TILAPIA (*OREOCHROMIS MOSSAMBICUS*) BRAIN CELLS RESPOND TO HYPEROSMOTIC CHALLENGE BY INDUCING *MYO*-INOSITOL BIOSYNTHESIS

Alison M. Gardell[1,2,*], Jun Yang[2,3], Romina Sacchi[1], Nann A. Fangue[4], Bruce D. Hammock[2,3] and Dietmar Kültz[1,2]

[1]Department of Animal Science, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA

[2]NIEHS Superfund Research Program, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA

[3]Department of Entomology and UCDMC Comprehensive Cancer Center, University of California Davis, One Shields Avenue, Davis, CA 95616, USA

[4]Wildlife, Fish, and Conservation Biology, University of California Davis, One Shields Avenue, Davis, CA 95616, USA

Correspondence: Alison M. Gardell
Department of Animal Science, University of California Davis, Meyer Hall, One Shields Avenue, Davis, CA 95616, U.S.A. (Email: amgardell@ucdavis.edu; Phone: (530) 752-7322; Fax: (530) 752-0175

SUMMARY:

This study aimed to determine the regulation of the *de novo myo*-inositol biosynthetic (MIB) pathway in Mozambique tilapia (*Oreochromis mossambicus*) brain following acute (25 parts per thousand (ppt)) and chronic (30, 60, 90ppt) salinity acclimations. The MIB pathway plays an important role in cells for accumulating the compatible osmolyte, *myo*-inositol, in response to hyperosmotic challenge and consists of two enzymes, *myo*-inositol phosphate synthase and inositol monophosphatase. In tilapia brain, MIB enzyme transcriptional regulation was found to robustly increase in a time (acute acclimation) or dose (chronic acclimation) dependent manner. Blood plasma osmolality, Na^+, and Cl^- concentrations were also measured and significantly increased in response to both acute and chronic salinity challenges. Interestingly, highly significant positive correlations were found between MIB enzyme mRNA and blood plasma osmolality in both acute and chronic salinity acclimations. Additionally, a mass spectrometry assay was established and used to quantify total *myo*-inositol concentration in tilapia brain, which closely mirrored the hyperosmotic MIB pathway induction. Thus, *myo*-inositol is a major compatible osmolyte that is accumulated in brain cells when exposed to acute and chronic hyperosmotic challenge. These data show that the MIB pathway is highly induced in response to environmental salinity challenge in tilapia brain and that this induction is likely prompted by increases in blood plasma osmolality. Because the MIB pathway uses glucose-6-phsosphate as a substrate and large amounts of *myo*-inositol are being synthesized, our data also illustrate that the MIB pathway likely contributes to the high energetic demand posed by salinity challenge.

Keywords: osmoregulation, compatible osmolyte, *myo*-inositol, brain, tilapia;

1. INTRODUCTION:

The accumulation of osmolytes, specifically 'compatible' osmolytes, is a key regulatory mechanism utilized by cells to compensate for hyperosmolality (Yancey et al., 1982). Compatible osmolytes are small, organic molecules which are concentrated inside of cells in order to restore osmotic equilibrium (Burg et al., 2007; Hoffmann et al., 2009). *Myo*-inositol, a polyol, is one example of a compatible osmolyte (Parthasarathy et al., 2006; Yancey et al., 1982). The use of *myo*-inositol in countering the negative effects of hyperosmolality is ubiquitous across phyla, ranging from plants to animals (Burg and Ferraris, 2008). Various molecular pathways relating to osmolyte accumulation, including cotransporter activity and biosynthesis enzymes, have been shown to be induced in order to accumulate *myo*-inositol within a number of different cell types of various tissue origins (Fiess et al., 2007; Hasegawa and Eisenberg, 1981; Law, 1994; Strange et al., 1991).

In fishes, the *myo*-inositol biosynthesis pathway (MIB) has been demonstrated to play an important role in *myo*-inositol accumulation in osmoregulatory tissues in response to hyperosmotic challenge. The MIB pathway utilizes two enzymes, *myo*-inositol phosphate synthase (MIPS) and inositol monophosphatase (IMPA) to generate *myo*-inositol endogenously from glucose-6-phosphate (G-6-P) in a two-step reaction (Geiger and Jin, 2006). The study by Fiol et al. (2006b) was the first to identify upregulation of MIPS mRNA in response to acute hyperosmotic challenge in tilapia gill, and since then, several studies have confirmed induction of the MIB pathway in other euryhaline species exposed to salinity challenge (Evans and Somero, 2008; Kalujnaia et al., 2013; Kalujnaia et al., 2010; Kalujnaia et al., 2009). In mammals, IMPA has at least two isoforms, originating from different genes (Ohnishi et al., 2007; Shamir et al., 2001), while MIPS can have alternative splice variants (Seelan et al., 2009) derived from the same gene. Interestingly, differential expression of isoforms following gene duplication events may have evolved in animals that are frequently exposed to variable environments (Schulte, 2004) as an adaptive mechanism for responding to environmental challenges, as seen in fishes. For example, Richards et al. (2003) found that sodium potassium ATPase isoforms are differentially regulated in rainbow trout gill following acclimation to various salinities. It has not yet been investigated whether or not IMPA isoforms or MIPS splice variants are differentially regulated by environmental salinity in fishes.

The fish brain, particularly the hypothalamus, and neighboring pituitary gland serve important roles in maintaining osmotic homeostasis in the whole organism (Bernier, 2009). The specific regulatory mechanisms and signaling events involved in osmoreception and osmoregulation of the fish brain in response to hypo-osmotic stress have been extensively studied (Seale et al., 2005; Seale et al., 2002; Seale et al., 2012b). For example, in euryhaline teleosts, prolactin has been identified as primary hormone utilized in freshwater acclimation in order to decrease water uptake and allow for the retention of ions (Bernier, 2009; Manzon, 2002). In contrast, the molecular mechanisms employed by fish brain cells in response to hyperosmotic challenge still require additional investigation. Although brain cells (primarily neurons and glia) are not directly exposed to changes in environmental salinity, these cells still encounter and respond to hyperosmotic challenge. Mammalian brain cells have evolved to be very sensitive to small changes in extracellular osmolality, which are thought to be perceived through changes in blood plasma osmolality (Davson and Segal, 1996). Interestingly, the organum vasculosum of the lamina terminalis in the mammalian brain is believed to serve as the primary 'osmostat' and provides feedback regulation for the osmoregulatory response (Bourque et al., 2007). The acute osmosensitivity of the mammalian brain is critical because increases in plasma osmolality outside of the normal range (~280-310mOsm/kg) can have damaging consequences for brain function, including interference with the maintenance of cell volume which is crucial for proper functioning of the central nervous system (Bourque et al., 2007; Strange, 1992).

Teleost fishes have evolved to regulate their blood plasma osmolality around the set point of 300mOsm/kg, however, rapid changes (+100mOsm/kg) in plasma osmolality are known to occur after salinity acclimation (Baldisserotto et al., 2007). Interestingly, the baseline plasma osmolality of saltwater acclimated fish (~350mOsm/kg) is higher than freshwater acclimated fish (~310mOsm/kg) (Evans and Claiborne, 2006; Seale et al., 2003). Although the brain is additionally protected by the blood brain barrier (BBB), deviations in plasma osmolality are reflected rapidly through changes in volume of the extracellular fluid surrounding brain cells due to water movement across the BBB (Abbott et al., 2010). This increase in extracellular osmolality induces water flux out of brain cells to the surrounding fluid through the semi-permeable cell membrane. To avoid prolonged cell shrinkage, brain cells employ regulatory volume increase by temporarily accumulating inorganic ions (e.g., Na^+, Cl^-) within the cell via

various membrane transport systems and ion channels (Lang et al., 1998; Wehner et al., 2003). These damaging ions are rapidly (hours-days) replaced by compatible osmolytes, which do not disrupt macromolecular structure and function when accumulated at high concentrations (Burg et al., 2007; Hochachka and Somero, 2002). Volume regulation has been documented as a response of fish cells to osmotic challenge, with more studies focusing on regulatory volume decrease in response to hypo-osmotic challenge (Chara et al., 2011).

Mozambique tilapia (*Oreochromis mossambicus*), a euryhaline teleost, is a commonly used species for studying elements of the osmotic stress response. *O. mossambicus* can tolerate a variety of salinities ranging from 0-120 parts per thousand (ppt) (Stickney, 1986) Many novel physiological and molecular mechanisms have evolved in tilapia in order to promote a high tolerance to saline and hyper-saline conditions, including the rapid induction of osmotic stress transcription factor and ubiquitin ligase (Fiol et al., 2006a; Fiol et al., 2006b; Fiol et al., 2011; Kültz et al., 2007). A previous study by Fiess et al. (2007) measured compatible osmolyte accumulation in multiple tissues of tilapia using high-performance liquid chromatography after acclimation to increased environmental salinity and temperature. The authors identified *myo*-inositol as a major osmolyte in tilapia brain and suggested that it may play a central role in responding to these environmental stressors (Fiess et al., 2007). However, the specific biochemical pathway utilized for the observed *myo*-inositol accumulation in tilapia brain in response to hyper-salinity has not yet been investigated. Interestingly, *myo*-inositol has also been demonstrated to be important for dietary health in cultured juvenile tilapia, suggesting that the implications of this compatible osmolyte go beyond osmotic regulation (Shiau and Su, 2005). For example, inositol derivatives are important for the structure of many second messengers and are also involved with multiple cell signaling events (Downes and Macphee, 1990; Michell, 2008).

To gain mechanistic insight into how tilapia brain cells respond to increases in environmental salinity, this study investigated the osmotic regulation of the MIB pathway in brain and its relationship to brain *myo*-inositol levels and key blood chemistry parameters, including plasma osmolality.

2. METHODS:

2.1. Animals:

Sub-adult Mozambique tilapia (*O. mossambicus*) weighing (57.7 ± 3.4g) were maintained in de-chlorinated freshwater at 25-27°C in 208L recirculating tanks at the UC Davis Cole B Animal Facility. The room was kept on a 12hr:12hr (light: dark) photoperiod and fish were fed daily with a commercial trout pellet diet (Silvercup SCD 2.0mm) at approximately 1% of fish body weight. All animal procedures used in this study were approved by the UC Davis Institution of Animal Care and Use Protocol #16604 and 16609.

2.2. Salinity Acclimations:

Acute: *O. mossambicus* were acclimated to 25 parts per thousand (ppt) with a single increase in salinity from freshwater conditions using Instant Ocean salt mix. This increment is approximately the maximum salinity tolerated during acute acclimation without showing signs of behavioral stress or mortality (Kammerer et al., 2010; Stickney, 1986). Three 76L tanks were used to repeat the 25ppt salinity treatment and two fish from each tank replicate (n=6 fish total) were randomly collected after 2, 4, 8, 16, and 24 hours. The whole brain was quickly harvested from each fish and snap-frozen in liquid nitrogen.

Chronic: *O. mossambicus* were acclimated to 7.5ppt/day increases in salinity using Instant Ocean salt mix. This increment of salinity increase was selected because behavioral stress and/or mortality was generally not observed (Gardell, unpublished observations). Daily salinity changes were made by quickly (~10 min) replacing 20% of the water with a hyperosmotic stock solution and the final salinity was validated using a calibrated YSI Model 85 (Yellow Springs, OH, USA) handheld dissolved oxygen, conductivity, salinity and temperature system. Three 76L replicate tanks were used to repeat salinity increases and fish (n=6) were sampled randomly after being held for 24 hours at each of the three salinity endpoints (30, 60, and 90ppt) following a 4, 8, and 12 day step-wise increment in salinity. Brain was quickly harvested from each fish and snap-frozen in liquid nitrogen.

Control: *O. mossambicus* for each of the three salinity endpoints were held at constant salinity (0.3ppt) in three 76L freshwater tank replicates. Control fish underwent identical water change procedures as described above in order to account for handling stress imposed during the acute and chronic salinity increases. All samples collected from fish (n=6 per time point) were kept at -80°C until analysis.

2.2. Blood chemistry analyses:

Fish (n=6 per time point and salinity treatment) were anesthetized using a moderate blow to the head and blood was collected immediately after via caudal severance using heparinized capillary tubes. Capillary tubes were kept at 4ºC and then centrifuged in a microhematocrit centrifuge (International Equipment Co., Needham, MA, USA) at 5,000*g for three minutes. Percent hematocrit was measured using a hematocrit reader and plasma was then separated from red blood cells. Plasma was stored at -80ºC until analyses.

Plasma osmolality (mOsm/kg) was measured on a vapor pressure osmometer (Wescor Vapro 5520, Logan, UT, USA). Sodium and potassium ion concentrations (mM) were measured on a flame photometer using lithium as the internal standard (Instrumentation Laboratory 343, Bedford, MA, USA). Chloride concentration (mM) was measured using a chloride titrator (Radiometer CMT10, Copenhagen, Denmark). Subsamples of blood plasma were run in technical duplicates and an average of the two values was reported.

2.3. mRNA Expression Assay:

Reaction conditions:

Quantitative real-time PCR (qRT-PCR) was performed in order to measure mRNA levels of MIPS alternative transcripts (MIPS-160, MIPS-250) and IMPA isoforms (IMPA1, IMPA2) as described previously by our laboratory (Fiol et al., 2006b; Sacchi et al., in review). Briefly, total RNA was extracted from tilapia brain samples from both acute and chronic acclimations using the RNeasy Kit (Qiagen, Hilden, Germany). RNA was then treated with Turbo DNA-free (Life Technologies, Grand Island, NY, USA) in order to remove any residual DNA contamination. Samples were incubated with an inactivation reagent according to the manufacturer's (Life Technologies, Grand Island, NY, USA) instructions in order to inactivate the DNase enzyme. Complementary DNA (cDNA) was then synthesized by reverse transcribing 2µg total RNA using Superscript III (Life Technologies, Grand Island, NY, USA) using a 1:1 mix of random hexamers and oligo(dT) as primers. Semi-quantitative PCR reactions were set up with tilapia specific primers using synthesized cDNA as template. PCR amplicons were run on a 2% agarose gel stained with GelRed (Biotium, Hayward, CA, USA) to confirm expected PCR product size for a given gene. In order to optimize qRT-PCR reaction conditions, a standard curve was run for each gene primer pair (Table 1) to determine proper dilutions of cDNA. For IMPA1, different dilutions of control (freshwater) and treated (salinity-exposed) cDNA were run in order to obtain C_t values within an acceptable working range (C_t = 18-32). Samples were run in

duplicate on a 96-well plate using Sybr Green (Life Technologies, Grand Island, NY, USA) as the method of detection. β-actin and 18S rRNA, which do not significantly change in response to hyperosmotic challenge in tilapia brain, were used as reference genes.

qRT-PCR Data Analysis:

Target C_t values for MIB enzymes were first normalized against the reference genes (β-actin and 18S rRNA) after correcting by efficiency using LinRegPCR software (Ruijter et al., 2009). C_t values were then converted to a fold change value using the Pfaffl method (Pfaffl, 2001). A dilution factor was applied to calculated fold changes in IMPA1 mRNA in order to account for differences in cDNA dilutions used for control and treated samples. Data presented are normalized against β-actin, however 18S rRNA produced similar results (data not shown).

2.4. *Myo*-inositol Quantitative Assay:

This method was established using Kindt et al. (2004) as a reference for optimization of extraction and liquid chromatography-tandem mass spectrometry (LC-MS/MS) procedures.

Tissue Extraction: First, frozen whole brain was quickly weighed and then placed in a 15ml glass mortar and pestle (Corning, Tewksbury, MA, USA). Tissue mass (~20-fold dilution, w/v) was homogenized in LC-MS/MS grade water (Thermo Fisher Scientific, Rockford, IL, USA) spiked with 9.3ng/ml d_6-*myo*-inositol at room temperature. The homogenate was then centrifuged at 4ºC at 10,000*g for five minutes and the liquid interface (excluding cell pellet and lipids) was removed. The interface was centrifuged again for five minutes at 10,000*g and homogenate was stored at -80ºC until analyses.

To prepare samples for downstream processing, tissue homogenates were first thawed slowly on ice and samples were centrifuged at 10,000*g. The supernatant was transferred to an Ultrafree Durapore PVDF 0.1µm centrifugal filter (EMD Millipore, Billerica, MA, USA) and centrifuged at 14,167*g at 4ºC for 15min. Flow through was then transferred to sterile LC-MS vials (Waters, Milford, MA, USA) which contained 150µl inserts (Waters, Milford, MA, USA).

LC-MS/MS Method Conditions: The concentrations of *myo*-inositol were measured using an Agilent 1200 SL (Santa Clara, CA) ultra-high performance liquid chromatography coupled with an AB Sciex 4000 QTRAP quadrouple-linear ion trap tandem mass spectrometer (Foster City, CA, USA) equipped with an electrospray source (Turbo V ®). The stationary phase was a Luna 5µm NH_2 150 x 2.0 mm column (Phenomenex, Torrance, CA, USA) and the mobile phase was 5mM ammonia acetate in 50% MeOH/water solution. An isocratic method was used with

0.2ml/min flow rate with an injection volume of 10µl. The column oven was set at 40ºC and the autosampler was kept at 4ºC. In order to establish the LC-MS/MS method, the standards of *myo*-inositol and d_6-*myo*-inositol were first infused into the mass spectrometer and MRM transitions and source parameters were optimized for each compound. Source parameters were then re-optimized under flow injection acquisition mode (infusion of analytes into the column eluent flow). The instrument was operated in negative MRM mode for analyzing samples and the final optimized mass spectrometric parameters are given in Table 2.

LC-MS/MS Data Analysis:

The concentrations were quantified according to the calibration solutions of *myo*-inositol (Sigma-Aldrich, St. Louis, MO, USA, >99% purity) ranging from 0.1 – 1000ng/ml using the Analyst 1.5.2 Software (AB Sciex, Foster City, CA, USA). The total concentration of *myo*-inositol in each tissue sample was calculated based off of the standard curve and converted to mg/ml. A standard curve of d_6-*myo*-inositol (Cambridge Isotope Laboratories, Inc., Tewksbury, MA, USA, 98% purity) at concentrations ranging from 0.745-93ng/ml was run in parallel with samples in order to determine percent recovery of the target analyte.

2.5. Statistical Analysis:

Analysis of variance (ANOVA) was performed separately on data obtained from the acute and chronic experiments using IBM SPSS software (v. 21, USA). Normality and homoscedasticity of variance were tested prior to ANOVA using Wilk-Shapiro and Levene tests, respectively. In some cases, data were logarithmically transformed, or occasionally, statistically significant outliers were removed in order to meet the assumption of normality. In order to determine if there was an effect of sampling time on control fish, a one-way ANOVA with time as a factor was performed for all freshwater samples ("handling controls") for every time point or salinity endpoint. If non-significance was determined (data not shown), all freshwater fish were grouped together in a zero time point. Since variance heteroscedasticity was generally observed in data sets, weighted least squares (WLS) were conducted by grouping samples by the factors of salinity and time (Draper and Smith, 1998; Hartmann et al., 1998; Sadray et al., 2003). A weight for each sample grouping was calculated by taking the inverse of the unstandardized residual variance per assigned group. Subsequently, a one-way WLS ANOVA was performed with time or salinity as a factor which compared salinity-treated groups to the combined freshwater control group (0hr). Post-hoc analyses were then conducted using Tukey's multiple comparison test to

determine differences between time points (acute acclimation) and salinity endpoints (chronic acclimation). Correlation analyses were also performed on MIB enzyme mRNA data and plasma osmolality for both chronic and acute data sets. In acute data sets, MIB enzyme mRNA data and plasma osmolality were log-transformed prior to performing the correlation analysis. Statistically significant correlations were identified using Pearson's correlation coefficient, however, due to heteroscedasticity in these data, a non-parametric Spearman correlation analysis was also performed. Slope differences between correlation lines were evaluated using a repeated measures analysis of covariance, identifying plasma osmolality as the covariate. The significance threshold of $p<0.05$ was set for all statistical tests.

3. RESULTS:

3.1. Hematocrit, plasma osmolality, Na^+, Cl^-, and K^+:

Percent hematocrit was significantly higher in treatment fish compared to freshwater control (0hr) at 2hr and 24hr. At 16hr, hematocrit levels in treated fish were lower than those in treated fish at 2hr and 24hr. (Fig. 1D). Percent hematocrit was not found to significantly change for the chronic salinity acclimation. Total blood plasma osmolality, Na^+, and Cl^- all showed similar patterns of regulation under acute and chronic acclimations. In the acute acclimation, salinity-treated fish had significantly higher blood plasma osmolality, Na^+, and Cl^- at 2, 4, 8, 16, and 24hrs compared to freshwater controls (0hr). These parameters all reached peak values (~460mOsm/kg, ~215mM Na^+ and Cl^-) at 16hr post acclimation and gradually tapered off to levels similar to 4-8hrs at 24hrs (Fig. 1A-C). In the chronic acclimation, a typical dose response was observed with regard to total osmolality and the plasma ions. The highest plasma osmolality, Na^+, and Cl^- (~475mOsm/kg, ~215mM Na^+ and Cl^-) concentrations were observed at 90ppt (Fig. 2A-C). Plasma K^+ concentration was not found to be significantly different from controls in acute and chronic acclimations (data not shown).

3.2. MIB pathway mRNA expression:

MIPS-160, MIPS-250, and IMPA1 mRNA abundances were significantly higher in acute hyperosmotic treatment groups versus the freshwater control at every time point tested (Fig. 3A-C). MIPS-160 alternative splice variant was generally expressed at a higher level (~2 times higher) than the MIPS-250 splice variant in the later time points in the acute acclimation (16, 24hr) or higher salinity endpoints for the chronic acclimation (Fig. 3A-B, Fig. 4A-B). IMPA1

mRNA abundance was much higher than that of IMPA2 in brain under both acute and chronic salinity acclimations (Fig. 3C, Fig. 4C). Under acute acclimation, IMPA1 mRNA peaked (~1500 fold relative to controls, $p<0.001$) at 16 hours, which is the same time MIPS-160 (~100 fold relative to controls, $p<0.001$) showed highest expression. IMPA1 was expressed at the highest level (~780 fold relative to controls, $p<0.001$) at the 90ppt salinity endpoint for the chronic experiment. The IMPA2 isoform remained relatively stable across treatments, but was significantly higher than controls at 8, 16, and 24hrs (acute, Fig. 3D) and 90ppt (chronic, Fig. 4D).

3.3 *Myo*-inositol levels:

Sample recovery was determined to be an average of ~50% across samples as determined with the internal standard d_6-*myo*-inositol. *Myo*-inositol concentrations were found to be the most significantly increased in later time points (24hr, $p<0.001$) following acute hyperosmotic challenge and trailing the mRNA induction of MIB enzymes (Fig. 5A). *Myo*-inositol concentration was also significantly higher ($p<0.001$) at all salinity endpoints in the chronic acclimation compared to the freshwater control (Fig. 5B). *Myo*-inositol was found to be more robustly regulated under chronic acclimation (especially 90ppt) compared to acute acclimation.

3.4. Correlation and slope analyses:

MIPS-160, MIPS-250, and IMPA1 mRNA relative abundances (salinity treated/ handling controls) were positively correlated ($p<0.01$, Pearson and Spearman) to blood plasma osmolality in both acute and chronic acclimation data sets (Fig. 6A-D). Generally, IMPA mRNA abundance changes showed a stronger correlation to blood plasma osmolality than MIPS splice variant mRNA abundance changes. Significant differences between the slopes of MIPS-160 and MIPS-250 correlation lines were observed under acute ($p<0.044$) and chronic ($p<0.017$) acclimations.

4. DISCUSSION:

The objective of this study was to gain deeper insight into how tilapia brain cells respond to acute and chronic hyperosmotic challenge. Specifically, we were interested in determining whether the MIB pathway is an important mechanism used by tilapia brain cells to accumulate the compatible osmolyte, *myo*-inositol, and secondly, to determine if blood plasma osmolality

changes precede and if brain *myo*-inositol levels follow salinity-induced changes in in MIB enzyme mRNA expression.

4.1. *Acute and chronic salinity acclimation alters blood plasma chemistry*

Salinity treatment had a clear effect on blood plasma chemistry. Plasma osmolality was found to be significantly increased under both acute and chronic salinity acclimations. Na^+ and Cl^- displayed the same overall pattern as plasma osmolality, suggesting that these two ions are key contributors to increased plasma osmolality. Under acute acclimation, ion concentrations and plasma osmolality were both highest at 16 hours. Similarly, Hwang et al. (1989) also detected peak values in inorganic ions and plasma osmolality before 24 hours after acute hyper-salinity acclimation of tilapia. Under chronic acclimation plasma osmolality, Na^+ and Cl^- were highest at the 90ppt salinity endpoint. Surprisingly, we found that plasma osmolality in chronic acclimation was maintained at elevated levels (~475mOsm/kg) for 24 hours without mortality. Sardella et al. (2004) reported that hybrid Mozambique 'hybrid' tilapia kept at 95ppt salinity for five days following transfer maintained an elevated plasma osmolality of ≥450mOsm/kg, which is indicative of osmoregulatory failure. In contrast, tilapia transferred to 60ppt salinity were able to return to lower plasma osmolality values following 24 hour exposure (Sardella et al., 2004). The current study and others clearly demonstrate that fish are able to tolerate much larger deviations from the plasma osmolality set point than their mammal counterparts (Evans and Claiborne, 2006). In mammalian systems, a blood plasma osmolality of only 15% above the baseline level will not be tolerated without significant damage to the central nervous system (Bourque and Oliet, 1997; Hall and Guyton, 2011; Seale et al., 2012b). In particular, elevated sodium concentration in the plasma above 160mM will cause hypernatremia in humans (Hall and Guyton, 2011)

Blood hematocrit was found to be significantly higher in salinity-treated fish compared to freshwater control fish during acute acclimation at 2 and 24 hour time points. This increase has not been previously documented in other work done in tilapia (Kammerer et al., 2010; Sardella et al., 2004). However, Kammerer et al. (2010) observed significantly increased opercular ventilation at 3 hours and a significant increase in respiration at 24 hours in tilapia that were acutely exposed to 25ppt salinity challenge. Increases in respiration rate may signal for increased production of red blood cells for delivery of oxygen to the tissues and could be related to the observed increase in hematocrit in this study. Our acute hematocrit data may also indicate

365 that tilapia could have experienced dehydration in response to the acute salinity challenge which
366 may have also resulted in decreased plasma volume. Under chronic acclimation, hematocrit is
367 likely more stable because fish have had time to adjust to the stressor and have overcome the
368 physiological crisis stage which occurs around 6-12 hours in tilapia (Hwang et al., 1989).

369 **4.2. *MIB enzymes in tilapia brain robustly respond to plasma osmolality***

370 This study has clearly demonstrated that the MIB pathway is a major component of the
371 biochemical response to hyperosmotic challenge in tilapia brain cells. We have shown that the
372 two MIB enzymes, MIPS (MIPS-160 and MIPS-250 alternative splice variants), and IMPA
373 (IMPA1 isoform) are robustly upregulated in tilapia brain at the mRNA level. The mRNA
374 abundance increase of IMPA1 was generally much higher than that of MIPS alternative
375 transcripts. This is surprising given the fact that the synthesis of *myo*-inositol phosphate from G-
376 6-P is the more rate limiting step of the MIB pathway (Majumder et al., 1997) but does agree
377 with other studies that compare the regulation of the two enzymes (Sacchi et al., in review).
378 Significant up- or down-regulation of IMPA1 mRNA under hyper- and hypo-osmotic challenge,
379 respectively, has been reported in other teleost fishes (Evans and Somero, 2008; Kalujnaia et al.,
380 2010; Whitehead et al., 2012). In leopard sharks, an osmoconforming species, inositol-related
381 proteins have also been reported to be regulated in rectal gland and gill tissues in response to
382 hypo-osmotic challenge (Dowd et al., 2010). Under acute acclimation, MIPS splice variants and
383 IMPA1 displayed peak induction around 16 hours, which closely corresponds with the highest
384 inorganic ion concentration (Na^+ and Cl^-) and plasma osmolality. Similarly, in the chronic state,
385 peak induction of MIB enzymes is at the highest salinity (90ppt), when inorganic ion (Na^+ and
386 Cl^-) concentrations and plasma osmolality were most significantly elevated. This agreement
387 between a key physiological stimulus (plasma osmolality) and MIB mRNA levels suggests
388 hyperosmotic blood plasma triggers transcriptional induction of MIB enzymes to alleviate the
389 damaging effects of hypertonicity.

390 The brain is an important tissue for systemic osmoregulation (Bourque, 2008; Seale et al.,
391 2012b; Sinke and Deen, 2011). The significant positive correlations observed between blood
392 plasma osmolality and MIB mRNA abundance observed in this study strongly suggest a role for
393 hyperosmotic blood plasma in prompting induction of the MIB pathway in tilapia brain.
394 Although ions are tightly regulated across the BBB, water can move more freely and rapidly
395 results in changes in intracranial extracellular osmolality. In fish, deviations in blood plasma

osmolality from the ~310-350mOsm/kg set point are likely detected by osmosensitive neurons and supporting glial cells in the extracellular fluid (Sinke and Deen, 2011). Some other aspects of the neuroendocrine response to osmotic challenge in tilapia, such as prolactin release, have also been reported to be stimulated under changing plasma osmolality (Seale et al., 2006). Interestingly, prolactin cells of freshwater acclimated tilapia are more sensitive to changes in osmolality than prolactin cells of saltwater acclimated fish (Seale et al., 2012b; Watanabe et al., 2012). The osmotic sensitivity of tilapia brain cells (neurons and glia) has not yet been investigated in response to changes in extracellular osmolality. It is also still unclear whether plasma osmolality or changes in particular ions trigger induction of MIB enzymes in brain. Some studies in mammals have suggested that osmoreceptor cells in the brain primarily respond to plasma tonicity rather than to total plasma osmolality (Bitoun and Tappaz, 2000; Verbalis and Gullans, 1991; Weber et al., 2004). The reported increase in plasma [Na^+] and [Cl^-] would lead to hypertonicity and, therefore, support such a scenario.

It is possible that tilapia brain cells indirectly respond to salinity challenge by inducing the MIB pathway in response to a second messenger (e.g., neurotransmitter), which binds to a brain cell membrane receptor. Osmotic homeostasis in fish is maintained by multiple osmosensors which activate neural and hormonal signals that are involved in regulating ion and water transport across osmoregulatory tissues (Kültz, 2012). These signaling events, which precede the induction of the MIB pathway in tilapia brain cells, are yet to be investigated in fish. In mammals, stretch-activated proteins are known to prompt vasopressin release which then acts on the kidney, driving increased thirst (Bourque et al., 2007). Tonicity response element binding protein has been shown to be responsive to hyperosmotic challenge (Woo et al., 2002) and may also serve a function in osmosensing signaling cascades in fish (Fiol and Kültz, 2007).

4.3. *Differential regulation of MIPS splice variants by environmental salinity*

In this study we found evidence for differential regulation of MIPS splice variants by environmental salinity. The MIPS-160 variant was found to more responsive to changes in plasma osmolality than the MIPS-250 variant in brain tissue under both acute and chronic salinity challenges. Similarly, prolactin (PRL) isoforms of tilapia, PRL177 and PRL 188, have been found to be differentially responsive to extracellular osmolality (Borski et al., 1992). Additionally, Seale et al. (2012a) found that transient receptor potential vanilloid 4, a member of the TRP channel family, is differentially regulated by plasma osmolality. These studies clearly

indicate that environmental selection pressure has allowed for diversification in the function and use of genetic elements used in osmoregulation and osmoreception in euryhaline tilapia.

Positive selection for various isoforms of IMPA and MIPS may have occurred differentially in various tissues of tilapia. Kalujnaia et al. (2013) studied the transcriptional and protein regulation of four IMPA isoforms in response to environmental salinity and found evidence for tissue-specific profiles in two euryhaline species, the European eel and Nile tilapia. In particular, the osmoregulatory tissues (gill, kidney, and intestine) showed the most robust regulation of IMPA isoforms (Kalujnaia et al., 2013) It is also possible that differential regulation of isoforms can occur during various stages of fish life history (Ayson et al., 1994). This may be particularly true for anadromous and catadromous fishes that live in very different osmotic environments during juvenile and adult stages, like salmon and eel.

4.4. *Myo-inositol stably accumulates in tilapia brain cells to offset hyperosmotic challenge*

We have demonstrated that *myo*-inositol content in tilapia brain cells is significantly upregulated under both acute and chronic salinity acclimations as quantified by LC-MS/MS. This salinity-induced effect is confirmed by other hyperosmotic challenge studies on mammalian systems (Heilig et al., 1989; Lien et al., 1990; Lohr et al., 1988) and in fish (Fiess et al., 2007). On a broader level, our *myo*-inositol data agree with the proposed role of osmolytes as molecules, which are used for compensating increased extracellular osmolality. Increasing or stable levels of *myo*-inositol in both acute and chronic experiments were observed, suggesting that this metabolite is accumulated and is not biochemically metabolized to produce cellular energy equivalents. A similar observation was made in rat brain exposed to acute and chronic hypernatremia (Lohr et al. 1988). The high stability of *myo*-inositol is quite surprising given that its structure is almost identical to that of glucose and further research is needed to explain its relatively inert nature

The teleost fish brain is separated from the systemic circulation by a BBB (Soengas and Aldegunde, 2002). Most of the energy consumed in the brain is used for maintaining ionic gradients which are essential for neural processing (Soengas and Aldegunde, 2002). Hyperosmotic challenge puts severe energetic demands on the organism and glucose is limited as it is needed to sustain essential cellular functions. It has been well documented that blood plasma and tissue (gill and fin) glucose levels become elevated in tilapia following hyperosmotic challenge and is likely due to mobilization of glycogen reserves, primarily from the liver (Fiess

et al., 2007; Kalujnaia et al., 2013). Chang et al. (2007) found that glycogen content in tilapia gill and liver significantly decreased after acute transfer to saltwater (25ppt). As mentioned earlier, the MIB pathway uses G-6-P as a substrate for the generation of *myo*-inositol. G-6-P normally enters the glycolytic pathway for aerobic respiration, which is necessary during times of stress. Since cells are heavily relying on intrinsic glucose reserves for supplying the MIB pathway with substrate, glucose must be taken up across the BBB. Under hypoglycemic conditions, glucose transporters are known to increase in the brain (Duelli et al., 1999; Kumagai et al., 1995; McCall et al., 1986). Additionally, glucose transporter activity has also been demonstrated to significantly increase in fish brain following salinity acclimation (Balmaceda-Aguilera et al., 2012). Sangiao-Alvarellos et al. (2003) found an increased use of exogenous glucose in brain after acclimation of gilthead sea bream to hyper-saline conditions. Our findings strongly suggest that the high demand for *myo*-inositol production in brain cells exposed to hyperosmotic challenge increases the requirements for glucose uptake across the BBB, however, specific glucose analyses would need to be conducted in order to support this hypothesis.

4.5. *Selective permeability of teleost BBB favors MIB pathway*

The BBB serves to provide a microenvironment for the brain while maintaining brain homeostasis and protection from toxic agents (Cserr and Bundgaard, 1984). The endothelial cells of the BBB form tight junctions which act as a seal to protect the brain (Abbott et al., 2010). The accumulation of *myo*-inositol in brain cells can occur through multiple mechanisms including both endogenous and exogenous biochemical pathways. Brain cells can endogenously produce *myo*-inositol via the MIB pathway or membrane phospholipid (phosphatidylinositol) recycling in the cell, or alternatively, exogenous *myo*-inositol can be brought into the cell through various plasma membrane cotransporters, such as sodium/*myo*-inositol cotransporter (SMIT) and hydrogen/*myo*-inositol transporter (HMIT) (Bitoun and Tappaz, 2000). Even though *myo*-inositol levels are much lower in the blood than in brain cells (Davson and Segal, 1996), mammalian cells have the ability to increase intracellular concentrations of *myo*-inositol from exogenous sources at high enough levels to counter damage from hyperosmotic stress (Handler and Kwon, 1993).

Our current data favor the MIB pathway over other *myo*-inositol accumulation pathways in teleost fish brain in response to hyperosmotic challenge. Previous studies have indicated that the MIB pathway is particularly important for those tissues which possess a blood barrier, like

testis and brain (Stein and Geiger, 2002). Moreover, no known reported literature has cited exogenous pathways as highly inducible under salinity challenge in the brain of fishes. In contrast, several studies on mammalian systems highlight the exogenous cotransporter pathways as a primary mechanism for intracellular *myo*-inositol accumulation (Fenili et al., 2011; Ibsen and Strange, 1996; Inoue et al., 1996) in brain. It is possible that mammalian systems have diverged in their preferred mechanism for *myo*-inositol accumulation in the cell. Future studies should quantify the relative contribution of MIB pathways versus cotransporter activity to overall *myo*-inositol accumulation in tilapia brain in order to determine the relative contribution of each pathway. These studies could be performed by systematic inhibition of the various MIB enzymes or cotransporters using pharmacological agents. In mammalian systems, SMIT and other pathways have been localized in the brain of mammalian systems, demonstrating specialization in various areas of the brain (Ibsen and Strange, 1996; Inoue et al., 1996) and also may reflect differences in permeability of the capillaries. This may also be the case for MIB enzyme activity, and future studies should localize the specific region(s) of tilapia brain that contribute to the observed high MIB induction.

The permeability of molecules across the BBB in fish has yet to be investigated. It is possible that the MIB pathway may be favored over the use of cotransporters in brain because of lower BBB permeability towards *myo*-inositol relative to glucose (Pasquali et al., 2010). Interestingly, in mammals, an increase in general permeability of the BBB can be induced by hyperosmotic challenge (Lu et al., 2004; Mackie et al., 1986; Wilhelm et al., 2008). The likely mechanism for this effect is temporary cell shrinkage which creates openings in the tight junctions between brain capillary endothelial cells (Davson and Segal, 1996). This effect has been applied in human patients with central nervous system disorders by simultaneous administration of hyperosmotic challenge (e.g., mannitol, urea) with drugs to increase BBB permeability and improve drug delivery to the brain (Dorovini-Zis et al., 1987). Increased uptake of glucose across the BBB to supply the MIB pathway and meet energetic demands is likely mediated by activation of specific glucose transporters versus a result of non-specific increases in BBB permeability. In future studies, sampling of cerebrospinal fluid for osmolality and ion measurements as well as determination of glucose transporter activity in the BBB could serve to elucidate the roles of BBB permeability changes and glucose transport for supplying the

large amount of substrate required by the MIB pathway during hyperosmotic challenge in euryhaline fish.

In summary, this study has clearly demonstrated that both enzymes of the MIB pathway are highly induced, which leads to extensive accumulation of *myo*-inositol in tilapia brain in response to acute and chronic salinity challenge. Based on its rapid and high level of accumulation *myo*-inositol appears to be a major compatible osmolyte that protects tilapia brain cells from hyperosmotic challenge. MIB pathway induction and *myo*-inositol accumulation are both preceded and presumably triggered by an increase in plasma osmolality and plasma inorganic ion concentration. In particular, the role of plasma Na^+ and Cl^- concentrations for regulating compatible osmolyte levels in brain cells of euryhaline fish merits further attention and represents a promising avenue for future research.

ACKNOWLEDGEMENTS:

The authors are grateful to Dr. Robert Kaufman for providing training and technical assistance on blood chemistry equipment. Dr. Neil Willits is also thanked for providing statistical consultation and useful advice on data analyses. This content is solely the responsibility of the authors and does not necessarily represent the official views of the National Science Foundation (NSF) or the National Institutes of Health (NIH).

FUNDING:

Funding for this study was primarily provided by NSF Grant IOS-1049780 (DK) and NIEHS Superfund Research Grant P42 ES004699 (BDH, DK). This research was partially supported by NIH and the National Institute of Diabetes and Digestive and Kidney Diseases (NIDDK) Grant U24 DK097154 (BDH) and through the West Coast Central Comprehensive Metabolomics Resource Core Grant WC3MRC (BDH). Additional support was provided by NIEHS/UC Davis Superfund for a Pre-doctoral Training Fellowship (AMG), a NIEHS/UC Davis Superfund Enrichment Activity Award (AMG), and a UC Davis Jastro-Shields Research Fellowship (AMG).

REFERENCES:

Abbott, N. J., Patabendige, A. A. K., Dolman, D. E. M., Yusof, S. R. and Begley, D. J. (2010). Structure and function of the blood–brain barrier. *Neurobiology of Disease* **37**, 13-25.

Ayson, F. G., Kaneko, T., Hasegawa, S. and Hirano, T. (1994). Differential expression of two prolactin and growth hormone genes during early development of tilapia (Oreochromis mossambicus) in fresh water and seawater: implications for possible involvement in osmoregulation during early life stages. *General and Comparative Endocrinology* **95**, 143-52.

Baldisserotto, B., Mancera Romero, J. M. and Kapoor, B. G. (2007). Fish Osmoregulation / editors, Bernardo Baldisserotto, Juan Miguel Mancera Romero, B.G. Kapoor: Science Publishers.

Balmaceda-Aguilera, C., Martos-Sitcha, J. A., Mancera, J. M. and Martínez-Rodríguez, G. (2012). Cloning and expression pattern of facilitative glucose transporter 1 (GLUT1) in gilthead sea bream Sparus aurata in response to salinity acclimation. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* **163**, 38-46.

Bernier, N. J. (2009). Fish neuroendocrinology / edited by Nicholas J. Bernier ... [et al.]: Elsevier/Academic Press.

Bitoun, M. and Tappaz, M. (2000). Gene expression of taurine transporter and taurine biosynthetic enzymes in brain of rats with acute or chronic hyperosmotic plasma. A comparative study with gene expression of myo-inositol transporter, betaine transporter and sorbitol biosynthetic enzyme. *Molecular Brain Research* **77**, 10-18.

Borski, R. J., Hansen, M. U., Nishioka, R. S. and Grau, E. G. (1992). Differential processing of the two prolactins of the tilapia (Oreochromis mossambicus) in relation to environmental salinity. *Journal of Experimental Zoology* **264**, 46-54.

Bourque, C. W. (2008). Central mechanisms of osmosensation and systemic osmoregulation. *Nature Reviews-Neuroscience* **9**, 519-31.

Bourque, C. W., Ciura, S., Trudel, E., Stachniak, T. J. and Sharif-Naeini, R. (2007). Neurophysiological characterization of mammalian osmosensitive neurones. *Exp Physiol* **92**, 499-505.

Bourque, C. W. and Oliet, S. H. (1997). Osmoreceptors in the central nervous system. *Annu Rev Physiol* **59**, 601-19.

Burg, M. B. and Ferraris, J. D. (2008). Intracellular organic osmolytes: Function and regulation. *Journal of Biological Chemistry* **283**, 7309-7313.

Burg, M. B., Ferraris, J. D. and Dmitrieva, N. I. (2007). Cellular response to hyperosmotic stresses. *Physiological Reviews* **87**, 1441-1474.

Chang, J. C., Wu, S. M., Tseng, Y. C., Lee, Y. C., Baba, O. and Hwang, P. P. (2007). Regulation of glycogen metabolism in gills and liver of the euryhaline tilapia (Oreochromis mossambicus) during acclimation to seawater. *Journal of Experimental Biology* **210**, 3494-504.

Chara, O., Espelt, M. V., Krumschnabel, G. and Schwarzbaum, P. J. (2011). Regulatory volume decrease and P receptor signaling in fish cells: mechanisms, physiology, and modeling approaches. *J Exp Zool A Ecol Genet Physiol* **315**, 175-202.

Cserr, H. F. and Bundgaard, M. (1984). Blood-brain interfaces in vertebrates: a comparative approach. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* **246**, R277-88.

Davson, H. and Segal, M. B. (1996). Physiology of the CSF and blood-brain barriers. Boca Raton [etc.]: CRC Press.

Dorovini-Zis, K., Bowman, P. D., Betz, A. L. and Goldstein, G. W. (1987). Hyperosmotic urea reversibly opens the tight junctions between brain capillary endothelial cells in cell culture. *J Neuropathol Exp Neurol* **46**, 130-40.

Dowd, W. W., Harris, B. N., Cech, J. J., Jr. and Kültz, D. (2010). Proteomic and physiological responses of leopard sharks (*Triakis semifasciata*) to salinity change. *Journal of Experimental Biology* **213**, 210-224.

Downes, C. P. and Macphee, C. H. (1990). myo-inositol metabolites as cellular signals. *Eur J Biochem* **193**, 1-18.

Draper, N. R. and Smith, H. (1998). Applied regression analysis / Norman R. Draper, Harry Smith: Wiley.

Duelli, R., Staudt, R., Duembgen, L. and Kuschinsky, W. (1999). Increase in glucose transporter densities of Glut3 and decrease of glucose utilization in rat brain after one week of hypoglycemia. *Brain Res* **831**, 254-62.

Evans, D. H. and Claiborne, J. B. (2006). The physiology of fishes / edited by David H. Evans, James B. Claiborne: CRC/Taylor & Francis.

Evans, T. G. and Somero, G. N. (2008). A microarray-based transcriptomic time-course of hyper- and hypo-osmotic stress signaling events in the euryhaline fish Gillichthys mirabilis: osmosensors to effectors. *Journal of Experimental Biology* **211**, 3636-49.

Fenili, D., Weng, Y.-Q., Aubert, I., Nitz, M. and McLaurin, J. (2011). Sodium/*myo*-Inositol Transporters: Substrate Transport Requirements and Regional Brain Expression in the TgCRND8 Mouse Model of Amyloid Pathology. *PLoS ONE* **6**, e24032.

Fiess, J. C., Kunkel-Patterson, A., Mathias, L., Riley, L. G., Yancey, P. H., Hirano, T. and Grau, F. G. (2007). Effects of environmental salinity and temperature on osmoregulatory ability, organic osmolytes, and plasma hormone profiles in the Mozambique tilapia (Oreochromis mossambicus). *Comparative Biochemistry and Physiology Part A Molecular & Integrative Physiology* **146**, 252-264.

Fiol, D. F., Chan, S. Y. and Kueltz, D. (2006a). Regulation of osmotic stress transcription factor 1 (Ostf1) in tilapia (Oreochromis mossambicus) gill epithelium during salinity stress. *Journal of Experimental Biology* **209**, 3257-3265.

Fiol, D. F., Chan, S. Y. and Kültz, D. (2006b). Identification and pathway analysis of immediate hyperosmotic stress responsive molecular mechanisms in tilapia (Oreochromis mossambicus) gill. *Comparative Biochemistry and Physiology Part D Genomics & Proteomics* **1**, 344-356.

Fiol, D. F. and Kültz, D. (2007). Osmotic stress sensing and signaling in fishes. *FEBS J* **274**, 5790-8.

Fiol, D. F., Sanmarti, E., Lim, A. H. and Kültz, D. (2011). A novel GRAIL E3 ubiquitin ligase promotes environmental salinity tolerance in euryhaline tilapia. *Biochimica et Biophysica Acta* **1810**, 439-445.

Geiger, J. H. and Jin, X. (2006). The structure and mechanism of myo-inositol 1-phosphate synthase. In *Subcellular Biochemistry*, eds. A. L. Majumder and B. B. Biswas), pp. 157-180.

Hall, J. E. and Guyton, A. C. (2011). Guyton and Hall Textbook Of Medical Physiology / John E. Hall: Saunders/Elsevier.

Handler, J. S. and Kwon, H. M. (1993). Regulation of renal cell organic osmolyte transport by tonicity. *The American Journal of Physiology-Cell Physiology* **265**, C1449-55.

Hartmann, C., Smeyers-Verbeke, J., Massart, D. L. and McDowall, R. D. (1998). Validation of bioanalytical chromatographic methods. *Journal of Pharmaceutical and Biomedical Analysis* **17**, 193-218.

Hasegawa, R. and Eisenberg, F., Jr. (1981). Selective hormonal control of myo-inositol biosynthesis in reproductive organs and liver of the male rat. *Proc Natl Acad Sci U S A* **78**, 4863-6.

Heilig, C. W., Stromski, M. E., Blumenfeld, J. D., Lee, J. P. and Gullans, S. R. (1989). Characterization of the major brain osmolytes that accumulate in salt-loaded rats. *American Journal of Physiology-Renal Physiology* **257**, F1108-F1116.

Hochachka, P. W. and Somero, G. N. (2002). Biochemical Adaptation: Mechanism and Process in Physiological Evolution. New York, NY: Oxford University Press.

Hoffmann, E. K., Lambert, I. H. and Pedersen, S. F. (2009). Physiology of cell volume regulation in vertebrates. *Physiol Rev* **89**, 193-277.

Hwang, P. P., Sun, C. M. and Wu, S. M. (1989). Changes of plasma osmolality, chloride concentration and gill Na−K-ATPase activity in tilapia Oreochromis mossambicus during seawater acclimation. *Marine Biology* **100**, 295-299.

Ibsen, L. and Strange, K. (1996). In situ localization and osmotic regulation of the Na+-myo-inositol cotransporter in rat brain. *American Journal of Physiology-Renal Physiology* **271**, F877-F885.

Inoue, K., Shimada, S., Minami, Y., Morimura, H., Miyai, A., Yamauchi, A. and Tohyama, M. (1996). Cellular localization of Na+/MYO-inositol cotransporter mRNA in the rat brain. *Neuroreport* **7**, 1195-1198.

Kalujnaia, S., Gellatly, S. A., Hazon, N., Villasenor, A., Yancey, P. H. and Cramb, G. (2013). Seawater acclimation and inositol monophosphatase (IMPA) isoform expression in the European eel (Anguilla anguilla) and Nile tilapia (Oreochromis niloticus). *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* **305**, R369-84.

Kalujnaia, S., McVee, J., Kasciukovic, T., Stewart, A. J. and Cramb, G. (2010). A role for inositol monophosphatase 1 (IMPA1) in salinity adaptation in the euryhaline eel (Anguilla anguilla). *FASEB Journal* **24**, 3981-3991.

Kalujnaia, S., Osborne, C. J. and Cramb, G. (2009). Osmolytes and osmoregulation in the euryhaline European eel, Anguilla anguilla. *Comparative Biochemistry and Physiology Part A Molecular & Integrative Physiology* **153A**, S81.

Kammerer, B. D., Cech, J. J., Jr. and Kültz, D. (2010). Rapid changes in plasma cortisol, osmolality, and respiration in response to salinity stress in tilapia (Oreochromis mossambicus). *Comparative Biochemistry and Physiology Part A Molecular & Integrative Physiology* **157**, 260-265.

Kindt, E., Shum, Y., Badura, L., Snyder, P. J., Brant, A., Fountain, S. and Szekely-Klepser, G. (2004). Development and Validation of an LC/MS/MS Procedure for the Quantification of Endogenous myo-Inositol Concentrations in Rat Brain Tissue Homogenates. *Analytical Chemistry* **76**, 4901-4908.

Kültz, D. (2012). The combinatorial nature of osmosensing in fishes. *Physiology (Bethesda)* **27**, 259-75.

Kültz, D., Fiol, D., Valkova, N., Gomez-Jimenez, S., Chan, S. Y. and Lee, J. (2007). Functional genomics and proteomics of the cellular osmotic stress response in 'non-model' organisms. *Journal of Experimental Biology* **210**, 1593-1601.

Kumagai, A. K., Kang, Y. S., Boado, R. J. and Pardridge, W. M. (1995). Upregulation of blood-brain barrier GLUT1 glucose transporter protein and mRNA in experimental chronic hypoglycemia. *Diabetes* **44**, 1399-404.

Lang, F., Busch, G. l., Ritter, M., Völkl, H., Waldegger, S., Gulbins, E. and Häussinger, D. (1998). Functional Significance of Cell Volume Regulatory Mechanisms. *Physiological Reviews* **78**, 247-306.

Law, R. O. (1994). Regulation of mammalian brain cell volume. *Journal of Experimental Zoology* **268**, 90-96.

Lien, Y. H., Shapiro, J. I. and Chan, L. (1990). Effects of hypernatremia on organic brain osmoles. *J Clin Invest* **85**, 1427-35.

Lohr, J. W., McReynolds, J., Grimaldi, T. and Acara, M. (1988). Effect of acute and chronic hypernatremia on myoinositol and sorbitol concentration in rat brain and kidney. *Life Sci* **43**, 271-6.

Lu, T. S., Chen, H. W., Huang, M. H., Wang, S. J. and Yang, R. C. (2004). Heat shock treatment protects osmotic stress-induced dysfunction of the blood-brain barrier through preservation of tight junction proteins. *Cell Stress Chaperones* **9**, 369-77.

Mackie, K., Depasquale, M. and Cserr, H. F. (1986). Increased Permeability Of A Glial Blood-Brain Barrier During Acute Hyperosmotic Stress. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* **251**, R1186-R1192.

Majumder, A. L., Johnson, M. D. and Henry, S. A. (1997). 1-myo-Inositol-1-phosphate synthase. *Biochimica et Biophysica Acta (BBA) - Lipids and Lipid Metabolism* **1348**, 245-256.

Manzon, L. A. (2002). The role of prolactin in fish osmoregulation: A review. *General and Comparative Endocrinology* **125**, 291-310.

McCall, A. L., Fixman, L. B., Fleming, N., Tornheim, K., Chick, W. and Ruderman, N. B. (1986). Chronic hypoglycemia increases brain glucose transport. *American Journal of Physiology-Endocrinology and Metabolism* **251**, E442-7.

Michell, R. H. (2008). Inositol derivatives: evolution and functions. *Nat Rev Mol Cell Biol* **9**, 151-61.

Ohnishi, T., Ohba, H., Seo, K. C., Im, J., Sato, Y., Iwayama, Y., Furuichi, T., Chung, S. K. and Yoshikawa, T. (2007). Spatial expression patterns and biochemical properties distinguish a second myo-inositol monophosphatase IMPA2 from IMPA1. *Journal of Biological Chemistry* **282**, 637-46.

Parthasarathy, L. K., Seelan, R. S., Tobias, C., Casanova, M. F. and Parthasarathy, R. N. (2006). Mammalian inositol 3-phosphate synthase: its role in the biosynthesis of brain inositol and its clinical use as a psychoactive agent. *Subcell Biochem* **39**, 293-314.

Pasquali, L., Busceti, C. L., Fulceri, F., Paparelli, A. and Fornai, F. (2010). Intracellular pathways underlying the effects of lithium. *Behavioural Pharmacology* **21**, 473-492.

Pfaffl, M. W. (2001). A new mathematical model for relative quantification in real-time RT-PCR. *Nucleic Acids Res* **29**, e45.

Richards, J. G., Semple, J. W., Bystriansky, J. S. and Schulte, P. M. (2003). Na+/K+-ATPase alpha-isoform switching in gills of rainbow trout (Oncorhynchus mykiss) during salinity transfer. *Journal of Experimental Biology* **206**, 4475-86.

Ruijter, J. M., Ramakers, C., Hoogaars, W. M., Karlen, Y., Bakker, O., van den Hoff, M. J. and Moorman, A. F. (2009). Amplification efficiency: linking baseline and bias in the analysis of quantitative PCR data. *Nucleic Acids Res* **37**, e45.

Sacchi, R., Li, J., Villareal, F., Gardell, A. M. and Kültz, D. (in review). Salinity-induced activation of the *myo*-inositol biosynthesis pathway in tilapia gill epithelium. *Journal of Experimental Biology*.

Sadray, S., Rezaee, S. and Rezakhah, S. (2003). Non-linear heteroscedastic regression model for determination of methotrexate in human plasma by high-performance liquid chromatography. *Journal of Chromatography B* **787**, 293-302.

Sangiao-Alvarellos, S., Laiz-Carrion, R., Guzman, J. M., Martin del Rio, M. P., Miguez, J. M., Mancera, J. M. and Soengas, J. L. (2003). Acclimation of S aurata to various salinities alters energy metabolism of osmoregulatory and nonosmoregulatory organs. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* **285**, R897-907.

Sardella, B. A., Matey, V., Cooper, J., Gonzalez, R. J. and Brauner, C. J. (2004). Physiological, biochemical and morphological indicators of osmoregulatory stress in 'California' Mozambique tilapia (Oreochromis mossambicus x O. urolepis hornorum) exposed to hypersaline water. *Journal of Experimental Biology* **207**, 1399-1413.

Schulte, P. M. (2004). Changes in gene expression as biochemical adaptations to environmental change: a tribute to Peter Hochachka. *Comparative Biochemistry and Physiology Part B Biochemistry & Molecular Biology* **139**, 519-529.

Seale, A. P., Fiess, J. C., Hirano, T., Cooke, I. M. and Grau, E. G. (2006). Disparate release of prolactin and growth hormone from the tilapia pituitary in response to osmotic stimulation. *General and Comparative Endocrinology* **145**, 222-31.

Seale, A. P., Hirano, T. and Grau, E. G. (2005). Stimulus-Secretion Coupling in the Osmoreceptive Prolactin Cell of the Tilapia. In *Mechanosensitivity in Cells and Tissues*, eds. A. Kamkin and I. Kiseleva). Moscow: Academia Publishing House Ltd.

Seale, A. P., Itoh, T., Moriyama, S., Takahashi, A., Kawauchi, H., Sakamoto, T., Fujimoto, M., Riley, L. G., Hirano, T. and Grau, E. G. (2002). Isolation and characterization of a homologue of mammalian prolactin-releasing peptide from the tilapia brain and its effect on prolactin release from the tilapia pituitary. *General and Comparative Endocrinology* **125**, 328-339.

Seale, A. P., Richman, N. H., 3rd, Hirano, T., Cooke, I. and Grau, E. G. (2003). Cell volume increase and extracellular Ca2+ are needed for hyposmotically induced prolactin release in tilapia. *American Journal of Physiology-Cell Physiology* **284**, C1280-9.

Seale, A. P., Watanabe, S., Breves, J. P., Lerner, D. T., Kaneko, T. and Gordon Grau, E. (2012a). Differential regulation of TRPV4 mRNA levels by acclimation salinity and extracellular osmolality in euryhaline tilapia. *General and Comparative Endocrinology* **178**, 123-130.

Seale, A. P., Watanabe, S. and Grau, E. G. (2012b). Osmoreception: perspectives on signal transduction and environmental modulation. *General and Comparative Endocrinology* **176**, 354-60.

Seelan, R. S., Lakshmanan, J., Casanova, M. F. and Parthasarathy, R. N. (2009). Identification of myo-inositol-3-phosphate synthase isoforms characterization, expression, and putative role of a 16-kda gamma(c) isoform. *Journal of Biological Chemistry* **284**, 9443-9457.

Shamir, A., Sjoholt, G., Ebstein, R. P., Agam, G. and Steen, V. M. (2001). Characterization of two genes, Impa1 and Impa2 encoding mouse myo-inositol monophosphatases. *Gene* **271**, 285-91.

Shiau, S.-Y. and Su, S.-L. (2005). Juvenile tilapia (Oreochromis niloticus x Oreochromis aureus) requires dietary myo-inositol for maximal growth. *Aquaculture* **243**, 273-277.

Sinke, A. P. and Deen, P. M. (2011). The physiological implication of novel proteins in systemic osmoregulation. *FASEB J* **25**, 3279-89.

Soengas, J. L. and Aldegunde, M. (2002). Energy metabolism of fish brain. *Comparative Biochemistry and Physiology B-Biochemistry & Molecular Biology* **131**, 271-96.

Stein, A. J. and Geiger, J. H. (2002). The crystal structure and mechanism of 1-L-myo-inositol-1-phosphate synthase. *Journal of Biological Chemistry* **277**, 9484-9491.

Stickney, R. R. (1986). Tilapia Tolerance of Saline Waters: A Review. *The Progressive Fish-Culturist* **48**, 161-167.

Strange, K. (1992). Regulation of solute and water balance and cell volume in the central nervous system. *Journal of the American Society of Nephrology* **3**, 12-27.

Strange, K., Morrison, R., Heilig, C. W., Dipietro, S. and Gullans, S. R. (1991). Upregulation of inositol transport mediates inositol accumulation in hyperosmolar brain cells. *American Journal of Physiology-Cell Physiology* **260**, C784-C790.

Verbalis, J. G. and Gullans, S. R. (1991). Hyponatremia causes large sustained reductions in brain content of multiple organic osmolytes in rats. *Brain Res* **567**, 274-282.

Watanabe, S., Seale, A. P., Grau, E. G. and Kaneko, T. (2012). Stretch-activated cation channel TRPV4 mediates hyposmotically induced prolactin release from prolactin cells of mozambique tilapia Oreochromis mossambicus. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* **302**, R1004-11.

Weber, G. M., Seale, A. P., Richman, I. N., Stetson, M. H., Hirano, T. and Grau, E. G. (2004). Hormone release is tied to changes in cell size in the osmoreceptive prolactin cell of a euryhaline teleost fish, the tilapia, Oreochromis mossambicus. *General and Comparative Endocrinology* **138**, 8-13.

Wehner, F., Olsen, H., Tinel, H., Kinne-Saffran, E. and Kinne, R. K. (2003). Cell volume regulation: osmolytes, osmolyte transport, and signal transduction. *Rev Physiol Biochem Pharmacol* **148**, 1-80.

Whitehead, A., Roach, J. L., Zhang, S. and Galvez, F. (2012). Salinity- and population-dependent genome regulatory response during osmotic acclimation in the killifish (Fundulus heteroclitus) gill. *Journal of Experimental Biology* **215**, 1293-305.

Wilhelm, I., Nagyőszi, P., Farkas, A. E., Couraud, P.-O., Romero, I. A., Weksler, B., Fazakas, C., Dung, N. T. K., Bottka, S., Bauer, H. et al. (2008). Hyperosmotic stress induces Axl activation and cleavage in cerebral endothelial cells. *Journal of Neurochemistry* **107**, 116-126.

Woo, S. K., Lee, S. D., Na, K. Y., Park, W. K. and Kwon, H. M. (2002). TonEBP/NFAT5 stimulates transcription of HSP70 in response to hypertonicity. *Mol Cell Biol* **22**, 5753-60.

Yancey, P. H., Clark, M. E., Hand, S. C., Bowlus, R. D. and Somero, G. N. (1982). Living with water stress: evolution of osmolyte systems. *Science* **217**, 1214-22.

Table 1. Primers and cDNA dilutions of control (con) and treated (trt) samples used for qRT-PCR.

Gene	Forward (5' to 3')	Reverse (5' to 3')	Product Size (bp)	Accession Number	cDNA Dilution (con;trt)
MIPS-160	CAGAGTCGCGCAGACAATGT	CGTTGACCCCTGGGATGATA	164 and 251	DQ465381	1:9
MIPS-250	GTGCATGATCTTCCAGATGGAGCG	AGAAGCGCTCGGTGTTGGCG	110	Sacchi et al., in review	1:9
IMPA1	CGAAACTCTCCTAAGCAAGCCCCC	CCAGCTTTCCTAATTTCCGCGCCA	114	JQ943581	1:1; 1:9
IMPA2	TACCAGAATCCTCTTCTTGGCCACACC	ACCAGGACACTGATGCACAGCTA	121	XM_003439148	1:1
β-actin	CCACAGCCGAGAGGGAAAT	CCCATCTCCTGCTCGAAGT	104	AB037865	1:9
18S rRNA	CGATGCTCTTAGCTGAGTGT	ACGACGGTATCTGATCGTCT	260	AF497908	1:729

Table 2. Mass spectrometer parameter settings for analyte of interest, *myo*-inositol, and internal standard (d_6-*myo*-inositol) used in LC-MS/MS quantitative assay. Q1and Q3 represent the first and third quadrupole, respectively.

	Q1	Q3	Collision Energy (eV)
***myo*-inositol**	178.5	86.7	-24
d_6-*myo*-inositol	185.3	88.9	-24

FIGURE LEGENDS:

Figure 1 (A-D). Means ± SEM (n= 5-6) for blood plasma osmolality (A), sodium concentration (B), chloride concentration (C), and percent hematocrit (D) after acute acclimation to 25ppt salinity. Different letters indicate significant differences between groups evaluated by post-hoc Tukey HSD test ($p<0.05$) following a WLS ANOVA.

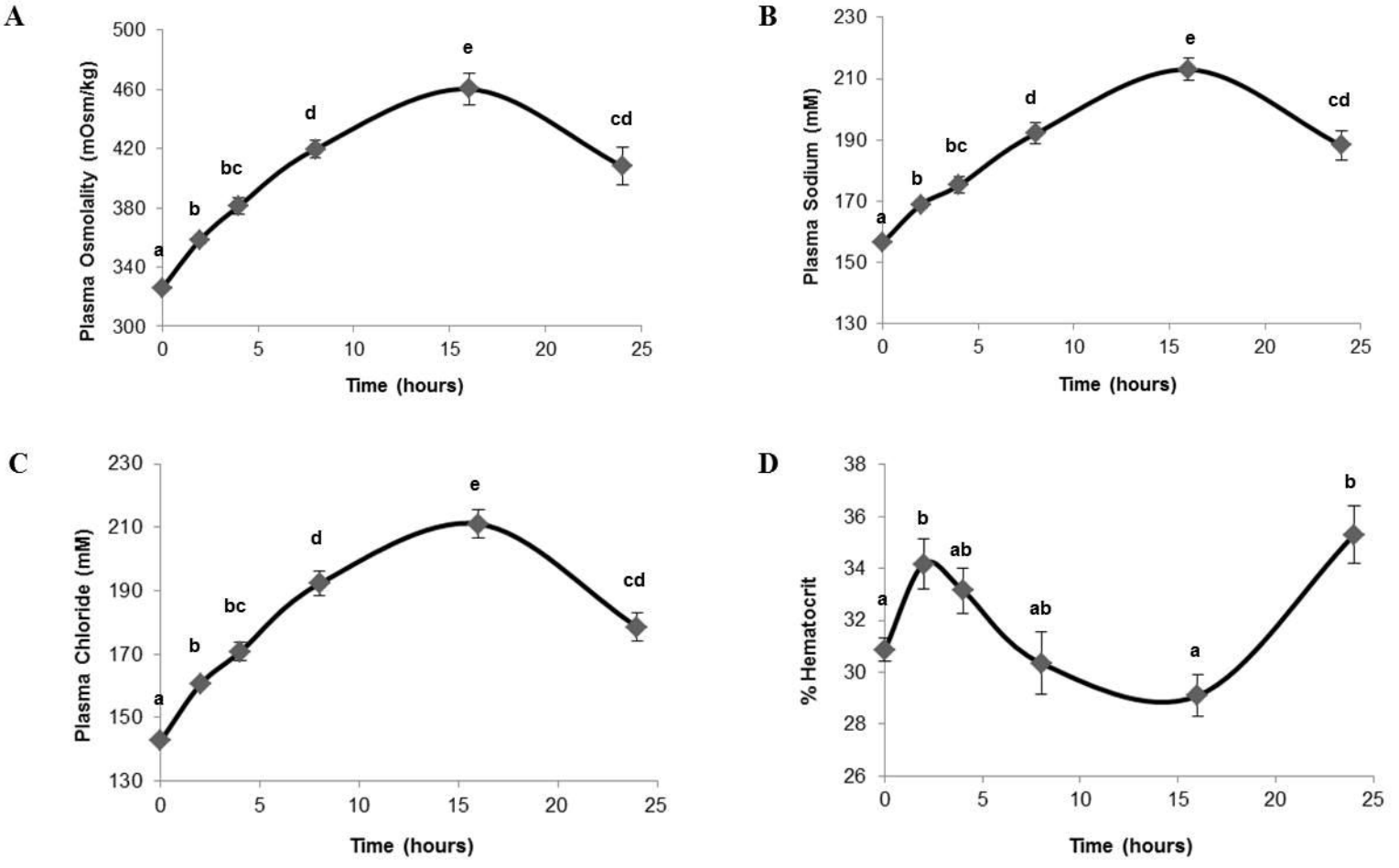
Figure 2 (A-D). Means ± SEM (n=5-6) of blood plasma osmolality (A) sodium concentration (B), chloride concentration (C), and percent hematocrit (D) following chronic acclimation to 30, 60, 90ppt treatments. Different letters indicate significant differences between groups evaluated by post-hoc Tukey HSD test ($p<0.05$) following a WLS ANOVA.

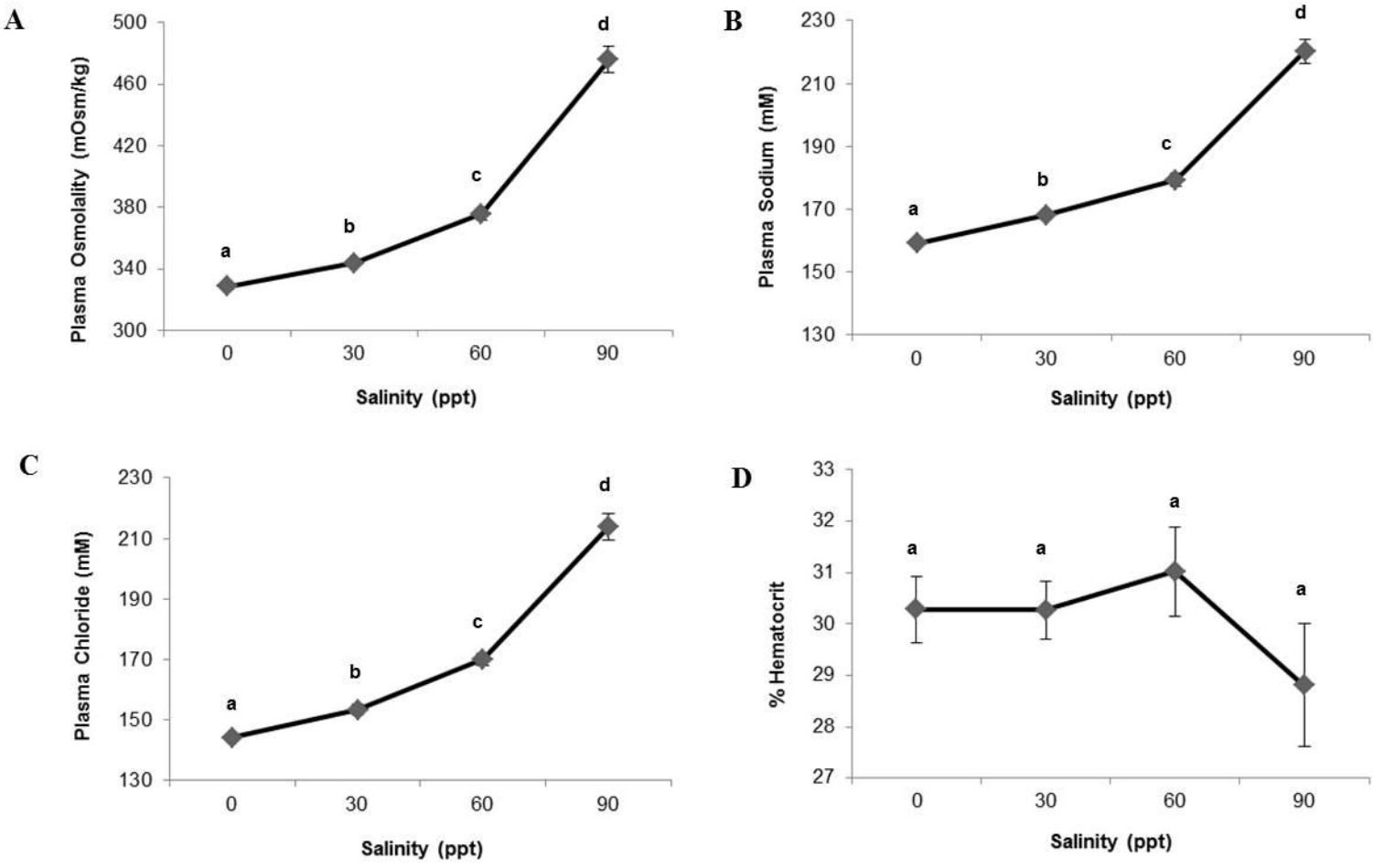
Figure 3 (**A-D).** Means ± SEM (n=5-6) for MIPS-160 (A), MIPS-250 (B), IMPA1 (C), and IMPA2 (D) mRNA abundances following acute acclimation to 25ppt at 0, 2, 4, 8, 16, and 24 hours. Different letters indicate significant differences between groups evaluated by post-hoc Tukey HSD test ($p<0.05$) following a WLS ANOVA.

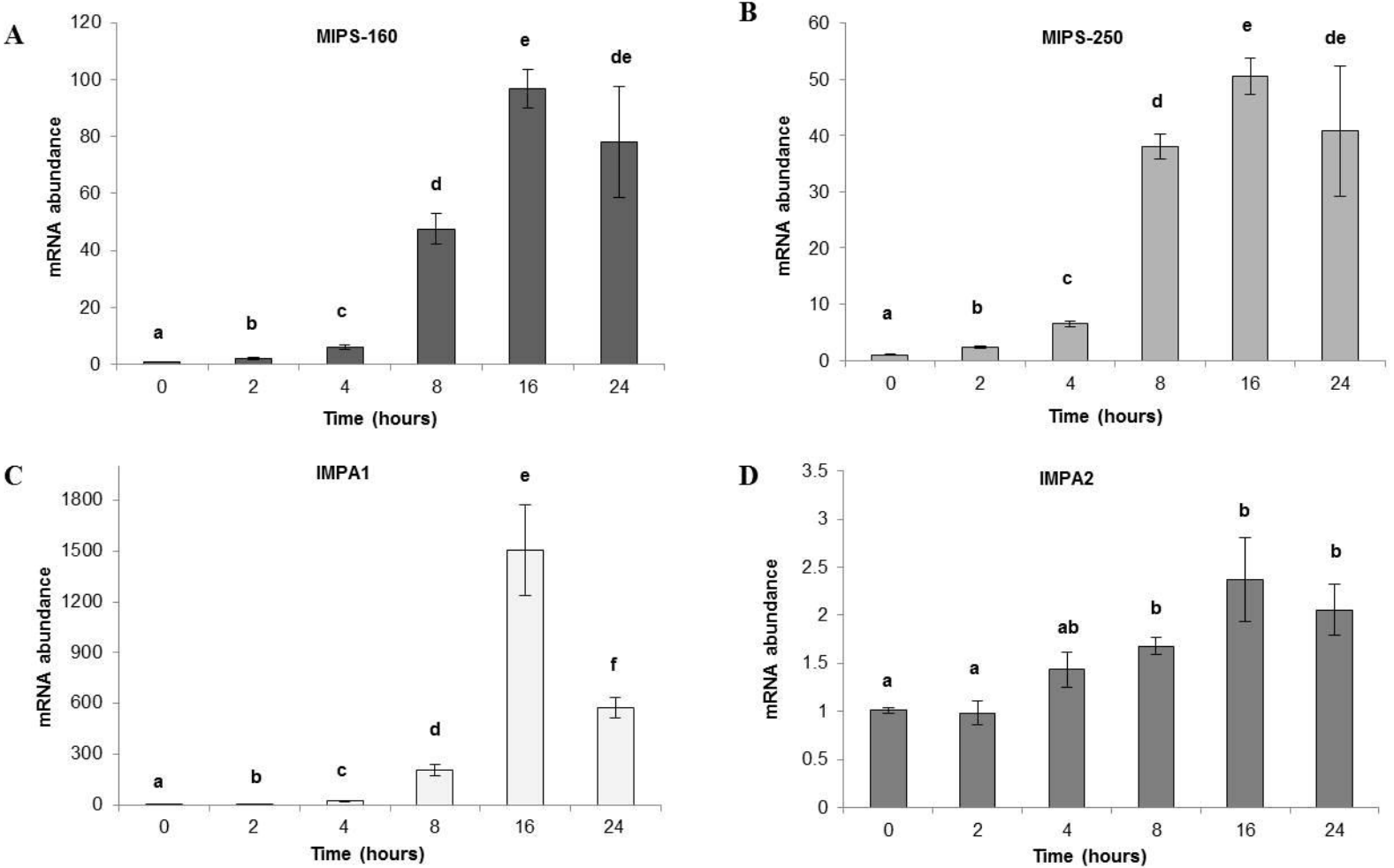
Figure 4 (**A-D).** Means ± SEM (n=5-6) for MIPS-160 (A), MIPS-250 (B), IMPA1 (C), and IMPA2 (D) mRNA abundances following chronic acclimation to 30, 60, and 90ppt. Different letters indicate significant differences between groups evaluated by post-hoc Tukey HSD test ($p<0.05$) following a WLS ANOVA.

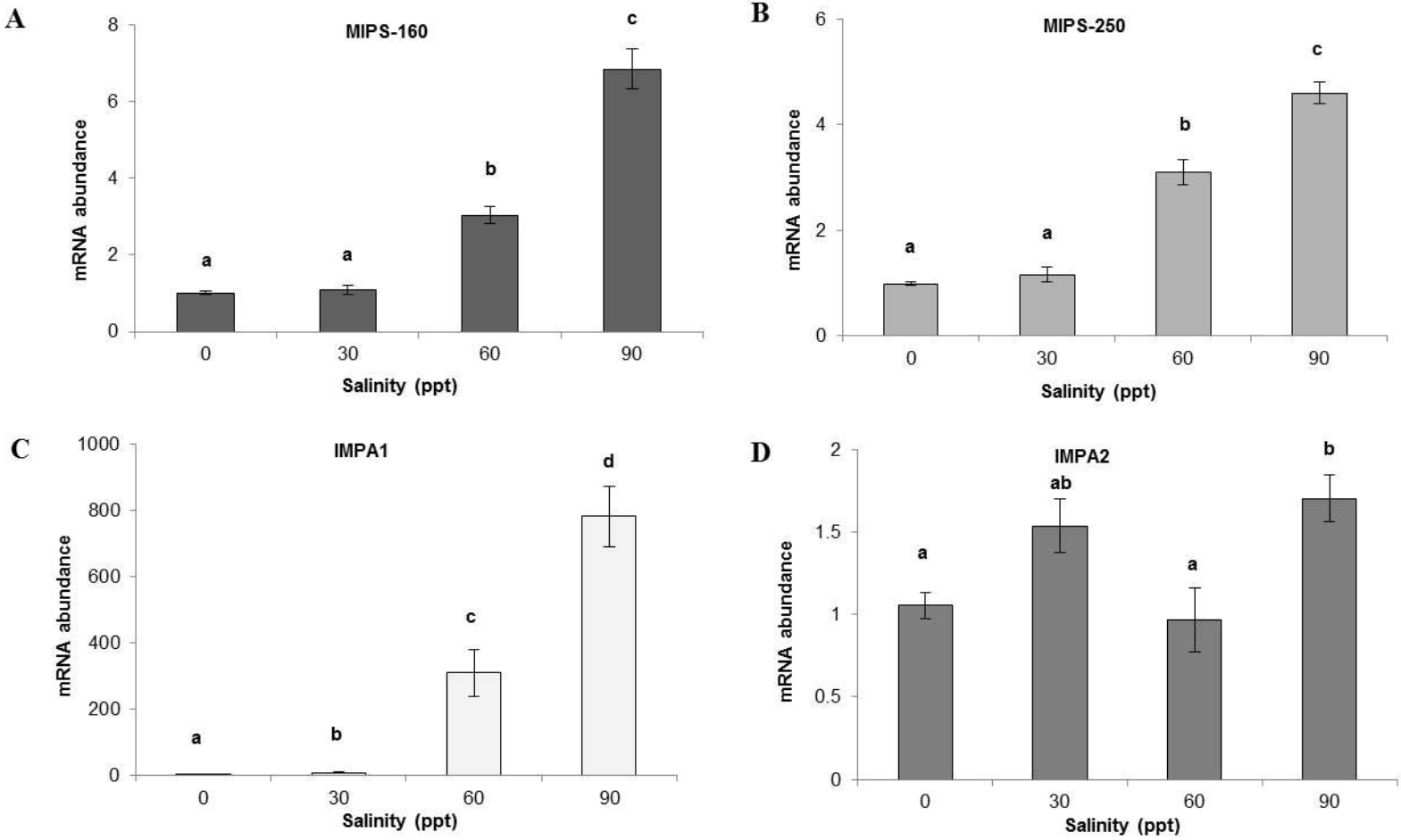
Figure 5 (A-B). Means ± SEM (n=6-7) *myo*-inositol concentration (mg/ml) in *O. mossambicus* whole brain homogenate after acute (A) and chronic (B) salinity acclimation detected using LC-MS/MS. Acute acclimation of fish involved a one-step increase to 25ppt salinity and collection of brain after 4, 8, 16, and 24 hours. Fish in the chronic exposure received 7.5ppt increases in salinity/day and brain was collected at the final salinities of 30 and 60ppt following 24 hours and at 90ppt salinity following 24 and 48 hours. Different letters indicate significant differences between groups evaluated by post-hoc Tukey HSD test ($p<0.05$) following a WLS ANOVA.

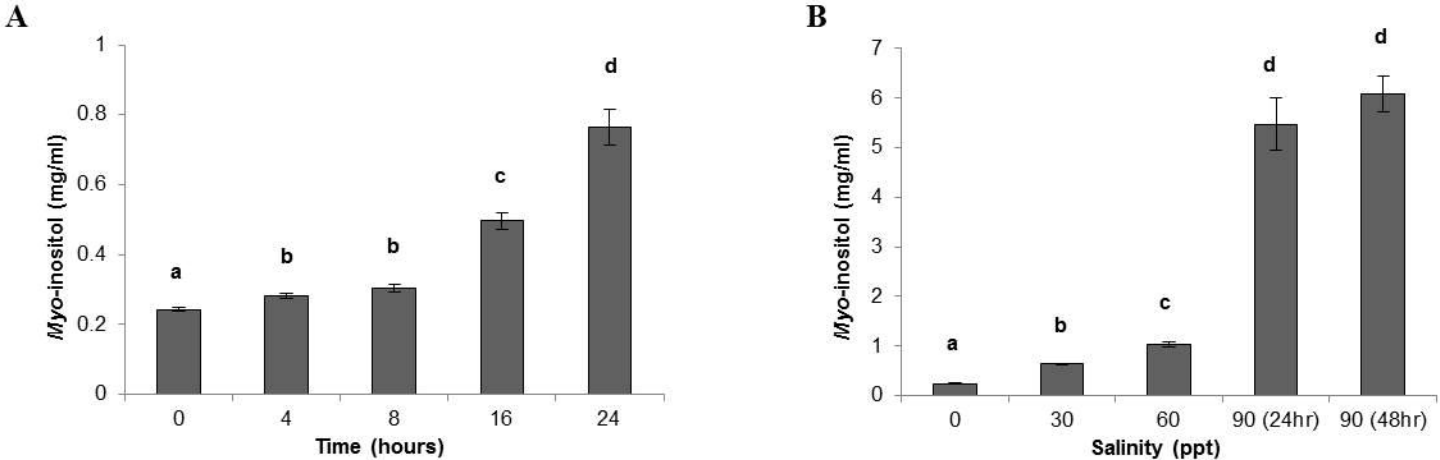
Figure 6 (A-D). Correlation analysis of MIPS-160 and MIPS-250 (A-B) or IMPA1 (C-D) mRNA abundance increase versus blood plasma osmolality increase performed separately for acute (A,C) and chronic (B,D) salinity acclimations. Pearson's correlation coefficients are reported with ** indicating $p < 0.01$.

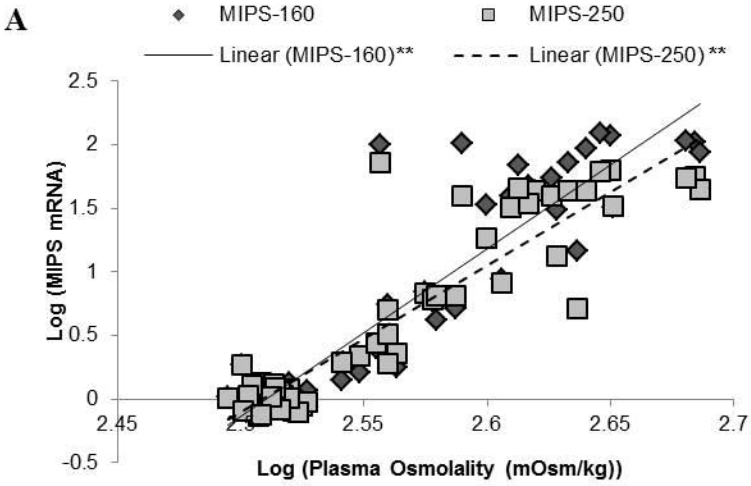

A
Plasma Osmolality (mOsm/kg)
500
460
420
380
340
300
a
b
bc
d
e
cd
0
5
10
15
20
25
Time (hours)
B
Plasma Sodium (mM)
230
210
190
170
150
130
a
b
bc
d
e
cd
0
5
10
15
20
25
Time (hours)
C
Plasma Chloride (mM)
230
210
190
170
150
130
a
b
bc
d
e
cd
0
5
10
15
20
25
Time (hours)
D
% Hematocrit
38
36
34
32
30
28
26
a
b
ab
ab
a
b
0
5
10
15
20
25
Time (hours)

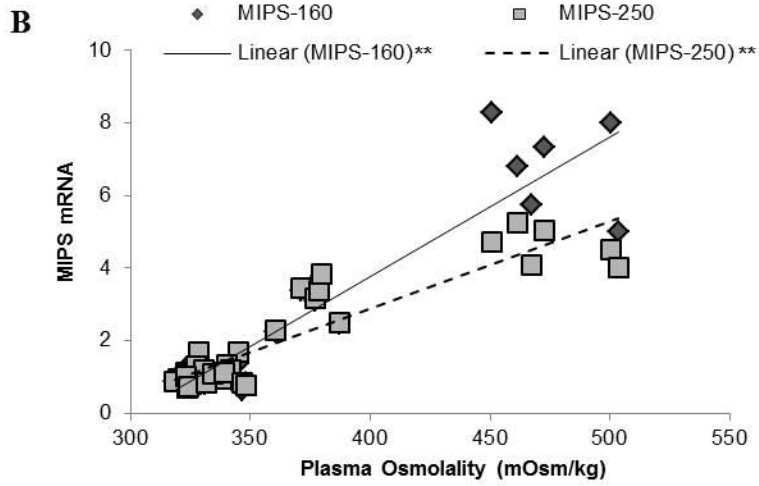

A
Plasma Osmolality (mOsm/kg)
500
460
420
380
340
300
a
b
c
d
0
30
60
90
Salinity (ppt)
B
Plasma Sodium (mM)
230
210
190
170
150
130
a
b
c
d
0
30
60
90
Salinity (ppt)
C
Plasma Chloride (mM)
230
210
190
170
150
130
a
b
c
d
0
30
60
90
Salinity (ppt)
D
% Hematocrit
33
32
31
30
29
28
27
a
a
a
a
0
30
60
90
Salinity (ppt)

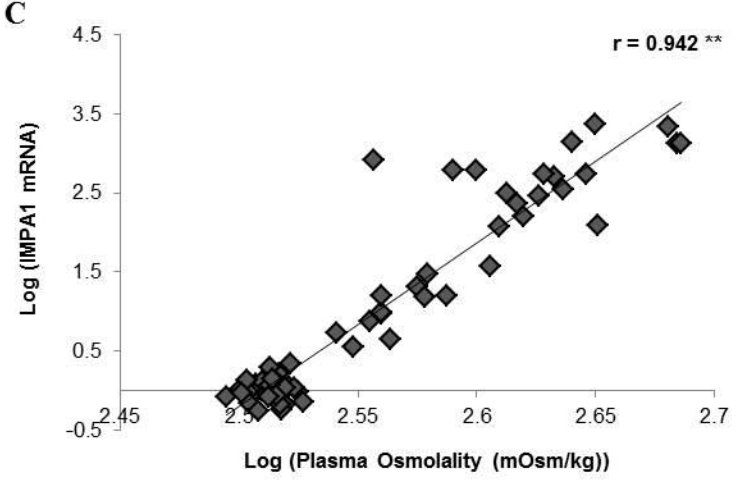

A
MIPS-160
mRNA abundance
120
100
80
60
40
20
0
a
b
c
d
e
de
0
2
4
8
16
24
Time (hours)
B
MIPS-250
mRNA abundance
60
50
40
30
20
10
0
a
b
c
d
e
de
0
2
4
8
16
24
Time (hours)
C
IMPA1
mRNA abundance
1800
1500
1200
900
600
300
0
a
b
c
d
e
f
0
2
4
8
16
24
Time (hours)
D
IMPA2
mRNA abundance
3.5
3
2.5
2
1.5
1
0.5
0
a
a
ab
b
b
b
0
2
4
8
16
24
Time (hours)

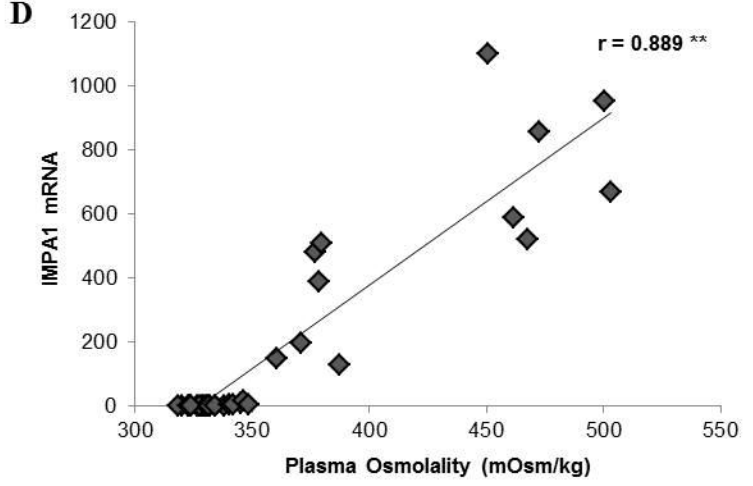

A
MIPS-160
mRNA abundance
Salinity (ppt)
a
a
b
c
B
MIPS-250
mRNA abundance
Salinity (ppt)
a
a
b
c
C
IMPA1
mRNA abundance
Salinity (ppt)
a
b
c
d
D
IMPA2
mRNA abundance
Salinity (ppt)
a
ab
a
b


A
1
0.8
0.6
0.4
0.2
0
Myo-inositol (mg/ml)
a
b
b
c
d
0
4
8
16
24
Time (hours)
B
7
6
5
4
3
2
1
0
Myo-inositol (mg/ml)
a
b
c
d
d
0
30
60
90 (24hr)
90 (48hr)
Salinity (ppt)


A
MIPS-160
MIPS-250
Linear (MIPS-160)**
Linear (MIPS-250)**
Log (MIPS mRNA)
Log (Plasma Osmolality (mOsm/kg))


B
MIPS-160
MIPS-250
Linear (MIPS-160)**
Linear (MIPS-250)**
MIPS mRNA
Plasma Osmolality (mOsm/kg)


C
r = 0.942 **
Log (IMPA1 mRNA)
Log (Plasma Osmolality (mOsm/kg))


D
r = 0.889 **
IMPA1 mRNA
Plasma Osmolality (mOsm/kg)