

26 **Abstract**

27 Tanning response and melanocyte differentiation are mediated by the central transcription factor MITF.
28 Enigmatically, these involve rapid and selective induction of melanocyte maturation genes, while
29 concomitantly maintaining the expression of other effectors. In this study using cell-based and zebrafish
30 model systems, we elucidate a pH mediated feed-forward mechanism of epigenetic regulation that enables
31 selective amplification of melanocyte maturation program. We demonstrate that MITF activation directly
32 elevates the expression of Carbonic Anhydrase 14 (Ca14) enzyme. Nuclear localized Ca14 increases the
33 intracellular pH, resulting in the activation of histone acetyl transferase activity of p300/CBP. In turn
34 enhanced H3K27 histone acetylation marks of select differentiation genes facilitates their amplified
35 expression by MITF. CRISPR-mediated targeted missense mutation of CA14 in zebrafish results in
36 immature acidic melanocytes with decreased pigmentation, establishing the centrality of this mechanism
37 in rapidly activating melanocyte differentiation. Thereby we reveal a novel epigenetic control through pH
38 modulation that reinforces a deterministic cell fate by altering chromatin dynamics.

39

40 **Introduction**

41 Gene expression networks as well as upstream pathways that govern their expression are well-studied for
42 skin melanocytes (Bennett, 1983). Precursors of these cells are neural crest derived and are present in
43 several locations in skin such as hair follicles, dermis and presumably the epidermis (Mort et al, 2015). In
44 response to specific cues from the wnt and melanocortin pathways, these precursors are believed to
45 migrate and rapidly mature into pigmented melanocytes in skin (Harris & Erickson, 2007).
46 Microphthalmia associated transcription factor (MITF), the central melanocyte specific transcription
47 factor is crucial for almost all aspects of development, maintenance and survival of melanocytes across
48 vertebrates (Levy et al, 2006).

49 To mediate these wide ranging effector functions, the MITF target genes are selectively activated
50 during specific melanocyte transitions (Levy & Fisher, 2011). The level and activity of MITF is governed
51 by cAMP/PKA and MAPK signaling pathways respectively (Johannessen et al, 2013). M/E-box mediated
52 direct activation is observed in several of the MITF target genes. Physical interaction of MITF with
53 factors such as YY1 and proximal interplay with Sox10 mediates activation of a subset of these effector
54 genes, thereby adding another layer of complexity to the selective activation (Li et al, 2012). Recruitment
55 of transcriptional co-regulators such as BRG1 and p300/CBP facilitates dynamic interaction of MITF to
56 subset of promoters (Sato et al, 1997). A key challenge still is to selectively activate certain gene modules
57 dynamically, while maintaining other effector functions of MITF (Li et al, 2012; Praetorius et al, 2013).
58 This is evident during tanning response and melanocyte differentiation wherein MITF activates
59 pigmentation genes several folds, while maintaining the expression of proliferation and survival genes
60 (Malcov-Brog et al, 2018). These recent findings highlights that multiple linked regulatory loops enable
61 selective outcomes in pigmentation during tanning response. Basis of this selectivity by MITF and the
62 mechanistic understanding is just beginning to emerge, wherein epigenetic factors are thought to play a
63 class-specific activator role (de la Serna et al, 2006; Keenen et al, 2010; Laurette et al, 2015; Malcov-
64 Brog et al, 2018). In this context, experiments by Laurette et al, followed by analysis by Malcov-Brog et

pH regulates melanocyte maturation

65 al recently identified heightened H3K27 acetylation pattern in the pigmentation genes downstream of
66 MITF.

67 Epigenetic regulation is likely to be intricately linked to cellular cues that cooperate with external
68 signals in modulating networks involved in determining cell fates. pH homeostasis is a crucial biological
69 process that is linked to several of the cellular pathways and is a plausible candidate (Boron, 2004)
70 (Simons et al, 2009; Tatapudy et al, 2017) . While the centrality of pH balance in cell homeostasis is well
71 appreciated, emerging evidence indicate that pH could signal cellular events by programmatically
72 modulating existing networks (McBrian et al, 2012; Tatapudy et al, 2017). An increase in the intracellular
73 pH is critical for the differentiation of mouse embryonic stem cells as well as drosophila adult follicle
74 stem cells, highlighting the role of pH in controlling key cell fates (Ulmschneider et al, 2016).

75 A large family of carbon dioxide metabolizing enzymes, carbonic anhydrases (CA) regulate pH
76 across life forms (Lindskog, 1997). Members of this family are ubiquitously expressed in many cell types
77 and localize to distinct subcellular compartments (Karler & Woodbury, 1960; Reibring et al, 2014). CA14
78 is a type I transmembrane protein expressed in a variety of cell types but has been studied in retina, brain,
79 kidney, smooth muscle and cardiomyocytes (Fujikawa-Adachi et al, 1999; Kaunisto et al, 2002). Studies
80 using knock-out mice have established a role of CA14 in buffering alkaline shifts in brain (Shah et al,
81 2005). Intracellular expression of CA14 in the sarcolemma of smooth muscle cells is known to modulate
82 impulse induced muscle contractions (Wetzel et al, 2007). Cells of the Retinal Pigmented Epithelium
83 (RPE) demonstrate high expression of CA14 on the apical region and *Cal4* knock out mouse is deficient
84 in eliciting a functional retinal light response (Ogilvie et al, 2007).

85 The emerging link between pH and melanin synthesis is several fold. The enzymes involved in
86 melanogenesis namely tyrosinase (Tyr), tyrosinase related protein (Trp1) and dopachrome tautomerase
87 (Dct) that reside within the melanosomes is modulated by the luminal pH. V-type ATPases are involved in
88 maintaining an acidic pH of these lysosome related organelles. Optimal pH for melanogenesis has
89 remained controversial and marginal luminal alkalization by protonophores is thought to promote
90 melanin synthesis (Watabe et al, 2004). pH changes in the endolysosomal compartments also alter the

pH regulates melanocyte maturation

91 trafficking and maturation of melanosomal enzymes in addition to their activity, as well as the type of
92 melanin being synthesized (Halaban et al, 2002), (Bellono et al, 2014), (Wakamatsu et al, 2017).
93 Predictable alterations of the cellular pH modulate the resultant pigmentation in melanocytes. The effect
94 of which is surprisingly high with a robust alteration in the net melanin synthesis. Therefore we decided
95 to systematically study the interplay of pH on the entire melanogenic program at various levels.

96 In this study we demonstrate that intracellular pH is a critical cue for amplifying the melanocyte
97 maturation program. We trace genes that follow a concordant pattern of regulation with pigmentation and
98 identify Carbonic Anhydrase 14 to be a MITF regulated gene. CA14 acts as a feed forward activator of
99 MITF regulatory network and amplifies the melanocyte maturation gene expression by altering the
100 histone acetylation marks via a programmed intracellular pH change. Using cell-based and zebrafish
101 model systems we demonstrate that the feed forward loop involving Ca14 is critical to mediate the
102 melanocyte maturation program downstream of MITF.

103 **Results**

104 *Alkaline intracellular pH induces pigmentation by enhancing the melanogenesis gene expression*

105 During the culture of B16 cells in DMEM medium CO₂-HCO₃⁻ buffering system maintains media pH.
106 Hence we resorted to establish the pH-pigmentation link by modulating the prevailing CO₂ levels. We set
107 up progressive pigmentation using the B16 cells as described earlier (Natarajan et al, 2014). In this set up
108 the cells progressively activate the melanogenesis gene expression program and increase pigmentation
109 over a course of 8 to 12 days. To alter the pH, 10% CO₂ levels were tested. We measured the extracellular
110 pH (pH_e) using the standard pH electrode under controlled conditions of temperature and CO₂ saturation.
111 While the cells grown in 5% CO₂ showed an increase in pH_e from around 7.4 to 7.8 on day 4 after
112 induction of the pigmentation program, the 10% CO₂ sustained a constant pH of around 7.4
113 (**Supplementary Fig 1A**). This trend was reflected in the intracellular pH (pH_i), which is close to 7.9 on
114 day 4 under the routine 5% CO₂ condition. However, under the 10% CO₂ the pH remained close to 7.0,
115 similar to the day 0 where the cells are depigmented (**Fig 1A**). When the cells were assessed for the
116 cumulative accumulation of melanin on day 8, under the 10% CO₂ condition we observed depigmented
117 cells (**Fig 1B**). Melanin content assay performed using synthetic melanin standard confirmed that the
118 level of melanin is significantly low (**Supplementary Fig S1B**). Further electron microscopic evaluation
119 of day 8 cells confirmed that indeed melanin laden stage III and IV melanosomes are dramatically
120 reduced under these conditions (**Fig 1C**).

121 We then analyzed steady state protein levels of the components of melanosomal machinery. All
122 the three pigmentation proteins Tyr, Dct and Gp100 were drastically reduced under 10% CO₂, however
123 the levels of MITF were not decreased, rather we observed a mild increase in the level of this central
124 transcription factor (**Fig 1D**). In concordance with earlier studies that suggested a pH dependent alteration
125 in the protein stability, the activity of tyrosinase enzyme assessed by L-DOPA based in-gel assay as well
126 as western blot analysis confirmed a dramatic reduction (Halaban et al, 2002). However a decrease in Dct
127 and Gp100 levels was unanticipated. Gp100 showed a greater decrease on day 8 and had comparable
128 level on day 4 with alterations in the mobility suggesting processing differences (Hoashi et al).

pH regulates melanocyte maturation

129 Surprisingly, transcript levels of these downstream pigmentation genes were lower in 10% CO₂
130 condition (**Fig 1E**). We therefore identified that retaining the cells in an acidic state of pH_i, suppresses
131 pigmentation by the decreased expression of pigmentation genes despite comparable levels of MITF. We
132 also observed an increase in the cell numbers at 10% CO₂ (**Supplementary Fig S1C**). Therefore there is
133 seemingly an additional level of cellular program by intracellular pH that governs melanogenesis beyond
134 enzyme activity and protein stability, involving transcriptional regulation.

135

136 *A candidate effector CA14 follows a concordant expression pattern with pigmentation genes*

137 We set out to identify the molecular mechanism behind the pH dependent transcriptional response. Based
138 on our earlier work, we had established the B16 cell autonomous model and demonstrated the utility of
139 this model to identify underlying networks that govern pigmentation. The other model involves the
140 growth of pigmented melanoma tumor derived from mice and grown *in vitro* for four consecutive
141 passages. A set of genes showed a concordant regulation across the two reversible models
142 (**Supplementary Fig S2**). Among the common set of regulated genes, five of the fifty candidates, *Tyr*,
143 *Tyrp1*, *Mlana*, *Mcoln3*, *Si* and *Rab27a* are targets of the central melanocyte transcription factor MITF.
144 These are well-known pigmentation genes directly involved in the process of melanogenesis and
145 melanosome maturation, which are directly linked to the process of melanocyte differentiation. From this
146 analysis Carbonic anhydrase 14 emerged as a putative candidate gene that could directly regulate pH, as it
147 is regulated with pigmentation in both the cellular model systems.

148 We then analyzed the pattern of expression of carbonic anhydrases from the data and observed
149 that of the several CAs expressed in melanocytes, only CA14 showed regulation pattern similar to the
150 melanocyte differentiation genes *tyr*, *dct* and *tyrp1* based on microarray studies (**Fig 2A**) (Natarajan et al,
151 2014). Hence we proceeded to characterize the regulation of Ca14 with an aim to establish its role in
152 melanocyte maturation.

153

154 *CA14 expression is induced upon activation of the melanocortin pathway via MITF*

pH regulates melanocyte maturation

155 As *Ca14* showed concordant expression with pigmentation genes and correlated with the activity of MITF,
156 we set out to identify whether *cal14* is indeed a downstream gene and could play an important role in
157 mediating the effects of MITF in melanocytes. Overexpression of *Mitf*, followed by global gene
158 expression analysis revealed a set of regulated genes (Hoek et al, 2008). Chromatin immunoprecipitation
159 studies have independently identified several promoters occupied by this transcription factor (Strub et al,
160 2011). Combined analysis of both these approaches resulted in a set of genes enriched in known targets of
161 *Mitf*, along with several other putative candidates. In this set of genes *Ca14* features and hence emerged
162 as a promising downstream target of MITF.

163 α -melanocyte stimulating hormone (α -MSH) and Iso-Butyl Methyl Xanthine (IBMX) were used
164 as inducers of *Mitf* to stimulate melanocytes (Motiani et al, 2018). We carried out these experiments in
165 mouse Melan-A cells, as well as the primary human melanocytes. Treatment of Melan-A cells with 60
166 μ M IBMX or 1 μ M α -MSH for 48h and 72h resulted in the induction of *Mitf* and the downstream target
167 gene *Dct*, confirming activation of the melanocortin pathway. The antibody used to detect CA14 was
168 validated by western blot analysis wherein we could identify the 25 kDa form of CA14 protein. The
169 intensity of the band was reduced upon silencing with a pool of siRNA against *Ca14* and increased with
170 expression of CA14 ORF in an expression vector, confirming specificity of the antibody (**Supplementary**
171 **Fig S3 A & B**). With IBMX as well as α -MSH treatments we could observe elevation of the 25kDa form
172 of *Ca14* protein, indicating that activation of *Mitf* mediates *Ca14* induction (**Fig 2B**). We observed a
173 similar induction of CA14 in primary human melanocytes treated with IBMX for 48 h (**Fig 2C**).

174 We performed qRT-PCR analysis to monitor the mRNA levels in B16 cells treated with α -MSH
175 for 12 and 24h, as the transcript-level changes are expected earlier than protein level changes. We
176 observed a robust elevation in the expression of pigmentation gene transcripts *Tyr*, *Dct* and *Trp1*.
177 Moreover the elevation in *Mitf* and *Ca14* levels were comparable, modest but significant (**Fig 2D**).

178

179 ***MITF directly binds to Ca14 promoter and regulates its expression***

pH regulates melanocyte maturation

180 To probe the induction of *cal4* by *Mitf* further, we cloned 3 kb upstream region of *cal4* in a reporter
181 vector and performed dual luciferase assays. Substantial elevation of reporter activity with IBMX and α -
182 MSH was observed confirming that the induction to be a transcriptional response (**Fig 2E**). Analysis of
183 MITF binding sites in the promoters of *Ca14* gene indicated multiple sites in both the human and mouse
184 promoter regions (**Supplementary Fig S4**). To fine-map the responsive site we adopted two strategies, in
185 the first strategy we created three clones of mouse *Ca14* promoter carrying the 1kb transcription start site
186 proximal region, the mid or the distal 1 kb region (**Fig 2E**). Luciferase assays confirmed that the IBMX
187 inducibility was present in the proximal and the distal regions whereas the middle 1 kb promoter sequence
188 was not IBMX inducible.

189 Further, chromatin immunoprecipitation using C5 monoclonal antibody to MITF demonstrated
190 binding to 3kb as well as the proximal and distal regions was observed. Comparable binding of *Mitf* to
191 the intronic site in *Ca14* gene as well *Tyrp1* and *Cdk2* promoters confirmed direct binding of MITF to
192 *Ca14* for its regulation. However the middle region did not show appreciable binding of MITF (**Fig 2F**).
193 We propose that there are multiple binding sites within the *CA14* promoter responsible for its direct
194 induction by MITF. Finally, *Mitf* dependence of *cal4* expression was probed by the downregulation of
195 this transcription factor by siRNA followed by western blot analysis. While the known downstream *Mitf*
196 target gene *Dct* was dramatically downregulated, both *Mitf* and *Ca14* showed a comparable
197 downregulation of around 80% (**Fig 2G**). Similar observations were made from primary human
198 melanocytes using a siRNA against human *Mitf*, confirming the *Mitf* dependency of *CA14* expression
199 (**Fig 2H**). Hence we establish that melanocyte differentiating melanocortin signaling pathway controls
200 *Ca14* expression in a MITF dependent manner in both mouse as well as human cells.

201

CA14 is essential for melanocyte maturation in zebrafish

203 In cultured melanocytes pH is governed by prevailing CO₂ concentrations which may override
204 intracellular pH programs. Therefore to address the role of *CA14* on melanocyte functions we utilized a
205 morpholino (MO) based transient silencing approach using the zebrafish model system. Herein the

pH regulates melanocyte maturation

206 pigment producing cells termed melanophores are ontologically equivalent to higher vertebrate
207 melanocytes and the underlying gene networks are highly conserved. During embryogenesis
208 melanophores rapidly mature between 48 to 72 hours post fertilization (hpf). Additionally in the absence
209 of melanosome transport, melanocyte maturation is easy to visualize and monitor.

210 After titrating the dose of the Ca14 MO based on viability of embryos, scoring of the phenotypes
211 was carried out (**Supplementary Fig S7**). Analysis of melanophores at 48 hpf indicated that the *ca14*
212 morphants were lightly pigmented compared to control non-targeting MO-injected embryos at the same
213 concentration (**Fig 3A & C**). To assess melanophore numbers, we generated morphants in transgenic
214 zebrafish line *Tg:tyrp1-GFP* wherein the melanophores are fluorescently marked with GFP driven by a
215 fugu *Tyrp-1* promoter (Zou et al, 2006). To prevent masking of GFP fluorescence by melanin, the
216 embryos were treated with phenylthiourea (PTU), a potent tyrosinase inhibitor. Similar pattern of
217 melanophore positioning and comparable number of melanophores were observed in the morphant fishes
218 suggesting that the melanophore numbers are unaltered which indicates melanocyte specification and
219 survival are unaffected (**Fig 3B** right panel & **3D**). However, the mature heavily pigmented melanophores
220 were drastically reduced in the *ca14* morphants. Quantitation of the bright field images using Image J
221 platform suggested that the morphant melanophores had a higher mean grey value, indicating that they
222 were lighter with less melanin content (**Fig 3C**). These observations strongly suggest that CA14 plays an
223 important role in the process of melanogenesis, a crucial event associated with melanocyte maturation.
224 Furthermore, upstream events such as specification, migration and patterning of melanocytes are
225 seemingly unperturbed. We observed a progressive increase in the expression of pigmentation genes *tyr*,
226 *dct* and *tyrp1b*, concomitant with the known melanocyte maturation process; however in the *ca14*
227 morphants that elevation was severely curtailed (**Fig 5E-G**). Therefore CA14 mediated melanocyte
228 maturation by altering the pigmentation gene expression. We then went ahead to elucidate the mechanism
229 of CA14 mediated pigmentation using cultured cells as the model system.

230

231

232 ***CA14 increases intracellular pH during pigmentation***

233 Since Ca14 is a MITF dependent gene, expression changes during pigmentation and a downstream
234 modulation of pH due to its carbonic anhydrase activity emerged as a possibility. To study this we
235 induced pigmentation in B16 cells using the pigmentation oscillator. On different days of the
236 pigmentation oscillator the levels of the Ca14 mRNA and protein using q-PCR and western blot analysis
237 respectively was quantified. CA14 expression at both protein as well as mRNA levels was high during
238 early phase (day 4) and progressively decreased at the later days of pigmentation (**Fig 4A**,
239 **Supplementary Fig S5**).

240 As carbonic anhydrases mediate pH buffering, we measured pH_i using the ratiometric pH
241 sensitive dye (BCECF-AM) that reports intracellular pH (pH_i). We observed a consistent increase in pH_i
242 from around 7.0 on day 0 to 7.9 on day 4, which is subsequently restored to around 7.0 on day 8 of the
243 oscillator (**Fig 4B**). Strikingly, this trend followed changes in Ca14 expression. The pigmentation non-
244 permissive condition involving 10% CO₂ did not demonstrate a sharp rise in pH_i on day 4. We observed a
245 decrease in Ca14 protein levels on day 8 in both 5% and 10% conditions, suggesting that CO₂ mediates its
246 effects on pH by shifting the equilibrium towards an acidic pH (**Fig 4C**). We then proceeded to
247 unequivocally establish the role of Ca14 in altering pH_i .

248 We transfected B16 cells with C-terminal mCherry tagged CA14 to trace the transfected cells for
249 pH measurements. There was a marginal but significant elevation of pH_i which could not be observed for
250 the catalytically inactive mutant form (CA14_{T166I}). Silencing *cal4* using a cocktail of four independent
251 siRNAs caused intracellular acidification and reduced pH_i (**Fig 4D**). Together the two data confirm the
252 role of CA14 in elevating intracellular pH. CA14 mediated elevation of pH_i in B16 cells raised the
253 question about the localization of CA14 in melanocytes.

254

255 ***CA14 is localized to the nucleus in melanocytes***

256 CA14 is an alpha-type carbonic anhydrase domain containing type I transmembrane protein, preceded by
257 a short signal sequence (Whittington et al, 2004). Hence the catalytic motif is predicted to function in

pH regulates melanocyte maturation

258 buffering extracellular pH (pH_e), alternately its localization to intracellular membranes would modulate
259 organelle pH. Expression of Ca14 is high in adult brain, retinal pigmented epithelium, liver, heart, and
260 skeletal muscle and its localization in various cell-types differ (Hallerdei et al, 2010; Purkerson &
261 Schwartz, 2007; Vargas & Alvarez, 2012; Wetzel et al, 2007). While in smooth muscle cells its
262 expression is detected in sarcoplasmic reticulum, in other cell-types expression in plasma membrane is
263 indicated (Wetzel et al, 2007). Being a MITF inducible gene Ca14 like other targets could be localized to
264 melanosomes, where the pH regulation is known to be critical (Ancans et al, 2001). However its control
265 over pH_i indicates its localization to the cytoplasmic or a connected subcellular compartment.

266 Immunofluorescence studies were carried out on B16 cells to identify the localization of CA14 in
267 melanocytes. Intracellular localization of CA14 could be detected in the nucleus of B16 cells (**Fig 4E**).
268 Fractionation of cells to enrich the nuclear and melanosomal fractions, followed by western blot analysis
269 confirmed CA14 localization to the nucleus and not to melanosomes (**Fig 4F**). This is strikingly similar to
270 another transmembrane paralog CA9 that localizes to the nucleus and is involved in nucleolar gene
271 expression (Sasso et al, 2015). CA9 has been an important target for pH modulation in several cancers
272 including melanoma (Supuran & Winum, 2015).

273 While culturing primary human melanocytes in the laboratory we had previously observed that
274 the cells grown under MBM-4 medium compared to M254 medium were more proliferative and had less
275 melanin content. Similar observations were also reported earlier (Kormos et al, 2011). We observed that
276 the expression of CA14 was higher in M254 medium and localization was primarily in the nucleus.
277 Whereas in MBM-4 media the cells had lower expression of ca14 and the immuno-localization was found
278 to be diffuse (**Supplementary Fig S6**). These observations further add credence to a possible role of
279 CA14 in melanocyte maturation. To understand the mechanism we proceeded to investigate the effect of
280 CA14 silencing on the expression of pigmentation genes in B16 cells.

281

282 *Ca14 mediates pigmentation gene expression through a transcriptional response*

pH regulates melanocyte maturation

283 *Ca14* by virtue of being regulated by *Mitf*, its control over pH_i and its role in sustaining melanin content
284 of zebrafish melanophores makes it a likely candidate to mediate melanocytes maturation. Hence we set
285 out to address the effect of down-regulating *cal4* on the expression of pigmentation genes. We
286 transfected B16 cells with a pool of four siRNAs targeting *cal4* or control non-targeting siRNA pool and
287 the cells were subjected to downstream experiments. Independently, shRNA mediated knockdown was
288 also carried out. Western blot analysis was performed on the cell lysates and a reduction of around 60%
289 was observed for CA14 (**Fig 5A and Supplementary Fig S3A**). Expression of pigmentation genes was
290 found out to be lower upon Ca14 silencing in both the approaches. mRNA levels of *dct* and *Tyr* was
291 found to be downregulated by q-RT PCR analysis (**Fig 5B**). We further confirmed that the down-
292 regulation is at the transcriptional level by performing luciferase assays using *dct* promoter driven firefly
293 luciferase (**Fig 5C**). The *Dct* promoter activity was marginally but consistently downregulated by around
294 30% upon silencing of *ca14*. We observed an increase in the promoter activity of an unrelated promoter
295 *kif1b* suggesting that the decrease is unlikely due to possible alterations in luciferase activity due to
296 changes in pH.

297 Given the nuclear expression of CA14, it is likely that the local pH changes may culminate in
298 specific transcriptional response. Since *Dct* and the other melanocyte differentiation genes are direct
299 targets for MITF, it is surprising that Ca14 is able to modulate gene expression without affecting MITF
300 levels. It is therefore likely that Ca14 could mediate transcriptional activation by facilitating chromatin
301 alterations, which in turn facilitate MITF mediated gene expression. This possibility also allows for
302 promoter specific alterations rendering selectivity in the downstream gene expression. In an earlier work
303 the authors reported changes in histone acetylation upon intracellular pH change (McBrian et al, 2012) ,
304 hence we set out to investigate this possibility.

305

306 *Ca14 promotes H3K27 acetylation marks on select MITF target genes*

307 Thus far we could establish that Ca14 is present in the nucleus, increases intracellular pH and enhances
308 the expression of pigmentation genes. We went ahead and monitored global changes in histone

pH regulates melanocyte maturation

309 acetylation using western blot analysis and observed a modest but consistent decrease across AcH3K27
310 (Acetylated Histone 3 at Lys 27 position) and AcH2A.Z, but not in AcH3K18, AcH3K9 or AcH4K12
311 (**Fig 5D**). This provided an exciting possibility of local pH changes culminating in epigenetic marks that
312 would in turn affect pigmentation gene expression profiles downstream of MITF. While the trend of
313 decrease in AcH3K27 was consistent across three independent biological replicate experiments, the effect
314 was marginal around 30 – 40% reduction in global acetylation. We then proceeded to query the specific
315 changes in a battery of promoters of MITF target genes using chromatin immunoprecipitation (ChIP).

316 We transfected B16 cells with control non-targeting or the CA14 targeting ShRNA construct and
317 allowed cells to initiate pigmentation by setting up pigmentation oscillation. Cells were subjected to
318 crosslinking on day 5, a day after the peak in pH_i is observed and chromatin immunoprecipitation was
319 carried out with acetylated H3K27 as well as control IgG. Relative enrichment with respect to the input
320 DNA was quantitated by q-RT PCR using promoter specific primers. The enrichment of AcH3K27 was
321 decreased at the promoters of *Tyr*, *Dct* and *Gp100* genes (**Fig 5F**). We observed that AcH3K27
322 occupancy at Tyr promoter was reduced by around 50%, *Dct* promoter by 33% and *Gp100* by a marginal
323 but consistent decrease of around 12%. However the promoters of other MITF targets *Tyrp1*, and *Cdk2* as
324 well as the promoter of *Mitf* itself remained unaltered upon Ca14 silencing (**Fig 5F**). This experiment
325 confirmed that Ca14 brings about the promoter specific changes in activation marks and provides a
326 molecular basis of pigmentation gene expression control mediated by MITF. This data also reinforces
327 earlier observations that the pigmentation gene targets of MITF have unusually high H3K27 acetylation
328 profiles as compared to global average or other targets of MITF (Malcov-Brog et al, 2018).

329

330 *Histone Acetyl Transferase activity of p300 is elevated at an alkaline pH*

331 We then set out to identify the pH dependent mechanism of histone acetylation. p300/CBP emerged as a
332 probable candidate as it mediates H3K27 acetylation, additionally physical interaction of MITF with
333 p300/CBP is already established (Sato et al, 1997). In vitro activity of recombinant p300 HAT domain
334 was carried out with a synthetic peptide of histone H3 and acetyl CoA, and the product CoA is measured

pH regulates melanocyte maturation

335 by coupling with a fluorophore. Activity at around the neutral pH 7.15 was 1/8th of its activity at pH 7.95;
336 thereby suggesting that acetylation by p300 would be clearly high at alkaline pH (**Fig 5G**). Hence this
337 study provided a possible effector of the pH_i that could control pigmentation gene expression.

338 To confirm the involvement of p300/CBP in pigmentation, we incubated the B16 cells with C646
339 a selective inhibitor of the p300/CBP HAT activity. Upon inhibition, B16 cells despite being subjected to
340 pigmentation permissive 5% CO₂ condition did not pigment (**Fig 5H**). The expression of melanocyte
341 differentiation genes was downregulated with marginal changes in MITF transcript levels, confirming that
342 p300/CBP facilitate the melanocyte maturation process by enhancing the expression of differentiation
343 genes. Taken together, we demonstrate that MITF activates Ca14 transcriptionally; Ca14 increases pH_i
344 that in turn can activate p300 HAT activity, which acetylates histone H3 in the promoters of melanocyte
345 differentiation genes facilitating their transcriptional activation by MITF (**Fig 5I**). Hence this feed
346 forward loop enables quick and heightened expression of differentiation genes under conditions where the
347 cells require rapid pigmentation.

348

349 *Targeted mutation of ca14 reiterates the role of feed forward loop on pigmentation*

350 We chose to address the role of this feed forward loop mediated by CA14 in pigmentation under
351 physiological conditions wherein rapid and programmed induction of pigmentation genes is involved. We
352 created a germline mutant in zebrafish by targeting the ca14 coding region using the CRISPR-Cas9
353 system. We injected Cas9 - guide RNA complex to fertilized zebrafish embryos at the single cell stage.
354 We observed a variety of phenotypes in F0, which include microcephaly, small eye size, mild
355 enlargement of heart and decreased pigmentation. These phenotypes recapitulate the known high
356 expression of Ca14 in brain, heart and eye. After screening for mutants using T7 endonuclease assay,
357 siblings were grown to adulthood. Genotyping revealed a frame-shift mutation at the third codon by the
358 deletion of two bases. Thereby the mutant gene would encode a truncated protein lacking most the coding
359 amino acids (**Supplementary Fig S8**). Further experiments were carried out using F2 embryos obtained
360 from the in-cross of a homozygous mutant male and a heterozygous female fish with the same mutation.

pH regulates melanocyte maturation

361 We obtained around 50% of embryos with a smaller eye size and decreased pigmentation, following a
362 Mendelian pattern of inheritance. Mutant embryos showed the two base deletion and the non-phenotypic
363 siblings were heterozygous based on PCR confirmation of the mutation. Thereby the pigmentation
364 phenotype observed in the morphant embryos is recapitulated in the genetic mutants, hence ascertaining
365 the regulatory role of Ca14 in the maturation of melanocytes (**Fig 6A**).

366 In the adult stage Ca14 mutation had a visible decrease in pigmentation, however high
367 melanophore density present in the lateral and dorsal region precluded assessment of melanin. We
368 therefore subjected the wild type adult and the *cal4^{fs003-/-}* fishes to dark adaptation to disperse the existing
369 melanin within the melanocyte so that the content could be easily assessed. We observed distinct non-
370 overlapping melanophores present in fourth and fifth stripes near the caudal fin and in this region a
371 substantial reduction in the melanin content could be observed in the mutant fish (**Fig 6B & C**).

372 We chose 36 hpf time point to analyze the expression of differentiation genes when the pigment
373 cells undergo migration and maturation. A decreased gene expression of *tyr*, *tyrp1b* and *dct* could be
374 observed in the mutant embryos (**Fig 6D**); confirming that the cells are in an immature less pigmented
375 state and the pigmentation promoting gene expression is severely reduced in the absence of Ca14.

376

377 *Ca14 mutant melanophores are acidic with reduced pigmentation*

378 We then subjected the wild type and the *cal4^{fs003-/-}* to intracellular pH measurements. Mutant
379 embryos had lower ratiometric values of BCECF (490/440) suggesting an acidic intracellular pH in
380 melanocytes (**Fig 6E**). We also attempted a chemical rescue approach by subjecting the mutant embryos
381 to embryo water buffered at various pH between 24 hpf to 36 hpf, when the melanocyte maturation
382 commences. While the acidic pH 5 did not show a rescue rather showed a marginal increase in
383 deformities, alkaline pH 10 rescued the phenotype marginally and animals with small eye had now
384 substantially high melanin content (**Fig 6F**). The extent of pH-mediated rescue was comparable when the
385 animals were injected with mouse Ca14 mRNA. It is interesting to note that; in the *cal4^{fs003-/-}* mutant
386 number of melanocytes remains unaltered but the expression of differentiation effectors is relatively low.

pH regulates melanocyte maturation

387 Therefore in the absence of ca14, melanocytes would still respond to external cues and activate Mitf,
388 however the extent of pigmentation would be severely curtailed. The mutant melanophores clearly
389 showed decreased melanin content, thereby unequivocally establishing the role of the feed forward loop
390 involving MITF, Ca14 and the differentiation genes in ensuring a heightened pigmentation.

391 **Discussion**

392 Several genes that alter melanin content and melanocyte functions are easily identified using naturally
393 occurring mutants and targeted gene disruptions (Bennett & Lamoreux, 2003). Recently, siRNA based
394 genome-wide screen revealed some of the important pigmentation genes (Ganesan et al, 2008). While
395 these perturbation-based approaches reveal the identity of components, biologically relevant regulators
396 and the physiological context are often the most difficult to decipher. In our earlier work, *cal4* gene was
397 observed to co-regulate with the pigmentation status in B16 melanoma cells (Natarajan et al, 2014).
398 Taking clue from this observation and the indication that *cal4* could be under the control of Mitf, we
399 have embarked on identifying the role of CA14 in melanocyte functions. In the current study, using cell
400 as well as whole animal based approach using zebrafish, we demonstrate an important role for CA14 and
401 the downstream pH changes as an amplifier of the maturation process in melanocytes.

402 As a general theme pH changes and cell fate decisions have attracted a lot of attention, but
403 precise mechanistic understanding is often limited by the widespread changes brought about by pH
404 (Tatapudy et al, 2017). CA14 was identified as a potential Mitf target gene based on promoter binding
405 and up-regulation of mRNA in melanocytes overexpressing Mitf (Hoek et al, 2008; Strub et al, 2011).
406 However the physiological implications of this observation was not readily apparent. Based on our study,
407 we propose a model wherein CA14 is an early gene induced by Mitf, and together the two accelerate the
408 gene expression of a subset of pigmentation genes resulting in a feed-forward amplification. This mode of
409 network interaction is seen often during cell differentiation programs. For instance, during chondrogenic
410 differentiation two key transcription factors Bmp2 and Shh, operate to regulate Sox9 in a positive
411 feedback loop to stimulate cellular differentiation (Zeng et al, 2002).

412 While the link between pH and cell differentiation is often observed across many systems,
413 mechanisms that could connect changes in pH to pigmentation gene expression were not immediately
414 apparent. An increase in intracellular pH (pH_i) is necessary for the differentiation of follicle stem cells in
415 drosophila (FSCs) as well as mouse embryonic stem cells (mESCs) (Ulmschneider et al, 2016).
416 *Drosophila* Na^+-H^+ exchanger *DNhe2* is involved in lowering the pH_i in differentiating cells and impairs

pH regulates melanocyte maturation

417 prefollicular cell differentiation, whereas increasing pH_i promotes excess differentiation toward a
418 polar/stalk cell fate through the suppression of Hedgehog pathway. Together with our observations, it is
419 now apparent that this metabolic link involving pH and cell differentiation may be a far more widespread
420 mechanism that would be operational in many cell types. Earlier studies indicate that *Mitf* regulates
421 differentiation of precursors to mature osteoclasts by the induction of carbonic anhydrase II, which is
422 responsible for extracellular acidification (Lehenkari et al, 1998; Lu et al, 2010). It is likely that pH-
423 mediated induction of differentiation and its regulation by *Mitf* may be an underlying theme conserved
424 across several cell types.

425 The role of p300/CBP in MITF mediated gene expression has emerged from multiple evidences.
426 Activated MITF physically interacts with p300/CBP, and *Mitf* immunoprecipitate has associated HAT
427 acitivity (Price et al, 1998) (Sato et al, 1997). However the physiological effect of this association
428 remained enigmatic, as MITF mutants defective in binding to p300/CBP still activated transcription
429 (Vachtenheim et al, 2007). The footprint of a SWI/SNF complex involving BRG1 on MITF targets has
430 distinct clusters of genes with high as well as low H3K27 acetylation status (Laurette et al, 2015).
431 Thereby it is likely that distinct subsets of MITF targets have different levels of activation. This is also
432 recently alluded to by (Malcov-Brog et al, 2018). The authors demonstrate that H3K27 acetylation pattern
433 is unusually high in pigmentation related MITF targets compared to proliferation and sustenance genes.
434 Hence making dynamic regulation of H3K27 acetylation a prerequisite for a subset of genes, while others
435 are less dependent on this activation. The identification of Ca14 mediated p300 activation elucidated in
436 this study provides a plausible mechanism for this crucial but so far intriguing observation on the context
437 dependent target selectivity by MITF.

438 p300 histone acetyl transferase is a central epigenetic regulator and the observed pH mediated
439 activation is likely to be a general phenomenon. The crystal structure of the p300 HAT domain revealed
440 an unusual hit and run catalytic “Theorell-Chance” mechanism (Liu et al, 2008). Subsequent molecular
441 dynamic simulations suggest a proton relay from the ϵ amino group of the acceptor lysine substrate and it
442 is predicted that the involved side chains have a high pK_a (Zhang et al, 2014). The standard enzymatic

pH regulates melanocyte maturation

443 assays involving p300 are routinely carried out at an alkaline pH 7.8 - 8.0 which would favour
444 deprotonation providing a molecular mechanism of pH-mediated HAT activation. Thereby the transient
445 increase in pH mediated by Ca14 facilitates H3K27 acetylation by p300 thereby rendering activation of
446 these genes.

447 Ca14 mediated feed-forward loop would be operational under conditions wherein rapid
448 melanocyte maturation is required. This is anticipated during UV induced sun tanning response as well as
449 developmental states wherein melanocytes mature into a high melanin containing cells. Recent study
450 identified *ca14* to be downregulated in the lesional depigmented skin of vitiligo subjects (Yu et al, 2012).
451 It is tempting to speculate that the depigmentation in vitiligo could be contributed by the decrease in
452 CA14 that could affect melanocyte maturation, in addition to the loss of mature melanocytes. Advances
453 made in this study are therefore of immense relevance in the recently emerging role of biochemical milieu
454 as an intermediate effector in determining the cell fate decisions.

455

456 **Materials and Methods**

457 *Cell line and culture*

458 B16 mouse melanoma cell line was cultured in DMEM-high glucose (Gibco, Life Technologies) medium
459 supplemented with 10% fetal bovine serum (FBS; Gibco, Life Technologies) and cells were maintained in
460 5% (or at 10% CO₂ when indicated) in a 37⁰C incubator. The orthologous non-cancerous murine
461 melanocyte line Melan-A was cultured at 10% CO₂ at 37⁰ C in RPMI-1640 medium (Gibco, Life
462 Technologies) supplemented with 10% fetal bovine serum (FBS; Gibco, Life Technologies), 400nM
463 Phorbol-Myristyl-13-acetate (PMA; Sigma) and 0.003% Phenylthiourea (PTU, Sigma). Primary human
464 melanocytes were grown in proliferative conditions in PMA containing medium MBM4 (Lonza). For
465 differentiation cells were switched to M254 medium for 3-4 population doublings (ThermoFisher
466 Scientific, Life Technologies).

467

468 *Setup of pigmentation oscillation model in B16 cells*

pH regulates melanocyte maturation

469 Detailed Protocol described in (Natarajan et al, 2014). Briefly, B16 cells were seeded at density of 100
470 cells/cm² in DMEM-high glucose medium supplemented with 10% FBS. Cells were cultured at 5% CO₂
471 and were harvested at day 4, 6, and 8 for downstream experiments. The cells progressively pigmented and
472 the expression of pigmentation genes were induced in this model system (**Supplementary Fig S2**). To
473 modulate the pH cells were alternatively cultured in 10% CO₂ and subsequent changes in pH, melanin
474 content and gene expression were investigated. P300/CBP inhibitor C646 or vehicle control DMSO
475 treatment was performed at Day 1 of pigmentation oscillator and terminated on Day 6 for downstream
476 analysis.

477

478 *Generation of ca14 promoter construct, Ca14 expression construct and the inactive mutant*

479 The *ca14* 3kb promoter (3000 bp upstream of transcription start site) was amplified from mouse genomic
480 DNA and cloned upstream of luciferase cassette in KpnI/HindIII site of pGL4.23 (Promega) using
481 primers listed in **Supplementary table 1**. Mouse Ca14 coding sequence was amplified from mouse B16
482 cDNA and cloned in mcherryN1 vector (Clontech) in KpnI/HindIII site. Site directed mutagenesis for
483 CA14 (Thr199Ile) was carried out using SDM II kit (Agilent) using primers listed in **Supplementary**
484 **table 1**. Truncated constructs of 1kb (proximal, middle, distal from TSS) were generated from *Ca14* 3kb
485 promoter. *Dct* promoter used in this study is reported elsewhere (Natarajan et al, 2014).

486

487 *Measurement of intracellular pH*

488 *For mammalian cells:* Intracellular pH (pH_i) was measured by using the ratiometric dye BCECF-AM
489 (Molecular probes, Thermo scientific), as described in (Natarajan et al, 2014). Briefly cells were plated in
490 35 mm dishes (IBIDI) and on the day of pH measurement cells were incubated with 0.2μM of BCECF-
491 AM dye for 2min at 37⁰C and 5% CO₂. In order to generate a pH calibration curve, cells were incubated
492 in pH calibration solution (in mM:1Glucose, 140KCl, 1MgSO₄, 30HEPES, 25NaCl, 1CaCl₂,
493 1NaH₂PO₄)with pH range of 6– 8.5 and added 10μMNigericin (Thermofisher Scientific). Quantitative

pH regulates melanocyte maturation

494 images were acquired and fluorescence ratio was measured at dual excitation wavelength of 440 and 490
495 nm in Leica SP8 confocal microscope.

496 *For zebrafish embryos:* 2 dpf zebrafish embryos were taken and dechorinated. 10 embryos were
497 incubated with 10mM BCECF-AM (Thermofisher scientific) in embryo water at 28C incubator for 15
498 minutes. After incubation the embryos were washed, embedded in methylcellulose and taken for
499 quantitative imaging using Leica SP8 confocal microscope.

500

501 *Plasmid and silencing RNA Transfections*

502 B16 cells were trypsinized and seeded at density of 1×10^5 cells/well in 6 well plate (BD Bioscience) and
503 incubated overnight in antibiotic containing DMEM + 10% FBS. At the time of transfection, the cells
504 were replaced with serum and antibiotic free media OptiMEM (Gibco, Life Technologies). Lipofectamine
505 2000 was used at a ratio of 1:2 with CA14 siRNA or the scrambled control siRNA (Dharmacon). The
506 cells were incubated for 6 hours with the transfection mixture containing Lipofectamine 2000, OptiMEM
507 and the siRNA. The media was then replaced with antibiotic containing DMEM+10% FBS and incubated
508 for 72 hours and downstream experiments were performed.

509 NHEM cells were trypsinized and seeded at density of 1×10^5 cells/well in 6-well plate (BD
510 Bioscience) and incubated overnight with antibiotic containing M254 (Thermofisher Scientific). Next day
511 cells were washed with DPBS (Gibco, Life Technologies) and were replaced with antibiotic free
512 OptiMEM media (Gibco, Life Technologies). Cellfectin (Invitrogen) was used at a ratio of 1:2 with MITF
513 siRNA and CA14 siRNA (Dharmacon) and incubated for 6 hours. The transfection mixture was replaced
514 with antibiotic containing M254 media and incubated for 72 hours.

515

516 *Treatment for the induction of MITF:*

517 Melan-a cells were trypsinized and seeded at density of 1×10^5 cells/well in 6 well plate (BD Bioscience)
518 and incubated overnight with antibiotic containing RPMI 1640+10% FBS. Next day fresh media was
519 added to the cells and treatment was performed with α -MSH (1000nM; Sigma) and IBMX (60uM; Sigma).

pH regulates melanocyte maturation

520 The cells were incubated at 37⁰ C at 10% CO₂ and were then harvested for protein isolation after 48 and
521 72 hours.

522 *RNA Isolation & cDNA synthesis*

523 Cells were trypsinised with 0.1% trypsin and the pellet was washed twice with 1X Phosphate Buffered
524 Saline (PBS; Gibco Life Technologies). To the pelleted cells 1ml of TriZol (Ambion, Invitrogen) was
525 added and stored at -80⁰ C overnight. The RNA was isolated using standard Trizol based method. The
526 isolated RNA was subjected to DNase (Qiagen) treatment for 20 minutes at room temperature. Column
527 purification of the RNA was performed using RNAeasy mini kit (Qiagen, Cat 74104) according to
528 manufacturer's protocol. 100-500 ng of RNA was taken for cDNA synthesis using Superscript III
529 (Invitrogen, Life Technologies) according to manufacturer's protocol. Q-RT pcr experiments were
530 performed either by SYBR green or TaqMAN assay probes (Details provided in **Supplementary table 1**)
531 according to manufacturer's protocol using Lightcycler 480 II (Roche).

532

533 *Isolation of nuclear and melanosomal fractions*

534 Nuclear proteins were extracted using NE-PERTM nuclear and cytoplasmic extraction reagents
535 (Thermoscientific; 78833) according to manufacturer's protocol. Melanosomes were isolated using
536 protocol previously described (Watabe et al, 2005). The B16 tumor from mice was excised and washed in
537 homogenization buffer and was homogenized with 120 strokes of dounce glass homogenizer. Post nuclear
538 supernatant was isolated and then separated on a stepwise density gradient and centrifuged at 1,00,000 g
539 for 1 hour at 4⁰ C in a swing out rotor. The stage III and IV melanosomes which preferentially localized to
540 the highest density fraction (1.8-2.0) were collected and protein was isolated using NP40 lysis buffer.

541

542 *Protein Isolation and Western Blot analysis*

543 Cells were trypsinised with 0.1% trypsin and the pellet was washed twice with 1X Phosphate Buffered
544 Saline (PBS; Gibco Life Technologies). NP40 lysis buffer (Invitrogen) was added to the pellet and was
545 incubated on ice for 30 minutes with pipetting at interval of 10 minutes. The cells were centrifuged down

pH regulates melanocyte maturation

546 at 13,000 rpm for 30 minutes at 4⁰C (Eppendorf Centrifuge 5415 R). The supernatant was collected and
547 transferred to a fresh microfuge tube. For Histone blots lamelli lysis buffer was used. The protein was
548 estimated using standard BCA protocol (Pierce BCA protein assay kit; ThermoScientific). Equal amount
549 of protein from each sample were resolved in 10 or 12% % SDS gel in 1X Tris glycine buffer. The gel
550 was blotted onto 0.45 uM PVDF membrane (Millipore) at 300mA for 2 hours. 5% Skim milk was used
551 for blocking for 1 hour at room temperature. Incubation with primary antibody was performed for
552 overnight at 4⁰ C. Primary antibody dilutions are provided in **Supplementary table 1**. After washing the
553 blot with 1X TBST, the blot was incubated with HRP conjugated secondary antibody for 1 hour at room
554 temperature. After washing with 1X TBST the blot was developed using Immobilon Western (Millipore)
555 in the Syngene GBOX Chemiluminescence instrument. Densitometry analysis was performed using
556 ImageJ software.

557

558 *Chromatin Immunoprecipitation and q-RT PCR*

559 B16 Melanoma cells at 80% confluence was fixed with 10% formalin (Sigma Cat No HT501128) and
560 incubated at 37 C for 10 minutes. 2.5 M Glycine was added to the cells and again incubated at 37 C for 10
561 minutes. Cells were washed with Ice cold 1X PBS containing protease inhibitors. Cells were then scraped
562 and centrifuged at 1000 rpm for 5 minutes at 4C. The cell pellet was lysed in SDS lysis buffer (1% SDS,
563 10mM EDTA, 50mM TRIS (pH 8.1)) on ice for 30 minutes. The cells were then sonicated on bioruptor
564 (DIAGENODE) in ice. The chromatin lysate was then estimated for protein content using BCA kit
565 (Pierce). 5ug of MITF C5 antibody (Abcam) was taken and incubated with Protein G Dynabeads
566 (ThermoScientific) overnight at 4 C on a rotator. 3ug of acetylated H3K27 antibody was incubated with
567 Protein A dynabeads (ThermoScientific) overnight at 4 C on a rotator. The next day the sera was cleared
568 and washed with Ice cold dilution buffer (2mM EDTA, 150mM NaCl, 20mM Tris HCl (pH 8)). 500 ug of
569 chromatin lysate was added to the beads and the final volume was made up to 750ul using the dilution
570 buffer and incubated for 6 hrs at 4C in a rotator. 10% of the lysate was kept separately as input. After
571 incubation the magnetic beads were washed with Low salt Buffer (0.1 % SDS, 1% Triton X 100, 2mM

pH regulates melanocyte maturation

572 EDTA, 20mM Tris HCl (pH 8), 150mM NaCl), high salt buffer (0.1 % SDS, 1% Triton X 100, 2mM
573 EDTA, 20mM Tris HCl (pH 8), 500mM NaCl) and LiCl buffer (0.25 M LiCl, 1% Igepal C-630, 1mM
574 EDTA, 10mM Tris HCl (pH 8), 1% deoxycholate). Finally the magnetic beads were incubated overnight
575 at 65 C in elution buffer (1% SDS, 0.75% sodium bicarbonate) and 1ul of 20mg/ml proteinase K (Sigma)
576 for elution and subsequent reverse crosslinking. The magnetic beads were separated from supernatant and
577 column purified using QIAgen pcr purification kit, the input control was also included in the purification
578 step. SYBR qRT PCR was setup using 5ul of eluted DNA and graphs were plotted as percentage input.

579

580 *Immunofluorescence*

581 The cells plated on coverslips were washed twice with 1X PBS and then fixed with 4% PFA at 37⁰C for
582 20 minutes. The cells were again washed twice with 1X PBS and permeabilized with 0.01 % Triton X100
583 (Sigma). The cells were blocked with 5% Normal goat serum (Jackson Laboratories) overnight at 4⁰C.
584 The cells were washed twice with PBST (1X PBS with 0.01% Tween-20). The cells were then incubated
585 with 1:50 dilution of CA14 antibody (Abcam) in a moist chamber for 1 h at room temperature. Incubation
586 with secondary antibody (Alexafluor488; Molecular probes, ThermoScientific) was performed at room
587 temperature for 1 h. The cells were again washed with PBST. The cells were then mounted on slides
588 using Antifade slowfade DAPI (Molecular probes, Invitrogen) and visualized using Confocal Microscope
589 (Zeiss LSM 510 or Leica SP8).

590

591 *P300 HAT activity assay*

592 HAT activity assay was performed using KAT3B/P300 inhibitor fluorometric assay screening kit (Abcam,
593 ab196996) according to manufacturers protocol with minor modification. Tris-Cl pH 7.15 and pH 7.95
594 was added at an additional concentration of 50mM to buffer provided in the kit and the assays were
595 performed with the modified buffers.

596

597 *Zebrafish Ethics Statement*

pH regulates melanocyte maturation

598 Fish experiments were performed in strict accordance with the recommendations and guidelines laid
599 down by the CSIR Institute of Genomics and Integrative Biology, India. The protocol was approved by
600 the Institutional Animal Ethics Committee (IAEC) of the CSIR Institute of Genomics and Integrative
601 Biology, India (Proposal No 45a). All efforts were made to minimize animal suffering.

602 *Zebrafish strains and maintenance*

603 The wild type strain Assam WT (ASWT) and Tyrp1 reporter, *Tg(ftyrp1: GFP)* zebrafish lines were used
604 for morpholino injections and were maintained according to standard zebrafish husbandry protocols.
605 *ftyrp1:GFP* plasmid was a kind gift from Dr Xiangyun Wei (Zou et al, 2006), University of Pittsburgh
606 School of Medicine and the transgenic line was created at CSIR-IGIB zebrafish facility using tol2
607 transposase microinjections in ASWT line. Phenylthiourea (PTU; 0.003%) was added to embryo water
608 before 24 hours post fertilization (hpf) to prevent melanin from masking the GFP fluorescence. For pH
609 rescue experiments the embryos were grown in embryo media buffered with 10mM HEPES.

610

611 *Morpholino knockdown of zebrafish Ca14:*

612 Antisense morpholino was synthesized from Gene Tools against Ca14 of zebrafish. The morpholino was
613 designed to block the translation of *car14* gene. Morpholino sequence with translation initiation site
614 (initiator ATG codon) is underlined CCATGATTTCACTATTCTCCCTACA. Standard control was
615 obtained from Genetools and injected at same dosage as *ca14* morpholino.

616

617 *ca14 CRISPR mutant generation*

618 Zebrafish *ca14* CRISPR was designed using ECRISP software (<http://www.e-crisp.org/E-CRISP/>). The
619 CRISPR sgRNA sequence was in vitro transcribed using mMessage mMachine T7 ULTRA kit
620 (ThermoFisher scientific). 300 pg of sgRNA was injected along with 500 pg of *spcas9* protein (kind gift
621 from Dr Souvik Maiti, CSIR-IGIB). The F0 embryos were screened using T7 endonuclease assay for

pH regulates melanocyte maturation

622 mutations and the putative mutant siblings were grown to adulthood and inbred to get F1 animals.

623 Mutations in the F1 fishes were confirmed using sanger sequencing.

624 The cross involving the ca14fs003 reported herein involves a $ca14^{fs003}/-$ male with a $ca14^{fs003}/+$
625 female that accounts for 50% of the embryos to be phenotypic. The genotypes of the phenotypic embryos
626 and normally pigmented embryos arising from this cross were ascertained to be $ca14^{fs003}/-$ and
627 $ca14^{fs003}/+$ respectively using PCR based amplification.

628

629 *Zebrafish imaging*

630 The embryos were manually dechorinated and embedded in 2% methylcellulose. Control and Morphant
631 embryos were imaged laterally and dorsally for melanophore quantitation. Brightfield Images were taken
632 using Zeiss Stemi 2000-C microscope; for fluorescence microscopy Zeiss Axioscope A1 was used.

633

634 *RNA Isolation from embryos*

635 Total RNA was extracted from zebrafish embryos using TriZol (Invitrogen). cDNA was synthesized
636 using Superscript III kit (Invitrogen). Real time quantitative PCR was performed using SYBR Green
637 (Kapa Biosystems) or TAQMAN probes (details provided in **supplementary table 1**) and data was
638 generated in ROCHE Lightcycler 480 II.

639

640 *mRNA injection in zebrafish embryos:*

641 For rescue experiments the coding sequence of mouse *Ca14* gene was cloned with kozak sequence
642 inserted in front of translation start site (**Supplementary table 1**). The amplicon was cloned into TOPO-
643 Zero blunt vector (Thermofischer Scientific). RNA was made using *in-vitro* transcription kit T7 Ultra
644 mRNA synthesis kit (Ambio – Thermofischer Scientific). 10 pg of Ca14 WT or Ca14_{T199I} RNA was
645 injected into the cell at one cell stage Ca14^{fs003} embryos.

646

647 *Estimation of Melanin content:*

pH regulates melanocyte maturation

648 Dorsal images of Control and ca14 morphant embryos were taken at 2 dpf. The images were imported to
649 ImageJ and mean grey values were taken for melanophores of each embryo set. Mean grey values are
650 inverse proportional to the melanin content of the cell. Corresponding values were then plotted using
651 Graphpad Prism.

652

653 *Statistical analysis and Graphs:*

654 Student's t test was performed to obtain statistical significance in the data. Asterisk on the error bar
655 corresponds to *($P \leq 0.05$), ** ($P \leq 0.01$), *** ($P \leq 0.001$), **** ($P \leq 0.0001$) and ns ($P > 0.05$). Graphs
656 were plotted using Graphpad prism.

657

658

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663

664 **Conflict of interest**

665 R.S.G. is the co-founder of the board of Vyome Biosciences, a biopharmaceutical company in
666 the area of dermatology unrelated to the work presented here. Other authors do not have any
667 competing interests.

668

669 **Author contributions**

670 D.A.R, V.G, R.S.G and T.N.V designed experiments. D.A.R, V.G, F.S and Y.J.S, executed the
671 experiments with cultured cells. A.S performed experiments pertaining to electron microscopy. D.A.R,
672 S.S and T.N.V were involved in the design and execution of zebrafish experiments. D.A.R, Y.J.S, V.G
673 along with S.S, R.S.G and T.N.V were involved in data analysis, interpretations and writing of the
674 manuscript.

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913 **Figure Legends**

914 **Fig 1: Modulation of intracellular pH by CO₂ results in predictable changes in pigmentation via a**
915 **transcriptional change**

916 A. B16 cells were maintained at 5 or 10% CO₂ for indicated days and intracellular pH (pH_i) was
917 measured by ratiometric imaging using BCECF-AM for the respective conditions. While the day
918 4 and day 8 of 10% CO₂ grown cells remained close to 7.0, in 5% condition the pH_i on day 4 was
919 high by almost one pH unit. Data is obtained from three biological replicates with around 60 cells
920 each.

921 B. Pellets of B16 cells at various days under 5 or 10% CO₂ culture conditions. While the initial day 4
922 pellets look comparable, but on day 8, 5% CO₂ grown cells accumulate melanin, while the 10%
923 CO₂ grown cells remain depigmented.

924 C. Transmission electron micrograph images of day 8 cells indicate that the 5% CO₂ grown cells
925 have many darkly stained melanosomes, whereas the 10% CO₂ grown cells are devoid of these
926 pigmented structures.

927 D. Top panel shows *in-gel* tyrosinase activity developed using L-DOPA as the substrate and below is
928 part of the gel stained using coomassie brilliant blue. (bottom panel) Western blot analysis of Tyr,
929 Gp100, Dct, Mitf and Ca14 proteins normalized to tubulin. Numbers represent tubulin normalized
930 fold changes corresponding to day 4 cells grown at 5% CO₂. 10% CO₂ reduces expression of
931 pigmentation related markers without a significant decrease in Mitf.

932 E. qRT-PCR analysis of pigmentation related gene transcripts Gp100, Dct, Tyrp1 and Tyr
933 normalized to 18s rRNA on days 4, 6 and 8 during pigmentation. The fold changes are depicted
934 for the corresponding days for cells grown at 5% CO₂. Progressive reduction in the mRNA
935 expression of pigmentation genes is observed at the transcript level.

936

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939 **Fig 2:CA14 expression is directly controlled by Mitf**

- 940 A. (top) Panel of carbonic anhydrases expressed in B16 cells along with (bottom) pigmentation
941 genes during the course of in vitro pigmentation oscillation. The expression changes are
942 represented as a heat-map relative to the expression on day 0. Notably Ca14 follows a concordant
943 pattern of expression with the pigmentation genes.
- 944 B. Western blot analysis of CA14, Mitf and normalization by Tubulin, on treatment with Mitf
945 inducers 60 μ M Isobutyl methyl xanthine (IBMX) and 600nM alpha-melanocyte stimulating
946 hormone (α -MSH) for 48 and 72h in Melan-A cells. Fold change with respect to control untreated
947 cells normalized to tubulin expression is depicted as numbers below each lane.
- 948 C. Western blot analysis of CA14, Mitf and normalization by Tubulin, on treatment with MITF
949 inducer Isobutyl methyl xanthine (IBMX) for 48h in primary human melanocytes. Fold change
950 with respect to control untreated cells normalized to tubulin expression is depicted below each
951 lane.
- 952 D. qRT-PCR for *ca14*, *mitf*, *dct*, *trp1* and *tyr* transcripts upon treatment with α -MSH for 12 and 24h
953 in Melan-A cells. Fold change is depicted (mean \pm SEM, n=2) calculated using *18s rrna* as the
954 reference.
- 955 E. Dual luciferase assay performed with IBMX for 24h on B16 cells transfected with luciferase
956 construct (pGL4.23) containing 3kb upstream region of *ca14* promoter, or the transcription start
957 sites proximal 1kb, middle, or the distal 1 kb region of the promoter. Renilla luciferase driven by
958 cytomegalovirus promoter (pGL4.75) was used for reference. Error bars represent SEM across
959 three independent experiments. IBMX responsive region appears to be in the 1kb proximal as
960 well as distal regions of the promoter.
- 961 F. Chromatin Immunoprecipitation using Mitf antibody (C5) or normal mouse IgG control, was
962 followed by qRT-PCR performed for mitf binding sites in Ca14 promoter and intron region.
963 Graphs are plotted as percent input. Trp1 and cdk2 were taken as positive control. Bars represent
964 mean \pm SEM across two biological replicate experiments.

pH regulates melanocyte maturation

965 G. Western blot analysis of Ca14, Mitf and Dct normalized to Gapdh upon knockdown using *Mitf*
966 siRNA in Melan-A cells.

967 H. Western blot analysis of CA14 and MITF normalized to tubulin upon knockdown using *MITF*
968 siRNA in primary human melanocytes.

969

970 **Fig 3: Transient silencing of *Ca14* in Zebrafish decreases melanocyte maturation**

971 A. Brightfield images of the lateral view of control and Ca14 morphant embryos at 48 hours post
972 fertilization (hpf). The black structures observed are melanophores, the melanin containing cells
973 equivalent to mammalian melanocytes. These are pale in the morphants. Scale bar 100 μ m.

974 B. Representative fluorescence images of control and Ca14 morphant embryos at 48 hours post
975 fertilization (hpf) from *ftyrp1*:GFP line, wherein the melanocytes are marked by the expression of
976 GFP. Number of melanocytes remain unaffected in the morphants.

977 C. Melanin quantitation from the bright field images of control and Ca14 morphants carried out
978 using Image J platform. The mean grey values are inversely linked to melanin content of the
979 embryo, and are represented as scatter plot across melanophores from multiple animals.

980 D. Number of *ftyrp1* promoter driven GFP positive melanophores from control and Ca14 morphant
981 embryos at 48 hours post fertilization remains unchanged.

982 E. qRT-PCR quantification of pigmentation genes tyrosinase (*tyr*), F. dopachrome tautomerase (*dct*)
983 and G. tyrosinase related protein 1b (*tyrp1b*) between control and ca14 morphants at 36 and 48
984 hpf, compared to 24 hpf using beta-actin as the normalization reference. Error bars represent
985 SEM across three independent experiments normalized to corresponding control MO set with
986 RPS11 as the normalization control.

987

988

989

990 **Fig 4: CA14 causes increase in intracellular pH observed during pigmentation program**

- 991 A. Western blot analysis of CA14 normalized to tubulin during pigmentation. Indicated days (day 0,
992 4, 6 and 8) represent number of days after initiating the pigmentation program in the pigment
993 oscillator model. Numbers indicate normalized fold change *wrt* to tubulin with day 0 as the
994 reference.
- 995 B. Intracellular pH (pH_i) probed by ratiometric pH sensitive fluorescent dye BCECF-AM in B16-
996 melanoma cells during different days of pigmentation. The data represents mean \pm standard
997 deviation of at least 100 randomly chosen cells. Statistical analysis was performed using unpaired
998 t test across three independent biological replicates. The trend in pH_i follows Ca14 expression in
999 5% CO_2 condition. While pigmentation conducive 5% CO_2 shows an increase in pH_i , the non-
1000 conducive 10% CO_2 does not show the elevation in pH_i .
- 1001 C. Western blot analysis of Ca14 normalized to tubulin on day 4 and day 8 of pigmentation from
1002 cells grown at 5% and 10% CO_2 respectively. Please note that the normalization blot for tubulin
1003 represented here is also depicted in Fig 1D. The increase in Ca14 expression on day 4 is evident
1004 under both conditions, thereby prevailing CO_2 levels in this system drives pH_i changes.
- 1005 D. pH_i probed by BCECF-AM in B16-melanoma cells on siRNA knockdown of *cal4* and on
1006 overexpression of wild type or the catalytically inactive form (CA14_{T199I}). The data represents
1007 mean \pm standard deviation of at least 30 transfected cells. Statistical analysis was performed using
1008 unpaired t test. The data is representative of two experimental sets.
- 1009 E. Confocal image of immunocytochemistry using CA14 antibody (green) on permeabilized B16
1010 melanoma cells, counter stained by PI (red). Nuclear localization of the Ca14 signal is evident.
- 1011 F. Western blot analysis of subcellular fractions enriched in nucleus and melanosome, using CA14
1012 antibody. H2AZ antibody was used as a marker for nuclear and DCT for melanosomal
1013 enrichments.

1014

1015 **Fig 5: CA14 brings about transcriptional regulation of downstream pigmentation genes through**
1016 **histone acetylation**

1017 A. Western blot analysis of Dct, Gp100 and Mitf proteins along with Ca14 and tubulin upon
1018 knockdown using *Cal4* shRNA in B16 cells. Numbers represent tubulin normalized fold changes
1019 wrt control non-targeting ShRNA.

1020 B. Gene expression analysis using qRT-PCR of Ca14 and Dct, upon *cal4* knockdown using shRNA
1021 in B16 cells. Fold change normalized to *gapdh* wrt control non-targeting ShRNA. Bars represent
1022 mean \pm SEM across 4 independent biological replicates.

1023 C. Luciferase assay of *Dct* promoter cloned downstream of firefly luciferase (pGL4.23), on
1024 knockdown using *cal4* shRNA. Bars represent mean \pm SEM across 3 independent biological
1025 replicates.

1026 D. Western blot analysis was carried out for specific acetylation of histones (H3K27, H2A.Z, H4K12,
1027 H2AK5 and H3K9) in Ca14 knockdown B16 melanoma cells. Bars represent log normalized fold
1028 changes wrt control non-targeting shRNA of mean \pm SEM across 2 independent biological
1029 replicates.

1030 E. Representative western blot of acetylations in histone H3.

1031 F. Chromatin Immunoprecipitation using acetylated H3K27 antibody or normal rabbit IgG as a
1032 control on day 4 pigmenting cells of the oscillator in control non-targeting ShRNA and Ca14
1033 shRNA transfected cells. qRT-PCR was performed for select promoters in the immunoprecipitate
1034 and input DNA. Relative normalized percent input DNA under each promoter is depicted as a
1035 heat-map.

1036 G. Histone acetyl transferase (HAT) activity as a function of pH for recombinant HAT domain of
1037 p300 protein is depicted. Compared to the HAT activity at pH 7.15, the activity at pH 7.95 was
1038 almost 8 fold.

pH regulates melanocyte maturation

- 1039 H. Cell pellets and real-time qRT-PCR levels of pigmentation transcripts *Dct*, *Tyr*, *Gp100* and *MITF*
1040 upon selective inhibition of p300/CBP HAT activity in B16 cells. p300 HAT inhibition resulted
1041 in depigmented cells with a decrease in pigmentation gene transcripts.
- 1042 I. Proposed model of melanocyte maturation depicts *Mitf* mediated induction of *Ca14*, which
1043 increases intracellular pH (pH_i) and changes chromatin activation marks (AcH3K27) on selective
1044 pigmentation genes, amplifying their expression by *MITF*.

1045

1046 **Fig 6: Targetted null mutation of *Ca14* by CRISPR demonstrates immature acidic melanocytes**

- 1047 A. Brightfield images of the lateral view of CRISPR targeted mutant *ca14*^{fs003} and control embryos at
1048 36 hours post fertilization (hpf) in F2 generation fishes. Scale bar 100 μm .
- 1049 B. Wildtype and *ca14*^{fs003/-} adult male animals were dark adapted for 24h. Image of the lateral view
1050 was captured under identical lighting and image capture settings.
- 1051 C. Zoomed up portion from the fourth lateral line demonstrates melanophores to be laden with less
1052 melanin content in the mutant animal.
- 1053 D. qRT-PCR quantification of pigmentation genes *tyrosinase* (*tyr*), *dopachrome tautomerase* (*dct*),
1054 *tyrosinase related protein 1b* (*tyrp1b*) and *microphthalmia associated factor a* (*mitfa*) between
1055 control and *ca14*^{fs003} at 36 hpf, using *rps11* gene as the normalization reference. While *mitfa*
1056 remains unaffected all other pigmentation genes are downregulated in the absence of functional
1057 *ca14*.
- 1058 F. Intracellular pH_i probed by BCECF-AM in *ca14*^{fs003} and sibling control zebrafish embryos.
1059 Readings were obtained from trunk region melanophores. n = 3 expts, at least 10 embryos each.
1060 A decrease in the ratio indicates acidification of melanocytes.
- 1061 G. Wild type as well as embryos obtained from the cross of *ca14*^{fs003/-} and *ca14*^{fs003+/-} were left
1062 uninjected or treated with embryo water buffered at pH 10.0 (between 18hpf till 36 hpf) or
1063 injected with 10 pg of in vitro transcribed mouse *Ca14* mRNA. Embryos were scored for

pH regulates melanocyte maturation

1064 pigmentation at 36 hpf. Ratios represent number of less pigmented phenotypic embryos to the
1065 total number of embryos scored. The proportion of less pigmented animals decreased upon
1066 mouse Ca14 mRNA injection as well as increased extracellular alkalinization.

1067

1068 **Supplementary Information**

1069 **SUPPLEMENTARY FIGURE LEGENDS:**

1070 **Fig S1: 10% CO₂ leads to extracellular acidification leading to decreased melanin content**
1071 **and increased proliferation**

1072 A. Line graph showing extracellular pH at various days of pigmentation in 5% and 10% CO₂
1073 cultured B16 cells.

1074 B. Bar graph depicts the colorimetric melanin estimation of B16 melanoma cells cultured under
1075 5% CO₂ and 10% CO₂ growth conditions for indicated days using synthetic melanin as a
1076 standard. Error bars represents independent biological replicate, n=3.

1077 C. Alteration of cellular pH by the modulation of CO₂ results in changes in cell proliferation in
1078 B16 cells as measured by cell count.

1079 **Fig S2: Gene expression data analysis from pigmentation models to identify putative**
1080 **effectors of melanocyte differentiation**

1081 B16 melanoma cells were made to transit between pigmented (differentiated) state and
1082 depigmented state state, using two methods: by passaging the depigmented cells in mouse as a
1083 tumor and culturing the cells in vitro. Microarray was performed on the four different *in vitro*
1084 passages (P1 to P4). Depigmented B16 cells were cultured *in vitro* at a low density and allowed
1085 to pigment for 12 days and to depigment for the next 8 days for two cycles. Microarray was
1086 carried out from Day 0 depigmented Day 4, Day 8 and Day 12 (pigmented) and Day 16 and Day

1087 20 (depigmented). Expression profiles of genes that showed a concomitant pattern of regulation
1088 across both models of melanocyte differentiation is listed. (GSE54359).

1089 **Fig S3: Validation of Ca14 antibody used in the study**

1090 A. Blots depicting the levels of Ca14 protein upon Ca14 siRNA mediated knockdown. Tubulin
1091 was used as normalizing control.

1092 B. Blots depicting the levels of Ca14 protein upon overexpression. Tubulin was used as
1093 normalizing control.

1094 **Fig S4: M box sequences in Human and Mouse ca14 promoter and genic regions.**

1095 **Fig S5: mRNA expression of carbonic anhydrase 14 during pigmentation**

1096 Bar graph depicting the relative mRNA levels of Ca14 during pigmentation in mouse B16
1097 melanoma cells. Error bars represent SEM from biological replicates across three different
1098 experiments.

1099 **Fig S6: Changes in CA14 expression correlate with pigmentation status of primary human
1100 melanocytes**

1101 A. Confocal image of Normal Human Epidermal Melanocytes (NHEM) cultured under different
1102 media conditions using MBM4 and M254 media available commercially. B16 cells were
1103 stained using for CA14 antibody (green) and the nucleus is counter stained using DAPI
1104 (blue).

1105 B. Protein levels of CA14 probed by western blot analysis in NHEM grown under different
1106 media conditions that retain melanocytes in a proliferative condition (MBM-4 medium with
1107 phorbol myristyl acetate (PMA)) and M254 (without PMA) that facilitates pigmentation.

1108 **Fig S7: ca14 morpholino causes pigmentation phenotype without affecting the survival of
1109 embryos**

1110 A. Percentage phenotype in Ca14 morpholino injected embryos w.r.t control morpholino
1111 represented as bar graph. Error bars represent SEM across four independent experiments.

1112 B. Percentage survival in Ca14 morpholino injected embryos w.r.t control morpholino
1113 represented as bar graph. Error bars represent SEM across four independent experiments.

1114 **Fig S8: Schematic of zebrafish gene ca14 depicting that CRISPR target region and the**
1115 **observed mutation in ca14^{fs003}**

1116

1117 **Supplementary Table 1**

1118 Excel sheet containing

1119 A. Sequences of primers

1120 B. qRT-PCR TAQMAN probes

1121 C. siRNA and shRNA catalog numbers

1122 D. Antibody catalog numbers and dilutions used in this study.

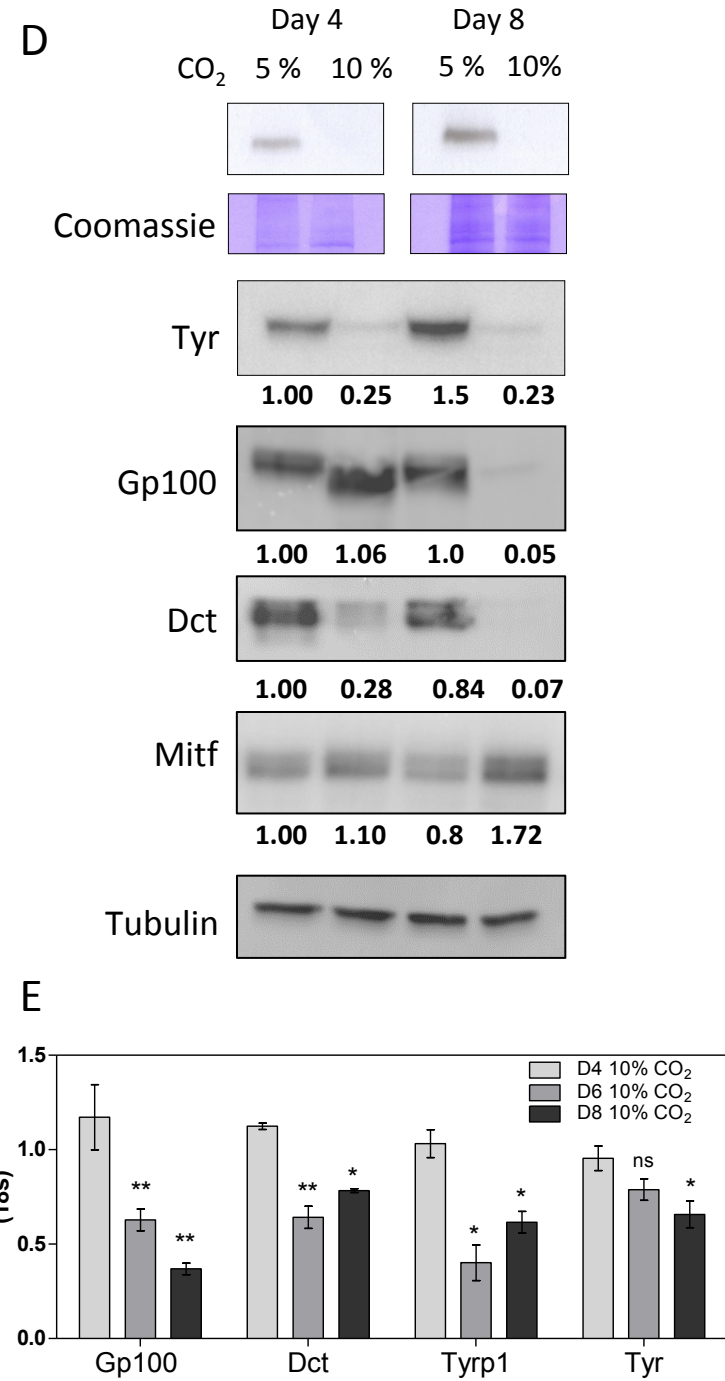
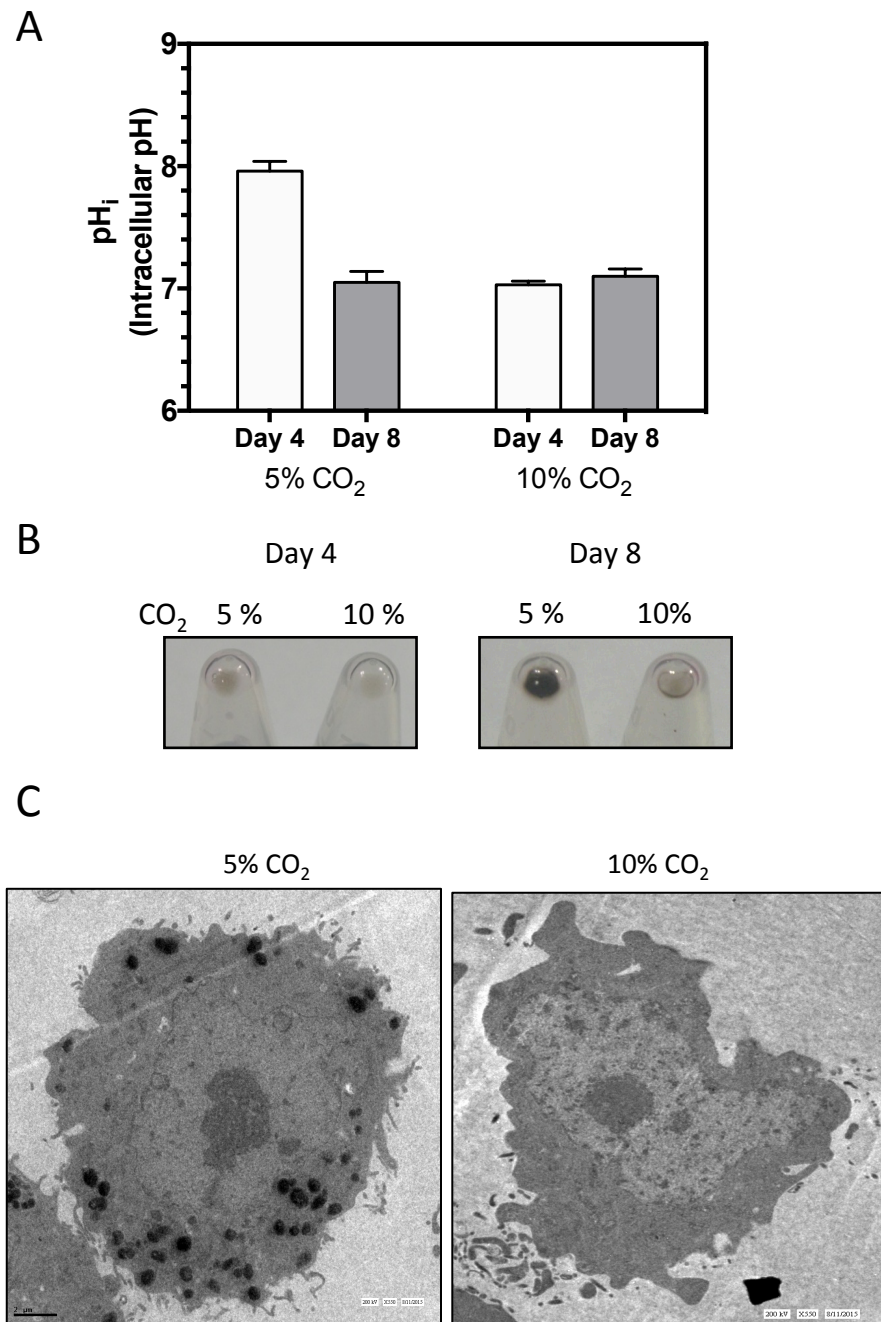


Fig 1

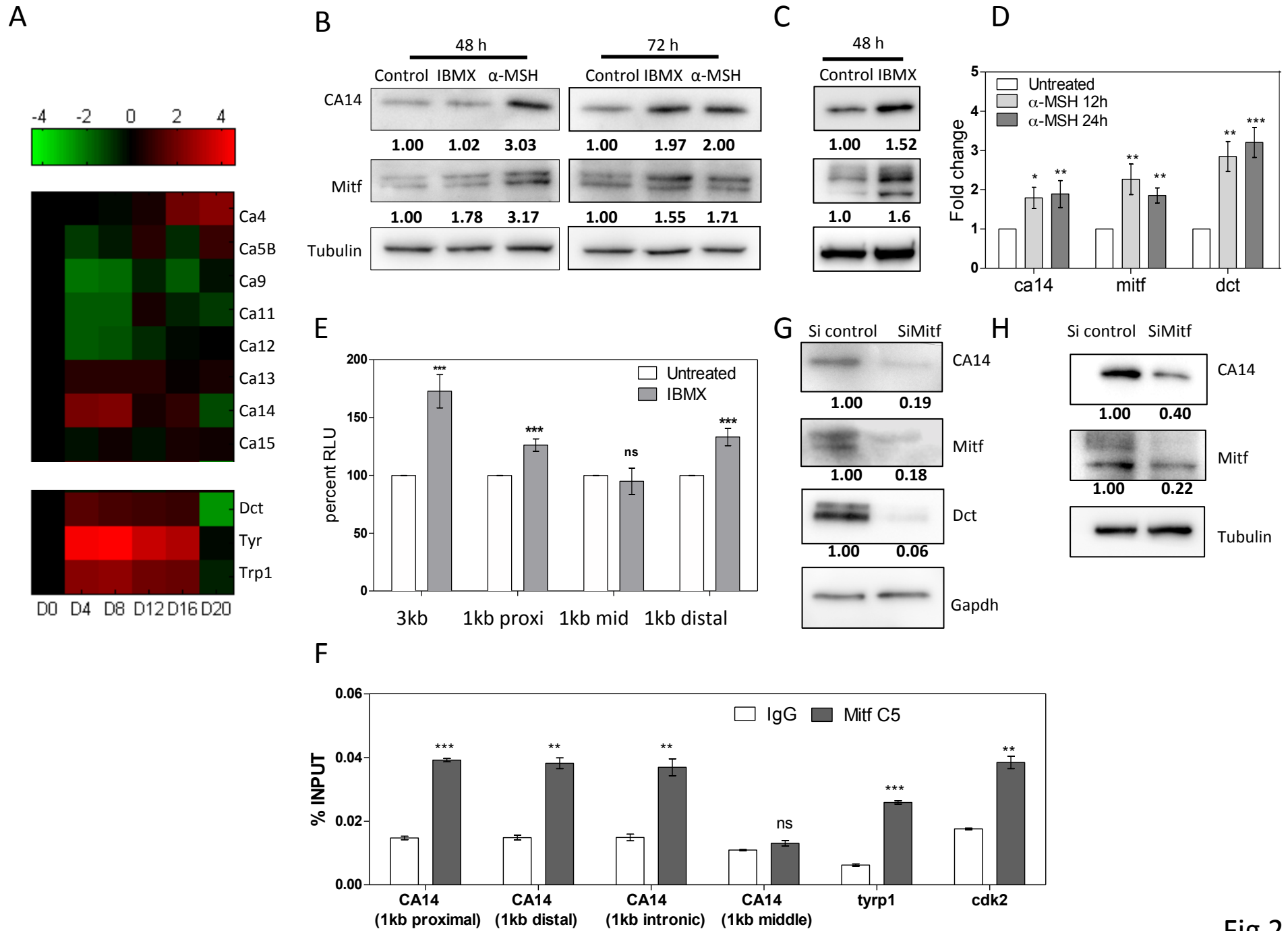


Fig 2

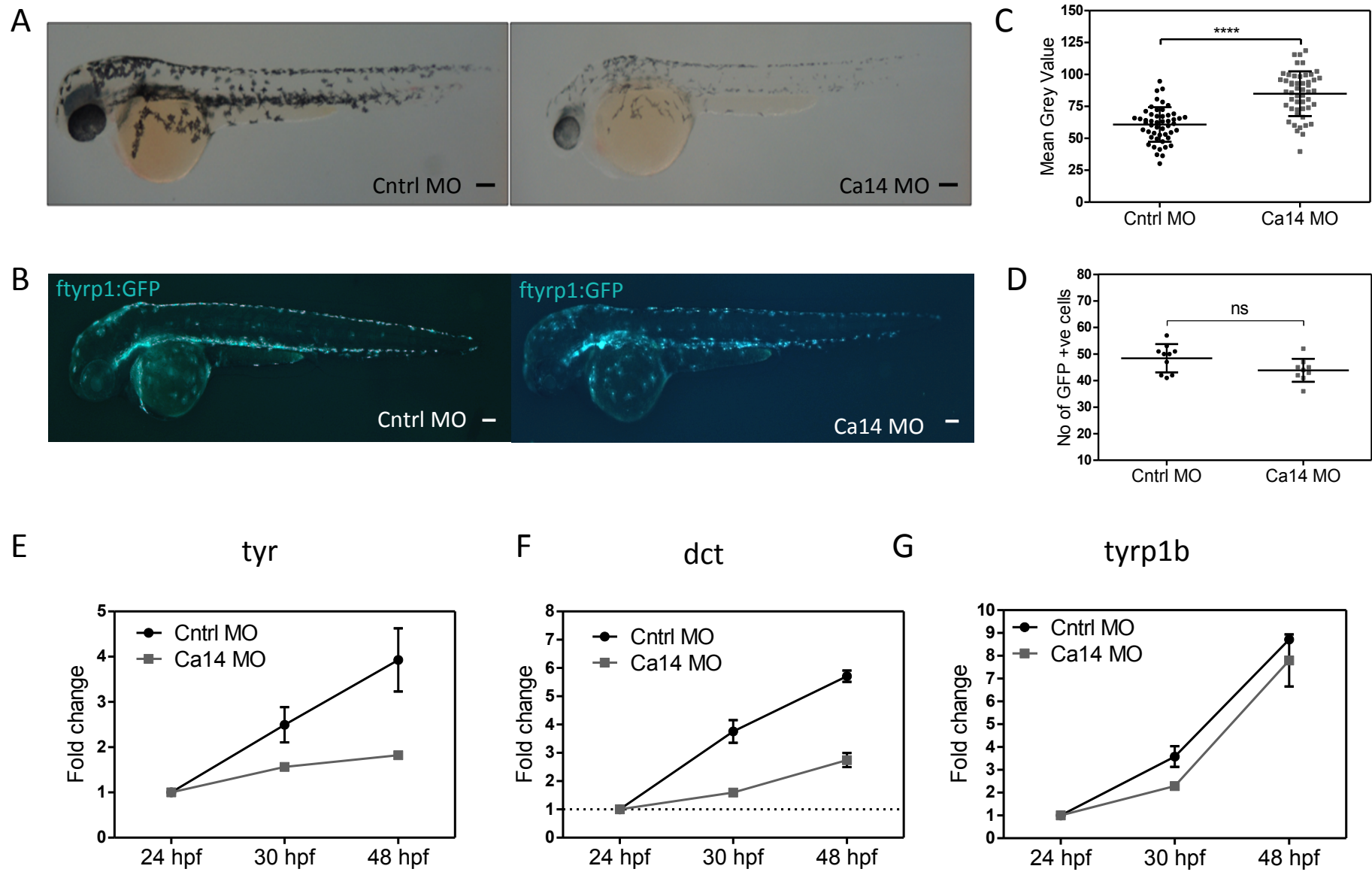


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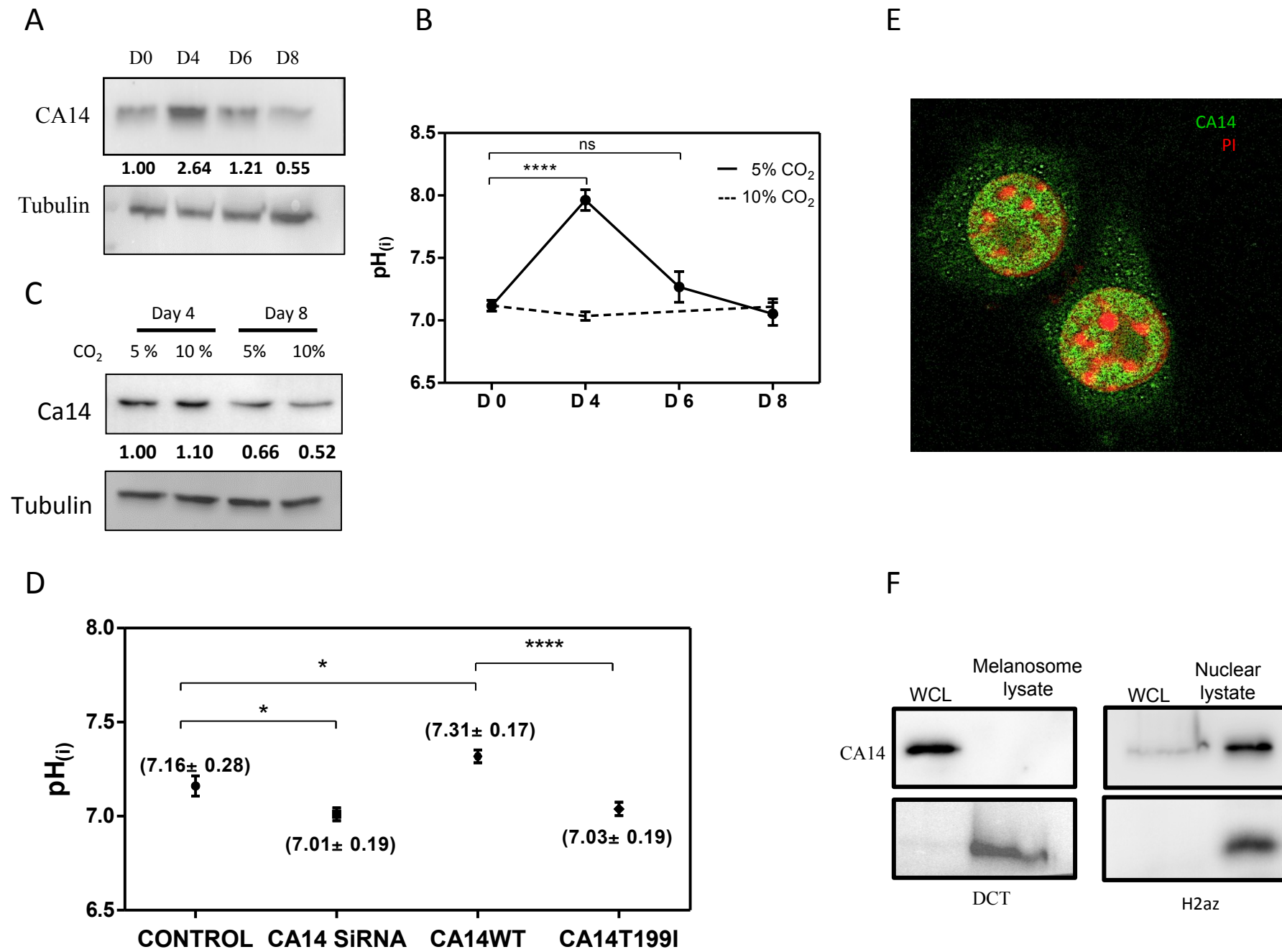


Fig 4

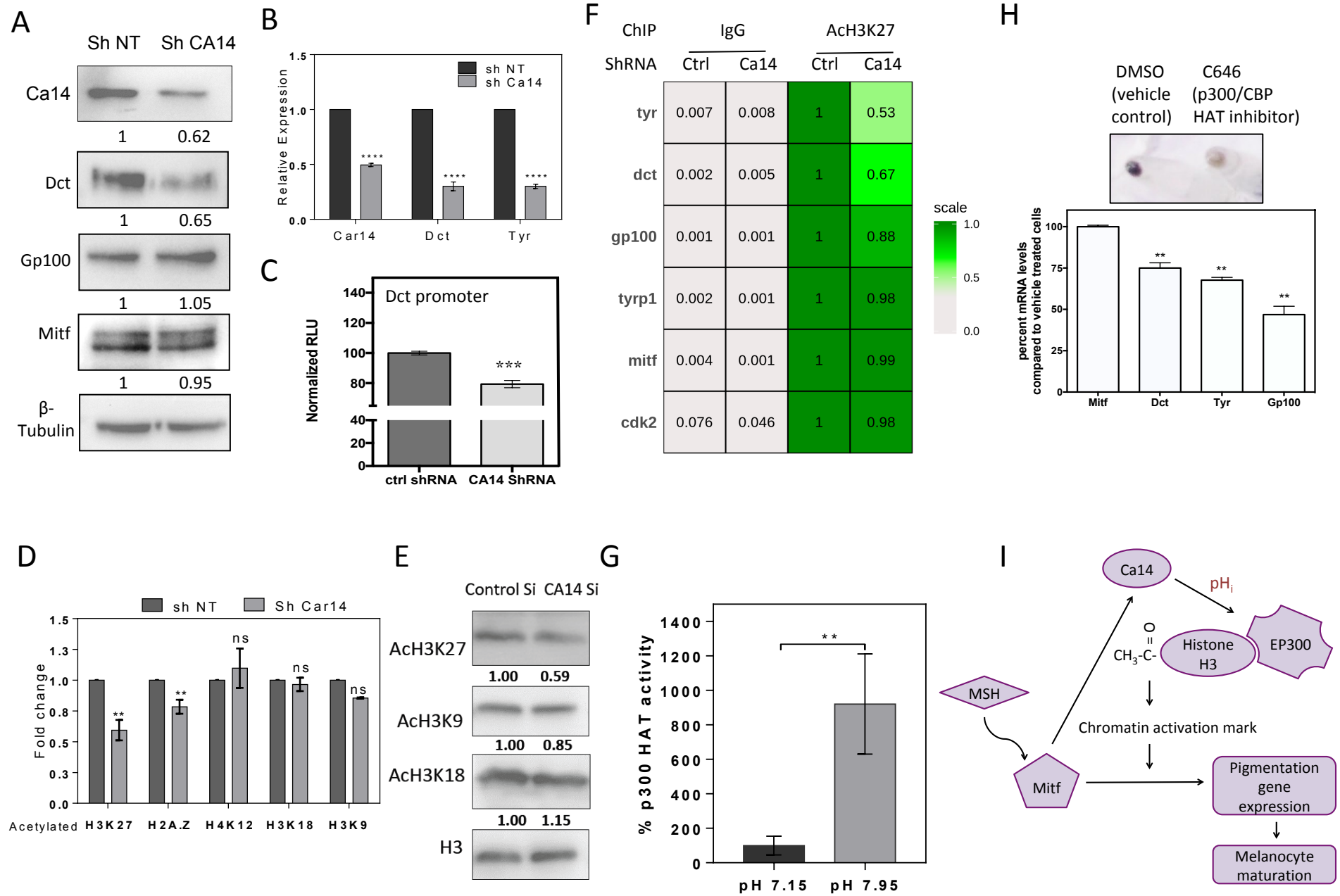
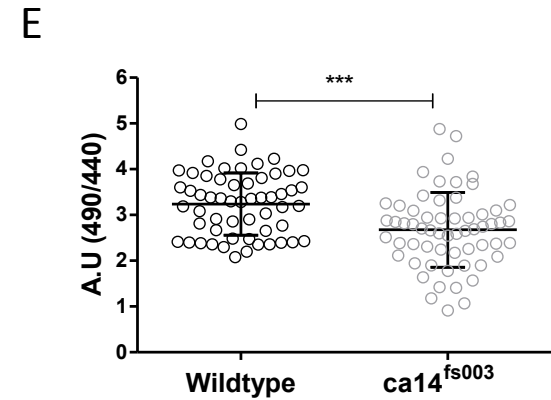
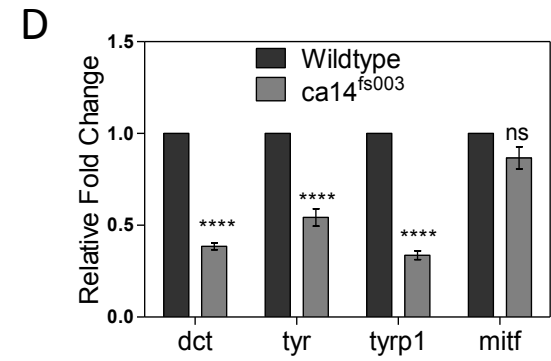
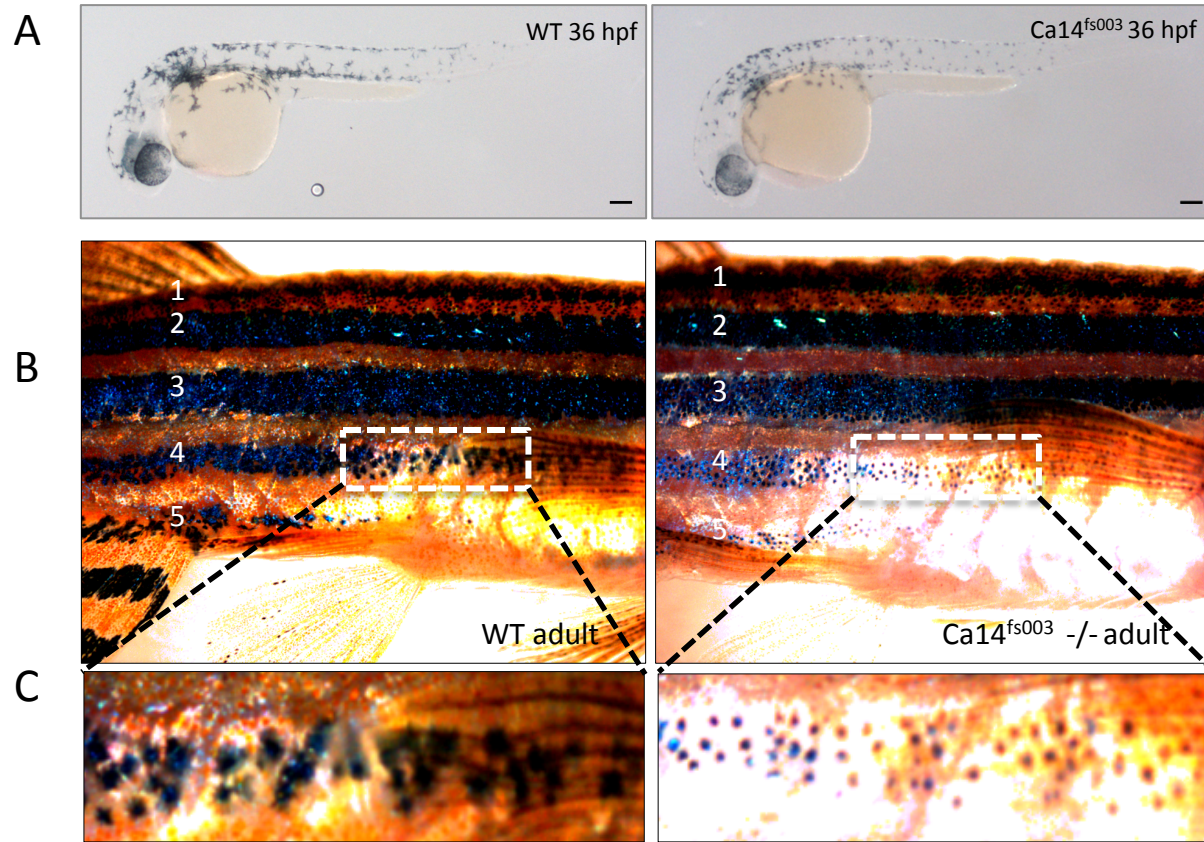


Fig 5



F

Treatment	number of phenotypic animals with less pigmented melanophores / total embryos analyzed	
	WT X WT	$Ca14^{fs003} +/-$ X $Ca14^{fs003} -/-$
Uninjected	1/57	30/64
mCA14 mRNA (10 pg)	0/67	17/52
pH 10.0 treatment	0/70	16/51

Fig 6

pH controlled histone acetylation amplifies melanocyte differentiation program downstream of MITF

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Supplementary Information

- Fig S1:** 10% CO₂ leads to extracellular acidification leading to decreased melanin content and increased proliferation
- Fig S2:** Gene expression data analysis from pigmentation models to identify putative effectors of melanocyte differentiation
- Fig S3:** Validation of Ca14 antibody used in the study
- Fig S4:** M-box sites in mouse and human Ca14 promoter and genic regions
- Fig S5:** mRNA expression of carbonic anhydrase 14 during pigmentation
- Fig S6:** Changes in CA14 correlate with pigmentation status of primary human melanocytes
- Fig S7:** ca14 morpholino causes pigmentation phenotype without affecting the survival of embryos
- Fig S8:** Schematic of zebrafish gene ca14 depicting the CRISPR target region and the observed mutation in ca14^{fs003}.

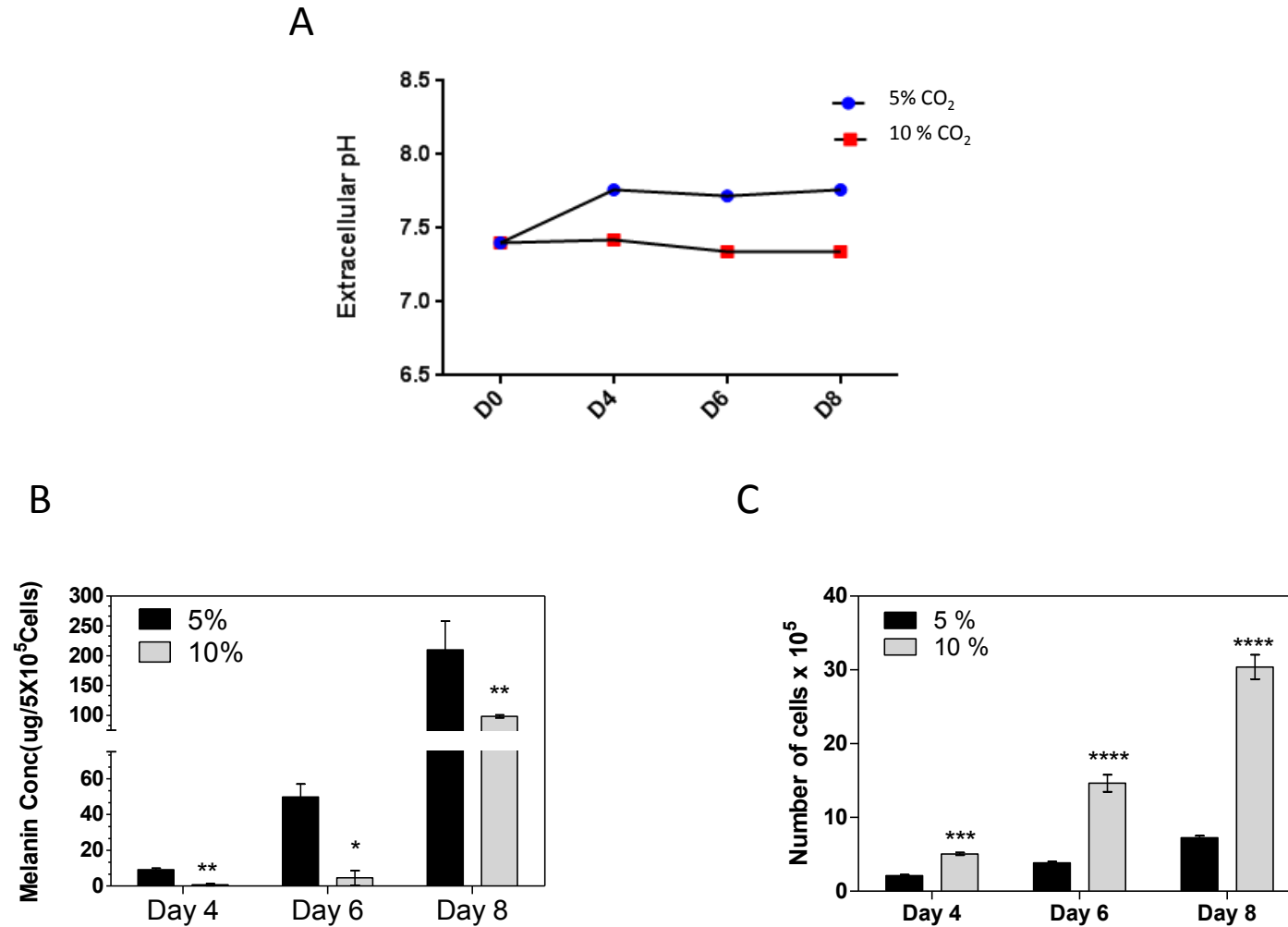
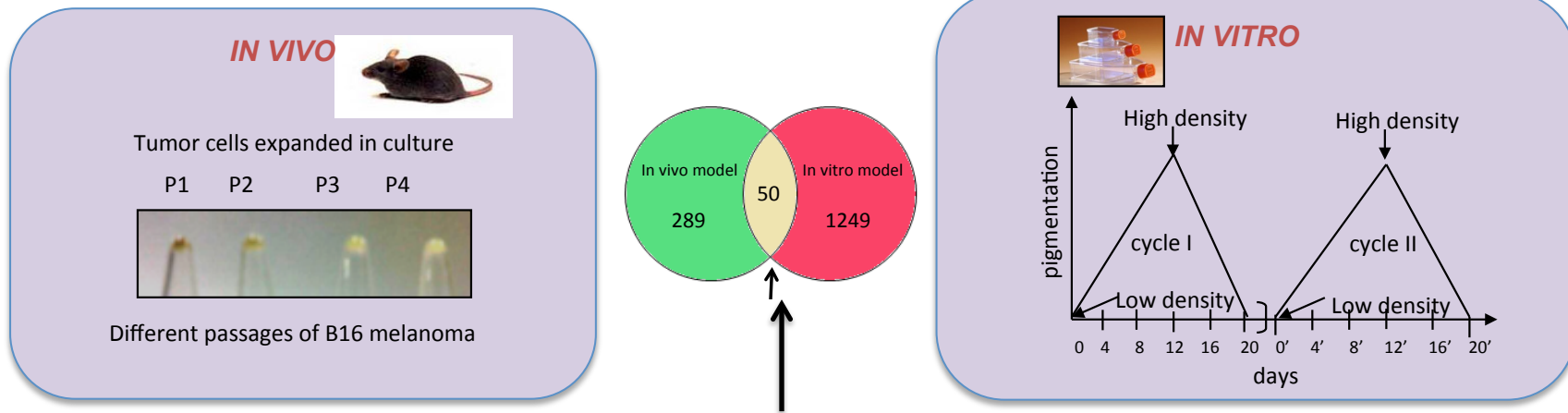


Fig S1: 10% CO₂ leads to extracellular acidification leading to decreased melanin content and increased proliferation

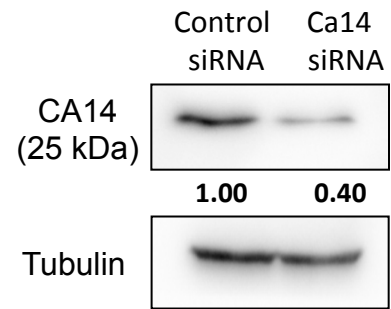


Potential regulators of melanocyte differentiation

0610011F0 6Rik	5031439G 07Rik	9930108O 06Rik	A830073O 21Rik	Bcl6	Bfsp2	Bglap-rs1	Bglap2	C130078N1 7Rik	Camk2d
H2afz	Ifitm3	Irf1	Kdelr3	Kif1b	LOC38070 6	Mcc	Mcoln3	Mlana	Mvp
D10Ertd61 0e	D11Lgp2e	D14Ertd66 8e	Daam1	Dlgap4	Gadd45a	Gsta1	Gsta2	Gsta3	H2-Q5
Plxnd1	Rab11fip5	Rab27a	Rapsn	Rrm2	Si	Socs3	Syt9	Tgfb3	Tyr
Ca14	Catnb	Cdk2	Nap1l1	Ndr2	Nos3	H2-T23	Aph1a	Tyrp1	Vcl

Fig S2: Gene expression data analysis from pigmentation models to identify putative effectors of melanocyte differentiation

A



B

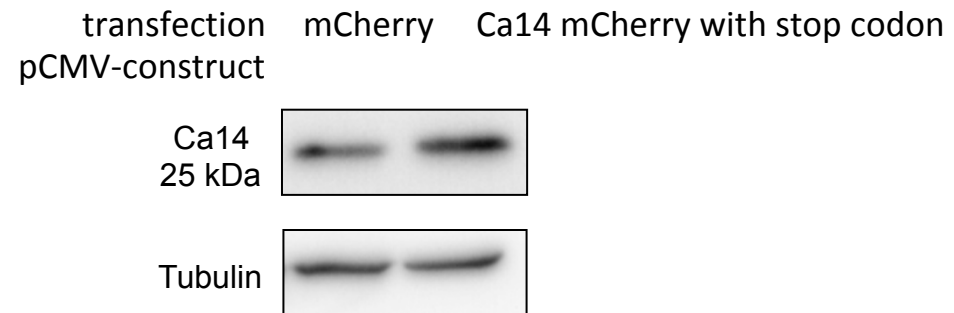


Fig S3: Validation of Ca14 antibody used in the study

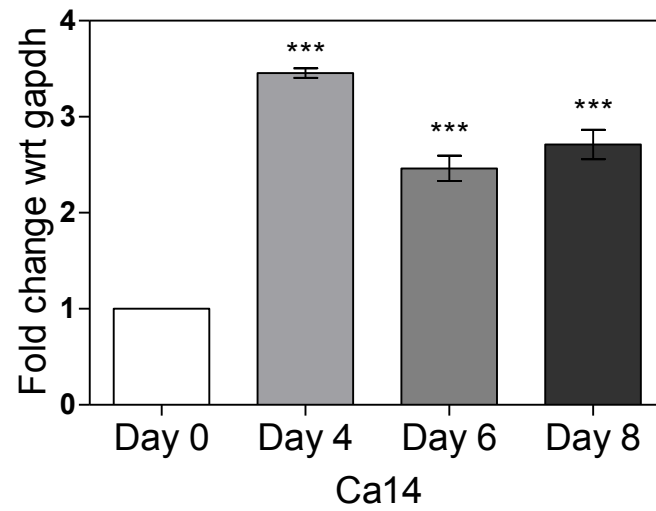
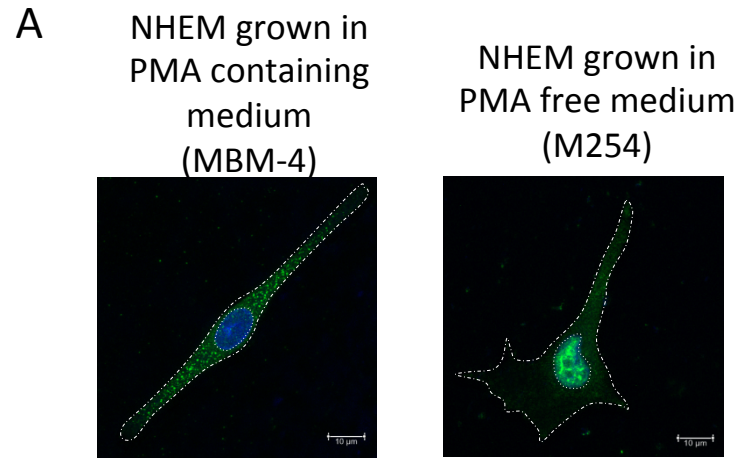


Fig S5: mRNA expression of carbonic anhydrase 14 during pigmentation



B

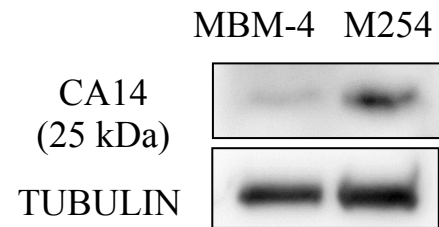


Fig S6: Changes in CA14 correlate with pigmentation status of primary human melanocytes

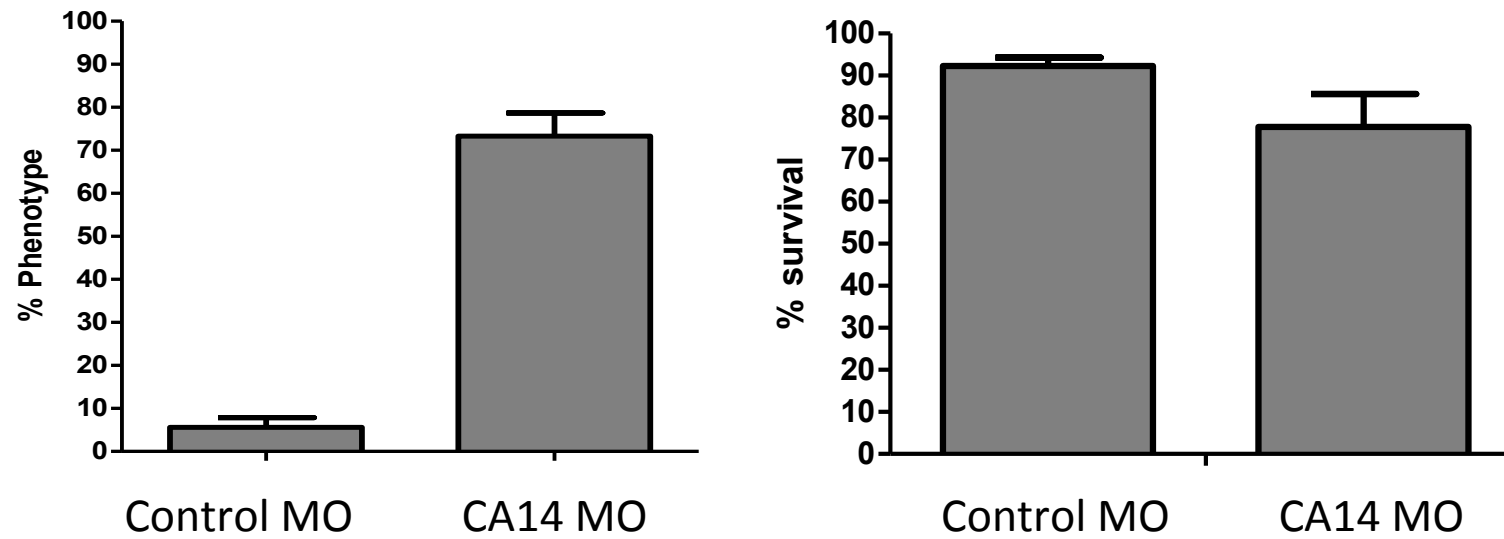
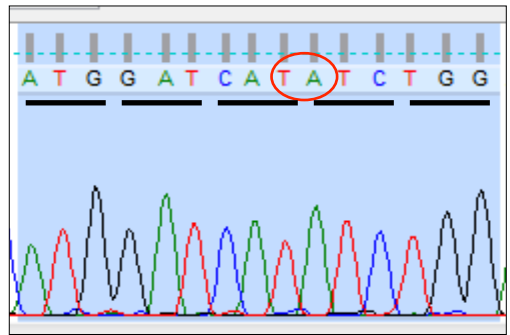


Fig S7: ca14 morpholino causes pigmentation phenotype without affecting the survival of embryos

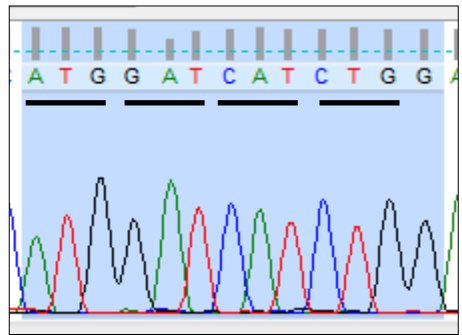
→ Translation start site

	*****	*****
ca14_wildtype	GGGAGAATAGTGAAATCATGGATCATATCTGGACAACCTTGGCTTTTTCTTTTGTGTTTGAAGTGTGTGGAGTGC	
ca14_mutant	GGGAGAATAGTGAAATCATGGATCA--TCTGGACAACCTTGGCTTTTTCTTTTGTGTTTGAAGTGTGTGGAGTGC	

 PAM sequence
 sgRNA target sequence



ca14 wildtype



ca14^{fs003}



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	
<i>ca14</i> wildtype	M	D	H	I	W	T	T	L	A	F	S	F	V	L	K	C	V	E	C	S	G	S	A	T	K	W	T	Y	T	G	A	V	G	Q	P	E	W
<i>ca14</i> ^{fs003}	M	D	H	L	D	N	L	G	F	F	F	C	F	E	V	C	G	V	L	R	K	C	N	K	M	D	I	Y	R	C	C	G	T	T	R	M	D	<u>STOP</u>

Fig S8: Schematic of zebrafish gene *ca14* depicting the crispr target region and the observed mutation in *ca14*^{fs003}.

Antibody	Catalog number	Company
ca14	ab92575	Abcam
dct	ab74073	Abcam
gp100	ab137078	Abcam
mitf (C5)	ab12039	Abcam
tubulin	ab21058	Abcam
gapdh	ab9385	Abcam
actin	ab20272	Abcam
Ac H2A.Z	ab18262	Abcam
H2A.Z	ab4174	Abcam
H2AK5	Acetyl histone antibody sampler kit (9933)	Cell Signalling Technology
H2A	Acetyl histone antibody sampler kit (9933)	Cell Signalling Technology
H3K9	Acetyl histone antibody sampler kit (9933)	Cell Signalling Technology
H3	Acetyl histone antibody sampler kit (9933)	Cell Signalling Technology
H4K12	Acetyl histone antibody sampler kit (9933)	Cell Signalling Technology
H4	Acetyl histone antibody sampler kit (9933)	Cell Signalling Technology
H3K27	ab4729	Abcam
Mitf C5 sera	Kind gift from Dr David Fischer	

Dilution used in study

1;750

1;1000

1;1000

1;100

1;10000

1;10000

1;10000

1;1000

1;1000

1;1000

1;1000

1;1000

1;1000

1;1000

1;1000

1;1000

1;100