Gain-of-function mutations in Aqp3a influence zebrafish pigment pattern formation through the tissue environment

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ABSTRACT
The development of the pigment pattern in zebrafish is a tightly regulated process that depends on both the self-organizing properties of pigment cells and extrinsic cues from other tissues. Many of the known mutations that alter the pattern act cell-autonomously in pigment cells, and our knowledge about external regulators is limited. Here, we describe novel zebrafish mau mutants, which encompass several dominant missense mutations in Aquaporin 3a (Aqp3a) that lead to broken stripes and short fins. A loss-of-function aqp3a allele, generated by CRISPR-Cas9, has no phenotypic consequences, demonstrating that Aqp3a is dispensable for normal development. Strikingly, the pigment cells from dominant mau mutants are capable of forming a wild-type pattern when developing in a wild-type environment, but the surrounding tissues in the mutants influence pigment cell behaviour and interfere with the patterning process. The mutated amino acid residues in the dominant alleles line the pore surface of Aqp3a and influence pore permeability. These results demonstrate an important effect of the tissue environment on pigment cell behaviour and, thereby, on pattern formation.

KEY WORDS: Aquaporin, Pattern formation, Pigmentation, Zebrafish

INTRODUCTION
The zebrafish adult colour pattern of alternating blue and gold stripes is the result of spatially and temporally controlled interactions among pigment cells (chromatophores): yellow xanthophores, silvery iridophores and black melanophores. In the light stripes, tightly packed light-reflective iridophores are covered by a layer of compact xanthophores (Hirata et al., 2003, 2005). Melanophores are confined to the dark stripes, where they are overlaid by a network of blue iridophores and loose xanthophores. This pattern arises during metamorphosis (3-6 weeks post fertilization), when iridophores migrate into the skin to form the first light stripe (Singh et al., 2014). In addition, external ligands can locally activate receptors expressed in pigment cells, e.g. Csfr1 in xanthophores or Ednrba (Ednrb1a) in iridophores (Krauss et al., 2014; Parichy et al., 2000b). Endocrine regulation also plays a role: thyroid hormone promotes xanthophore proliferation and represses melanophores (McMenamin et al., 2014). Finally, the communication between chromatophores via gap junctions and potassium channels may be regulated by the local tissue environment. Their conductivity depends on the polyamine spermidine (Ficker et al., 1994; Watanabe et al., 2012), and a mutation in the gene encoding spermidine synthase affects stripe width (Frohnhöfer et al., 2016).

Here, we describe zebrafish mau mutants, which have gain-of-function mutations in the gene encoding Aquaporin 3a (Aqp3a) that affect pigment patterning and fin growth. Aquaporins are tetrameric pore proteins that facilitate water diffusion through biological membranes while excluding ions. One subgroup, the aquaglyceroporins, can also transport non-polar solutes, such as glycerol, peroxide and urea. Some aquaporins can be permeable for other unconventional solutes such as ammonia and hydrogen...
peroxide, as well as some anions (Wu and Beitz, 2007). The zebrafish genome encodes a large repertoire of aquaporins, many of which show tissue-specific expression (Tingaud-Sequeira et al., 2010).

Point mutations in \textit{aqp3a} result in a dominant phenotype with broken, undulating stripes and short fins. The most severely affected pigment cells in \textit{mau} mutants are larval xanthophores, which deteriorate before metamorphosis and only partially recover during later development. We identified four alleles with altered amino acid residues that line the pore surface of Aqp3a and change pore permeability. A loss-of-function allele, generated by the CRISPR-Cas9 system, has no phenotypic consequences, indicating that Aqp3a is dispensable for normal development. In contrast to other zebrafish mutants with spotted patterns, namely \textit{leo}, \textit{luc}, \textit{sbr} or \textit{seurat} (Maderspacher and Nüsslein-Volhard, 2003; Irion et al., 2014; Fadeev et al., 2015; Eom et al., 2012), all three types of pigment cells from dominant \textit{mau} mutants are capable of forming a wild-type pattern when surrounded by wild-type tissues, but wild-type pigment cells fail to do so when surrounded by mutant tissues. Our results emphasize the importance of the tissue environment in regulating pigment cell behaviour during pattern formation.

\section*{RESULTS}

\textbf{mau} mutants have missense mutations in \textit{aqp3a}

In several screens for zebrafish mutants with pigment pattern defects we identified four \textit{mau} mutant alleles (\textit{tVE1}, \textit{tXGU1}, \textit{tWBU1}, \textit{tWGU2}), which exhibited similar phenotypes with undulating, broken stripes and short fins (Fig. 1A-E,K-M). The mutations are dominant, with heterozygous fish showing a similar but weaker phenotype (Fig. 1F,H). The mutations were mapped to a 3.7 Mb region on chromosome 5 between markers z9568 and z13641. Because this region shows a very low frequency of sequence polymorphisms among our mapping strains, we performed whole-genome sequencing of fish homozygous for the allele \textit{tVE1}. The only candidate for a phenotype-causing mutation in the entire region was a missense mutation in exon 5 of the \textit{aqp3a} gene. Sequencing of \textit{aqp3a} in the other three \textit{mau} mutant alleles also identified missense mutations (Table 1, Fig. 2A).

The mutations affect conserved amino acid residues of Aqp3a: R220, which is mutated in the strongest allele \textit{tVE1}, invariably follows the NPA motif that forms the water selectivity filter (Sui et al., 2001); V201, which is mutated in \textit{tXGU1}, and R225, which is mutated in \textit{tWBU1} and \textit{tWGU2}, are conserved among aquaglyceroporins (Fig. 2A) (Tingaud-Sequeira et al., 2010).

The pore permeability of Aqp3a is affected in \textit{mau} mutants

We modelled the zebrafish Aqp3a protein structure based on the known structure of the \textit{E.coli} glycerol transporter GlpF, which is homologous to animal aquaglyceroporins (Fu et al., 2000; Tajkhorshid et al., 2002). The model predicts that all of the affected amino acid residues line the pore surface (Fig. 2B) and are thus likely to affect pore permeability. To assess this, we tested the permeability for water, glycerol and peroxide, which are known cargos of Aqp3 (Ma et al., 1994; Echevarria et al., 1994; Miller et al., 2010; Tingaud-Sequeira et al., 2010), of wild-type and mutant zebrafish Aqp3a in \textit{Xenopus} oocytes. Permeability for water and glycerol was significantly reduced in all mutants, whereas peroxide permeability increased by 80% in \textit{tVE1}, but was reduced in the other alleles (Fig. 2C,D). Taken together, these results suggest that the structure and functionality of the Aqp3a channel are altered in the dominant \textit{mau} mutants.

The \textit{aqp3a} mutations of \textit{mau} mutants are neomorphic and dose dependent

To test if the dominance observed in \textit{mau} mutants is due to haploinsufficiency or caused by a gain-of-function, we used the CRISPR-Cas9 system (Hwang et al., 2013) to target \textit{aqp3a} exon 4, which is upstream of the identified point mutations. A 4 bp deletion induced in \textit{mau} embryos homozygous for the \textit{tVE1} allele leads to complete reversion of the phenotype, giving rise to heterozygous and homozygous fish of wild-type appearance (Fig. 1G,I). This deletion is predicted to be a null allele, as it causes a frameshift followed by a premature stop codon resulting in a truncated 158 amino acid polypeptide that lacks the last three transmembrane domains. The mutation leads to the downregulation of the corresponding transcript (Fig. 2E,F), possibly owing to nonsense-mediated mRNA decay. A comparable truncation, caused by exon 5 skipping, has been
reported in humans where it leads to a complete loss of AQP3 in red blood cells (Roudier et al., 2002).

To test whether the point mutations in Aqp3a might affect protein folding, we fused wild-type and mutant proteins to Strep-tag and super-folded GFP (sfGFP). When expressed in HeLa cells (Fig. S1A,B) or in the fin fold of zebrafish embryos (Fig. 3), wild-type and tVE1 fusion proteins localized to the plasma membrane; however, the remaining three mutant alleles showed either partial (xGU1) or strong (VB1U and WG2U) retention in the endoplasmic reticulum (ER). Interestingly, the amount of the mutant protein delivered to the plasma membrane, bypassing ER retention, appeared to correlate with the strength of the mau phenotype.

Together with the observations that heterozygous mau mutants have a weaker phenotype than homozygotes, and that the phenotype of Aqp3aLoVE1−/− fish is similar to that of Aqp3aLoVE1+/− (Fig. 1F,J), these data suggest that the Aqp3a mutations in mau mutants are neomorphic and act dominantly in a dose-dependent manner.

**Chromatophores are affected indirectly in mau mutants**

To test whether the patterning defects in mau mutants are caused by pigment cells, we generated mutants by blastomere injection of a single copy of the construct encoding Aqp3aLoVE1 fused to sfGFP under the ubiquitous ef1a promoter (Fig. 6A) and analyzed the phenotypes arising from mosaic overexpression of the protein in random tissues.

We observed pattern irregularities, the appearance of ectopic melanophores in the light stripe regions, and melanophore and iridophore death when large epidermal clones coincided with large muscle clones (Fig. 6B, top). Neither large muscle clones (Fig. 6B, bottom) nor epidermal clones alone were sufficient to affect the pigment pattern. Additionally, the expression of Aqp3aLoVE1Q in xanthophores did not affect stripe formation (Fig. 6B, bottom), substantiating our transplantation experiment results. No effect on pigment patterning was observed upon overexpression of the wild-type variant of Aqp3a (Fig. 6C). We also created a transgenic line expressing sfGFP-Aqp3a wild type (WT) or R220Q under the epidermis-specific keratin promoters krt1c19e [basal layer of epidermis, which gives rise to all the strata of adult skin (Lee et al., 2014)] and krt4 [also known as krt8, enveloping layer and periderm-specific (Gong et al., 2002)].

**Effect of the tissue environment on the behaviour of pigment cells**

Aqp3a is expressed in most tissues in zebrafish, including skin and muscle (Hamdi et al., 2009; Tingaud-Sequeira et al., 2010). To address which tissues affect the behaviour of the chromatophores in mau mutants, we expressed the tVE1 variant (i.e. Aqp3aLoVE1Q) fused to sfGFP under the ubiquitous ef1a promoter (Fig. 6A) and analyzed the phenotypes arising from mosaic overexpression of the protein in random tissues.

We observed pattern irregularities, the appearance of ectopic melanophores in the light stripe regions, and melanophore and iridophore death when large epidermal clones coincided with large muscle clones (Fig. 6B, top). Neither large muscle clones (Fig. 6B, bottom) nor epidermal clones alone were sufficient to affect the pigment pattern. Additionally, the expression of Aqp3aLoVE1Q in xanthophores did not affect stripe formation (Fig. 6B, bottom), substantiating our transplantation experiment results. No effect on pigment patterning was observed upon overexpression of the wild-type variant of Aqp3a (Fig. 6C). We also created a transgenic line expressing sfGFP-Aqp3a wild type (WT) or R220Q under the epidermis-specific keratin promoters krt1c19e [basal layer of epidermis, which gives rise to all the strata of adult skin (Lee et al., 2014)] and krt4 [also known as krt8, enveloping layer and periderm-specific (Gong et al., 2002)].

Both of these transgenes had any effect on the trunk patterning, although Tg(krt1c19e: sfGFP-Aqp3aLoVE1Q) fish showed slight defects in fin pigmentation (e.g. the stripes do not reach the margin of the caudal fin). Tg(krt4: Aqp3aLoVE1Q) fish occasionally exhibited spotted fins resembling the pigmentation of heterozygous tVE1 fish and weaker mau mutant alleles (Fig. 6D,E). Tg(krt4: sfGFP-Aqp3aLoVE1Q) fish have short fins, similar to Aqp3aLoVE1+/− (Fig. 6F). Although the krt4 promoter is known to drive expression in the periderm and simple epiderelia (Imboden et al., 1997; Gong et al., 2002), we observed weak fluorescence in fin ray segments of post-metamorphic and adult fish (Fig. 6G,H), and this expression is likely to be responsible for the short fin phenotype.

### Table 1. mau mutant alleles

| Allele | Nucleotide exchange in coding sequence | Amino acid exchange | Phenotype in homozygous fish |
|--------|---------------------------------------|---------------------|----------------------------|
| tVE1   | G659A                                 | R220Q               | Frequent disruptions of all dark stripes, short fins |
| tGXU1  | T602G                                 | V201G               | Undulating stripes with occasional disruptions, short fins |
| tVB1U  | G674T                                 | R225L               | Disruptions of dark stripes mainly in ventral and posterior regions, medium length fins |
| tWG2U  | G674A                                 | R225H               | Occasional disruptions of the dark stripes in ventral and posterior regions, medium length fins |
| aqp3a−  | CAA[A462-465]del                      | K155Ifs4            | Wild type |

The early larval pigment pattern of mau mutants appears similar to wild type (data not shown). To understand the changes in pigment cell development and behaviour that create the mau pattern, we followed the development of homozygous tVE1 fish carrying markers for the different pigment cells. The first pigment cells that will later contribute to the adult pattern are the larval xanthophores (Mahalwar et al., 2014). At 2 days post fertilization (dpf) they cover the entire flank of mau fish, similar to wild type. In wild type the larval xanthophores persist and begin to proliferate at the onset of metamorphosis (Mahalwar et al., 2014); however, in mau, the xanthophores lose contact with each other (visible at 10 dpf), begin to deteriorate, and by 15 dpf mostly disappear from the flank. Later on, they partially recover and persist to adulthood (Fig. 5A,B).
DISCUSSION

We describe novel mutations in aqp3a in zebrafish that result in an aberrant pigmentation pattern as well as short fins. We show that pigment cells are not directly affected, but that the tissue environment is changed by the mutations.

Aqp3a is known to facilitate the transmembrane transport of water and small non-polar solutes such as glycerol, peroxide and urea (Tingaud-Sequeira et al., 2010). The functionality of the pore is determined by six transmembrane domains and two semi-transmembrane loops, which work as a water selectivity filter and exclude ions from the pore (Sui et al., 2001). All four dominant mau mutant alleles have amino acid exchanges in the pore surface of the protein. The strongest allele (tVE1) replaces an invariant arginine residue of the water selectivity filter with glutamine, while the three weaker alleles affect other conserved residues. Each mutation alters the pore permeability for water and glycerol, which are known cargos for Aqp3 in mammals (Ma et al., 1994; Echevarria et al., 1994; Miller et al., 2010). However, the decrease in water and glycerol transport cannot explain the dominant mau phenotype, as the complete loss-of-function mutation reverts the mau phenotype to wild type. Our preliminary data suggest that there are alterations in calcium homeostasis in the skin of mau mutants (A.E., U.I. and C.N.-V., unpublished). In the three weaker alleles we find ER retention of the mutant proteins, implying that protein folding might be affected in addition to permeability, resulting in reduced amounts of protein reaching the membrane. This might lead to the attenuation of the phenotype compared with tVE1.

Mutations in the human gene leading to truncations of AQP3 also have no phenotypic consequences (Roudier et al., 2002). An Aqp3a null mutation in mice results in a weak phenotype with excess urine production and mild defects in skin thickness and hydration (Ma et al., 2000; Hara-Chikuma and Verkman, 2008). The fact that the aqp3a loss-of-function mutation that we generated by CRISPR-Cas9 shows no phenotype might also be due to redundancy between aqp3a and aqp3b, the two paralogues present in the zebrafish genome (Tingaud-Sequeira et al., 2010).

All three types of chromatophores from mau mutants can contribute to a normal pigment pattern in a wild-type environment. The development of pigment cells in mau shows that all three cell types initially appear normal, but later fail to form a proper striped pattern: the boundaries between the light and dark stripes are not well defined and the stripes break up into spots.
Interactions between chromatophores are required for their proliferation, survival and normal behaviour, and are essential for pigment pattern formation (Frohnhöfer et al., 2013; Singh and Nüsslein-Volhard, 2015; Parichy and Spiewak, 2015; Walderich et al., 2016; Mahalwar et al., 2016). In mau mutants the most severely affected cells are the larval xanthophores, which lose contacts and mostly disappear from the flanks of the fish shortly before metamorphosis. Larval xanthophores give rise to metamorphic xanthophores, which in mau are present in lower numbers and with an altered morphology. As xanthophores are

Fig. 4. Dominant mutations of aqp3a do not act cell-autonomously in pigment cells. (A-C) Blastomere transplantations of aqp3a<sup)tVE1/tVE1</sup> into mutants lacking one chromatophore type (nacre, transparent or pfeffer). (D-F) Typical chimeric animals resulting from transplantations show the striped wild-type pattern in the regions where mau pigment cells complement the host residual pattern. (G) Wild-type iridophores Tg(TDL358:GFP) do not form a wild-type pattern when transplanted into aqp3a<sup)tVE1/tVE1</sup>. Left: GFP-labeled iridophores; middle: corresponding bright-field image; right: merged image.
Fig. 5. See next page for legend.
Fig. 5. Development of the mau phenotype in aqp3atVE1/tVE1
(A) Xanthophores labelled by Tg(fms:GAL4; UAS:mCherry) in wild-type and in aqp3atVE1/tVE1 (mau) larvae. By 15 dpf, the numbers and the area covered by xanthophores are reduced in the mutants, but xanthophores later recover. (B) Numbers of xanthophores per segment in the mid-trunk of pre-metamorphic fish (n=8-10 fish); data points represent means ± s.e.m. ***P<0.0001, unpaired t-test. (C) Representative example of recurrent imaging of individual fish carrying Tg(TDL358:GFP) (green, labelling iridophores) and Tg(sox10:mRFP) (magenta, labelling all the pigment cells) in wild type and in mau. Standard length (SL) is indicated. White arrows point to contracted xanthophores [labelled in mau, Tg(sox10:mRFP)], whereas the wild-type xanthophores are spread and cover the entire flank of the fish. Yellow arrows indicate the position of the second light stripe. In mau, iridophores are present in the area but fail to form a continuous light stripe. (D) Increase in iridophore numbers per segment over the course of 4 days. The quantifications were obtained from recurrent imaging in the mid-trunk segments of the fish during the initial formation of the light stripe (SL 6-6.5 mm), and upon completion of the first light stripe (SL 6.5-7.5 mm). (E) mau melanophores are scattered and not confined to the dark stripe region. (F) Numbers of flank melanophores per segment in the mid-trunk (two segments above the anus) imaged in metamorphic wild-type and mau fish. Each data point represents the number of melanophores in one segment. Scale bars: 50 µm in A; 250 µm in C.

required for shaping the dark stripes (Parichy and Turner, 2003; Frohnhofer et al., 2013; Iwashita et al., 2006), the abnormal distribution of melanophores that we find in mau could be the result of impaired xanthophone-melanophore communication. In pfeffer (csf1ra) mutants, which completely lack xanthophores, the melanophores are scattered outside of the dark stripe region and their number is reduced (Parichy et al., 2000a; Parichy and Turner, 2003). However, unlike pfeffer mutants, mau mutants have the normal number of melanophores, suggesting that there are enough xanthophores to support the survival of melanophores. It is conceivable that the abnormal positioning of melanophores during stripe formation in mau prevents iridophores from aggregating and forming a regular second light stripe, ultimately yielding a broken striped pattern. Consistent with this, pfeffer and mau double mutants are similar to pfeffer mutants in terms of pigment pattern (data not shown).

Thus far, no mutants have been described that resemble mau in terms of larval xanthophone development. However, temporal inactivation of CsF1ra during the early stages of xanthophone development, using a temperature-sensitive csf1ra allele, and then reactivation during metamorphosis leads to a scattering of melanophores across the flank. Interestingly, fish carrying a temperature-sensitive allele and a null allele for csf1ra show stripe breaks (Parichy and Turner, 2003) resembling the pattern that we observe in heterozygous tVE1 fish. Nonetheless, the mau phenotype is stronger than phenotypes caused by temporary loss of xanthophores and of CsF1ra signalling (Parichy and Turner, 2003), implying that the cellular behaviour of the other two pigment cell types (melanophores and iridophores) is also affected in the mau mutant environment.

The failure of wild-type pigment cells to organize into stripes when transplanted into mau mutants suggests that they receive the wrong cues from non-pigment cells or the extracellular environment. As Aqp3a is a pore protein and the mutant variants act in a dose-dependent manner, it seems likely that they affect the pigment cells and fin growth locally. Skin pigment cells in zebrafish are located in the hypodermis. They are overlaid by layers of epidermal keratinocytes and loosely packed dermal fibroblasts (Hirata et al., 2003, 2005). Beneath them are thin layers of slow and fast muscle bundles (van Raamsdonk et al., 1982). We found that expression of the tVE1 variant (Aqp3aR220Q) in large areas of both the epidermis and the underlying muscles leads to some stripe disruption and the appearance of ectopic melanophores within the light stripe region, resembling the mau phenotype. Smaller patches of cells do not yield such a phenotype, nor do clones that are restricted to muscle or epidermal cells only, suggesting that a minimal number of cells in the adjacent tissues is needed to affect the behaviour of the chromatophores.

Pigmentation in zebrafish presents an attractive system with which to study the cellular basis of pattern formation processes in vivo. The cell-autonomous interactions between the three types of chromatophores, which are necessary to produce the stripes, occur in a tissue-specific context. Our study emphasizes the role that the cellular environment plays in pigment cell behaviour and pattern formation, and the role that it might play in the immense diversification of pigment patterns in fish and other ectothermic vertebrates.

MATERIALS AND METHODS
Zebrafish maintenance
Fish were maintained and bred as described by Nuesslein-Volhard and Dahm (2002). The following genotypes were used: TU and WIK wild-type strains; nacre<sup>−/−</sup> (Lister et al., 1999), pfeffer<sup>−/−</sup> (Odenthal et al., 1996), transpermantia<sup>−/−</sup> (Krausa et al., 2013), Tg(TDL358:GFP) (Levesque et al., 2013), Tg(sox10:mRFP) [M. Levesque (Singh et al., 2014)] and Tg(fms:GAL4), Tg(UAS:E1b:nfsB:mCherry), which is referred to in the text as Tg(fms:Gal4; UAS:mCherry) (Gray et al., 2011).

All animal experiments were performed in accordance with the guidelines of the State of Baden-Württemberg, Germany, and approved by the Regierungspäsidium Tübingen (35/9185.46-5, 35/9185.82-7, 35/9185.81-5).

Generating the aqp3a loss-of-function allele
CrisPR-Cas9 was used to generate aqp3a loss-of-function alleles as described (Hwang et al., 2013). The following oligonucleotides were cloned into pDR274 to create the vector for in vitro transcription of the gRNA: Aqp3a_<sub>KO_1</sub>, 5′-TAGGCGCGGGTGAGATTTGCTT-3′; and Aqp3a_<sub>KO_2</sub>, 5′-AAACAAGCAAAATATCACCACC-3′. The vector was linearized with Drul, and the 285 bp fragment was gel purified and used as template for in vitro transcription with the Megascript Kit (Ambion). Cas9 mRNA was transcribed from the linearized plasmid pMLM3613 using the MMessage mMachine Kit (Ambion). Embryos from an incross of aqp3a<sup>−/−</sup> were injected at the 1-cell stage with 2-5 nl 12 ng/µl gRNA and 120 ng/µl Cas9 mRNA. Juvenile fish were genotyped using primers Aqp3a_gen_fw (5′-ATAGGGAGCATCCCTG-3′) and Aqp3a_gen_rev (5′-GGAATT- TCACCGACCTGTG-3′) and aqp3atVE1/tVE1 mutants were identified. Indels of 1 bp and 4 bp were identified and used to establish the loss-of-function stock.

Cell culture, transfection and immunostaining
HeLa cells (ATCC CCL-2) were cultured in DMEM (Sigma-Aldrich) containing 10% fetal calf serum (FCS), 2 mM glutamine, 100 U/ml penicillin and 100 µg/ml streptomycin. Transfection of Streptagged Aqp3a (KY379154, KY379155, KY379156, KY379157, KY379158) was achieved using Lipofectamine 2000 (Invitrogen) according to the manufacturer’s protocol. Twenty-four hours after transfection, the cells were fixed in 4% paraformaldehyde, washed with 0.1% Triton X-100 in PBS (PBST), blocked in 10% normal goat serum (NGS) in PBST and incubated with anti-strep II antibody (1:200; IBA, 2-1507-001). For subsequent

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staining of calnexin, cells were permeabilized with methanol at −20°C, blocked with 5% NGS in PBST, and incubated overnight at 4°C with anti-calnexin antibodies (1:50; C5C9, Cell Signaling Technology, #2679S). Secondary antibodies were anti-mouse Alexa 647 and anti-rabbit Alexa 488 (1:300; Molecular Probes, A21236 and A11008).

Transgenic lines, transient and mosaic expression
The coding sequences of wild-type and mutant Aqp3a were amplified from the cDNA of fish using primers: AE1-fw, 5′-ATCAGGGCCGCATGG-GTTGGCCGAGAAAAGCG-3′; and AE2_rev, 5′-GATGAAATTCTCATTCTTGTGCCGACC-3′.

We expressed sfGFP-Aqp3a variants transiently in zebrafish embryos to assess protein localization. sfGFP was fused in-frame to the coding sequence of Aqp3a and cloned into pCS2+ (the resulting constructs were KU645301, KU645302, KU645303, KU645304, KU645305). The linearized plasmids were transcribed in vitro using the SP6 mMessage Machine Kit (Ambion), and 100 ng/µl of mRNA was injected into 1-cell stage embryos.

For ubiquitous mosaic expression (Perathoner et al., 2014), as well as epidermis-specific expression of Aqp3a WT and Aqp3aR220Q under the krt4 (Gong et al., 2002) and krtt1c19 (Lee et al., 2014) promoters, the constructs KU645306, KU645307, KU645308, KY379161, KY379160 and KY379159 were injected into 1-cell stage embryos as a mixture of circular DNA (10-20 ng/µl) and Tol2 mRNA (25 ng/µl).

Quantification of Aqp3a expression
Embryos from an aqp3a+/− incross were genotyped using primers Aqp3a_del_fw (5′-TGTTACATTTGCTCTCTG-3′) and Aqp3a_del_rev (5′-TAAACCATCCCCATGTCGCCAG-3′) to identify aqp3a+/− and wild-type siblings. RNA was extracted with TRIzol (Life Technologies) and
cDNA was produced using SuperScript II reverse transcriptase (Thermo Fisher Scientific). Aqp3a transcripts were amplified using Aqp3a_gen_fw and AE2_rev for 35 cycles. actb1 transcripts were amplified using primers actb1_fwd (5′-ACTGGGATGACATGGAGAAGAT-3′) and actb1_rev (5′-GTGTTGAAAGGTCTCGAACCATTG-3′) for 28 cycles. The relative abundance of the transcripts was quantified from the gel using Fiji (Schindelin et al., 2012) and averaged between biological replicates.

**Transplantations**

Chimeric fish were produced as described (Nüsslein-Volhard and Dahm, 2002) by transplanting 20-40 blastomeres from donor to host embryos at the 1000-cell blastula stage.

**Image acquisition and processing**

Fish were anaesthetized for imaging with 0.004% MS-222 (Sigma). Embryos at 1-5 dpf were embedded in 0.5% low-melting agarose. Images of embryos and metamorphic fish were acquired on a Zeiss LSM 780 NLO confocal microscope and processed with Fiji (Schindelin et al., 2012) and ZEN 2012 (Zeiss). Confocal z-stacks are shown as maximum intensity projections. Follow-up of pigment cell development was was time-lapse imaging of metamorphic fish, imaging the mid-body area once a day. Adult fish were anaesthetized as above and photographed with a Canon EOS 5D MarkII camera and a Macro 100 objective.

**Pigment cell counts**

Pigment cell counts were performed using maximum intensity projection images obtained from confocal z-stacks using the Fiji Cell Counter plugin. We counted pigment cells from two or three mid-body segments. For counts of melanophores, fish were treated with epinephrine, and only melanophores on the flank of the fish that contribute to the stripe pattern were taken into consideration. The xanthophores were counted in Tg(fms:GAL4),Tg(UAS: E1b:nsfB-mCherry) double-transgenic fish from 9 to 21 dpf. The iridophores were counted in Tg(TDL35:GFP) (Levesque et al., 2013) and Tg(sox10: mRFP) fish at SL 6-6.5 mm and 6.5-7.5 mm. The fish were imaged daily from 23 to 26 dpf. The number of iridophores per segment was normalized to the number of iridophores in the same segment at 23 dpf.

**Functional expression in Xenopus oocytes**

Wild-type and mutant cDNAs were cloned into pT7TS, and cRNAs for microinjection were synthesized with T7 RNA polymerase (Roche). Microinjections of stage V and VI oocytes were performed as described by Deen et al. (1994). Oocytes were transferred to modified Barth’s medium (MBS) [88 mM NaCl, 1 mM KCl, 2.4 mM NaHCO3, 0.82 mM MgSO4, 0.33 mM Ca(NO3)2, 0.41 mM CaCl2, 10 mM HEPES, 25 mg/ml gentamycin, pH 7.5] and injected with 50 nl distilled water (negative control) or 2 ng cRNA in 50 nl water.

At 24 h, the oocytes were manually defolliculated, and maintained in MBS at 18°C. To determine the osmotic water permeability (P0), the oocytes were transferred at 48 h to 10-fold diluted MBS (20 mOsm). Oocyte swelling was tracked by video microscopy using serial images at 2 s intervals for 20 s. P0 values were calculated taking into account the timecourse changes in relative oocyte volume (dV/V0)dt, the partial molar volume of water (Vw = 18 cm3/mol), and the oocyte surface area (S) using the formula Vw(dV/V0)dt/[SVw(Sm–Sm)w]. The surface area of the oocyte was considered to be nine times the apparent area because of membrane folding (Zampighi et al., 1995).

Glycerol permeability (Pgly) was also determined volumetrically in isotonic MBS, where NaCl was replaced by 160 mM solute. Oocyte swelling was measured by video microscopy, using serial images at 5 s intervals for 1 min. Pgly was calculated from oocyte swelling using the formula [d(V/V0)]t/dV0 (Verkman and Ives, 1986). The uptake of H2O2 was determined using the ROS-sensitive, cell-permeable fluorescent dye 5'-and-6-chloromethyl-2′,7′-dichlorodihydrofluorescein diacetate, acetyl ester (CM-H2DCFDA; C6827, Life Technologies), following a method described by Chauvigné et al. (2015). Oocytes were incubated with isotonic MBS plus 0.5% DMSO and 200 μM CM-H2DCFDA for 1 h at 18°C. After washing in MBS, the oocytes were exposed to 100 μM H2O2 in MBS for 30 min at 18°C. The CM-H2DCFDA fluorescence of each well (oocyte plus MBS) was measured at excitation and emission wavelengths of 495 nm and 525 nm, respectively, using a multiwell plate reader (InfiniteM200, Tecan). We corrected the background to remove nonspecific signals from MBS and from oocytes not exposed to the dye.

To study the relative expression of Aqp3a mutants with respect to wild type, constructs carrying the human influenza hemagglutinin (HA) tag at the N-terminus (nucleotide sequence: 5′-TACCCATACAGTGTCCAGATT-A CGCT-3′ or 5′-TATCCATATGATGTCTCAGATTATG-3′) were PCR amplified and 15 of the corresponding cRNAs was injected into Xenopus oocytes. For western blotting, total membranes were isolated from groups of ten oocytes as previously described (Kamsteeg and Deen, 2001). Protein samples equivalent to the total membrane extract of two oocytes per lane were denatured at 95°C for 10 min in Laemmli buffer, electrophoresed on a 12% polyacrylamide SDS gel, and then blotted onto nitrocellulose membranes (Bio-Rad). Membranes were blocked for 1 h with TBST (20 mM Tris, 140 mM NaCl, 0.1% Tween, pH 8) containing 5% nonfat dried milk (Sigma-Aldrich), and then incubated with 1:1000 HA polyclonal rabbit antibody (PA1-985, Life Technologies) in TBST with 5% nonfat dried milk at 4°C overnight. Horseradish peroxidase-coupled goat anti-rabbit IgG antibody (Santa Cruz Biotechnology, sc-2004) was used at 1:5000. Reactive protein bands were detected using enhanced chemiluminescence western HRP substrate (ECL, Millipore).

**Homolog modelling**

HHpred (Söding et al., 2005) was used to identify homologues of known structure. HHpred searches were conducted in default settings against the protein data bank (PDB) (Berman et al., 2000), as available on 1st February 2016, and clustered at 70% pairwise sequence identity. Searches of the *D. rerio* Aqp3a sequence retrieved glyceral uptake facilitator protein from *E. coli* (PDB identifier 1LDF) and aquaglyceroporin from *P. falciparum* (PDB identifier 3C02) as the closest homologues. These structures served as templates for generating homology models with Modeller (Sali and Blundell, 1993).

**Statistical analysis**

Statistical analysis was performed using InStat (GraphPad Software).

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**Competing interests**

The authors declare no competing or financial interests.

**Author contributions**

Conceptualization: A.E., J.C., C.N.-V., U.I.; Methodology: F.C.; Software: M.A.; Formal analysis: A.E., M.A.; Investigation: A.E., F.C., H.-M.M., U.I.; Writing - original draft: A.E., J.C., C.N.-V., U.I.; Writing - review & editing: A.E., J.C., C.N.-V., U.I.; Visualization: M.A.; Supervision: J.C., C.N.-V., U.I.; Project administration: C.N.-V., U.I.; Funding acquisition: C.-N.-V.

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**Supplementary information**

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