henry C, et al. (2010) A SNAP25 promoter variant is associated with early-onset bipolar disorder and a high expression level in brain. Mol Psychiatry 15: 748-755.

36. Scarr E, Gray L, Keriaikous D, Robinson PJ, Dean B (2006) Increased levels of SNAP-25 and synaptofysin in the dorsolateral prefrontal cortex in bipolar I disorder. Bipolar Disord 8: 133-143.

37. Perez RG, Waymire JC, Lin E, Liu JJ, Guo F, et al. (2002) A role for alpha-synuclein in the regulation of dopamine biosynthesis. J Neurosci 22: 3090-3095.

38. Greenwood TA, Schork NJ, Eskin E, Kelsoe JR (2006) Identification of additional variants within the human dopamine transporter gene provides further evidence for an association with bipolar disorder in two independent samples. Mol Psychiatry 11: 125-133.

39. Berk M, Dodd S, Kauer-Sant'anna M, Mahi GS, Bourin M, et al. (2007) Dopamine dysregulation syndrome: implications for a dopamine hypothesis of bipolar disorder. Acta Psychiatr Scand Suppl: 41-49.

40. Shears SB (1998) The versatility of inositol phosphates as cellular signals. Biochim Biophys Acta 1436: 49-67.

41. Chakraborty A, Kim S, Snyder SH (2011) Inositol pyrophosphates as mammalian cell signals. Sci Signal 4: r1.

42. Woods WS, Boettcher JM, Zhou DH, Kloepper KD, Hartman KL, et al. (2007) Conformation-specific binding of alpha-synuclein to novel protein partners detected by phage display and NMR spectroscopy. J Biol Chem 282: 34555-34567.

43. English JA, Dicker P, Fickling M, Dunn MJ, Cotter DR (2009) 2-D DIGE analysis implicates cytoskeletal abnormalities in psychiatric disease. Proteomics 9: 3368-3382.

44. Schloesser RJ, Martinowich K, Manji HK (2012) Mood-stabilizing drugs: mechanisms of action. Trends Neurosci 35: 36-46.

45. Laux T, Fukami K, Thelen M, Golub T, Frey D, et al. (2000) GAP43, MARCKS, and CAP23 modulate PI(4,5)P(2) at plasmalemmal rafts, and regulate cell cortex actin dynamics through a common mechanism. J Cell Biol 149: 1455-1472.

46. Korshunova I, Caroni P, Kolkova K, Berezin V, Bock E, et al. (2008) Characterization of BASP1-mediated neurite outgrowth. J Neurosci Res 86: 2201-2213.

47. Mosevitsky MI (2005) Nerve ending “signal” proteins GAP-43, MARCKS, and BASP1. Int Rev Cytol 245: 245-325.

48. Klemmer P, Meredith RM, Holmgren CD, Klyuchnikov OI, Stahl-Zeng J, et al. (2011) Proteomics, ultrastructure, and physiology of hippocampal synapses in a fragile X syndrome mouse model reveal presynaptic phenotype. J Biol Chem 286: 25495-25504.

49. Burstein DE, Seeley PJ, Greene LA (1985) Lithium ion inhibits nerve growth factor-induced neurite outgrowth and phosphorylation of nerve growth factor-modulated microtubule-associated proteins. J Cell Biol 101: 862-870.

50. Karve TM, Cheema AK (2011) Small changes huge impact: the role of protein posttranslational modifications in cellular homeostasis and disease. J Amino Acids: 207691.

51. Jovic A, Wade SM, Miyawaki A, Neubig RR, Linderman JJ, et al. (2011) Hi-Fi transmission of periodic signals amid cell-to-cell variability. Mol BioSyst 7: 2238-2244.

52. Sánchez Martín C, Díaz-Nido J, Avila J (1998) Regulation of a site-specific phosphorylation of the microtubule-associated protein 2 during the development of cultured neurons. Neuroscience 87: 861-870.

53. Sanchez C, Diaz-Nido J, Avila J (2000) Phosphorylation of microtubule-associated protein 2 (MAP2) and its relevance for the regulation of the neuronal cytoskeleton function. Prog Neurobiol 61: 133-168.

54. Manji HK, Bechchuk JM, Moore GJ, Glitz D, Hasanat KA, et al. (1999) Modulation of CNS signal transduction pathways and gene expression by mood-stabilizing agents: therapeutic implications. J Clin Psychiatry 60: 27-39.

55. Bezchlibnyk YB, Wang JF, McQueen GM, Young LT (2001) Gene expression differences in bipolar disorder revealed by cDNA array analysis of post-mortem frontal cortex. J Neurochem 79: 826-834.

56. Sun Y, Zhang L, Johnston NL, Torrey EF, Yolken RH (2001) Serial analysis of gene expression in the frontal cortex of patients with bipolar disorder. Br J Psychiatry Suppl: s137-s141.

57. Zarate CA, Manji HK (2009) Protein kinase C inhibitors: rationale for use and potential in the treatment of bipolar disorder. CNS Drugs 23: 569-582.

58. Wang HY, Friedman E (1996) Enhanced protein kinase C activity and translocation in bipolar affective disorder brains. Biol Psychiatry 40: 568-575.

59. Hahn CG, Friedman E (1999) Abnormalities in protein kinase C signaling and the pathophysiology of bipolar disorder. Bipolar Disord 1: 81-86.

60. Friedman E, Houa-Yan-Wang, Levinson D, Connell TA, Singh H (1993) Altered platelet protein kinase C activity in bipolar affective disorder, manic episode. Biol Psychiatry 33: 520-525.

61. Hahn CG, Umapathy, Wang HY, Konneru R, Levinson DF, et al. (2005) Lithium and valproic acid treatments reduce PKC activation and receptor-G protein coupling in platelets of bipolar manic patients. J Psychiatr Res 39: 355-363.

62. Hepp R, Cabaniols JP, Roche PA (2002) Differential phosphorylation of SNAP-25 in vivo by protein kinase C and protein kinase A. FEBS Lett 532: 52-56.