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Elucidating the acid-base mechanisms underlying otolith overgrowth in fish exposed to ocean acidification

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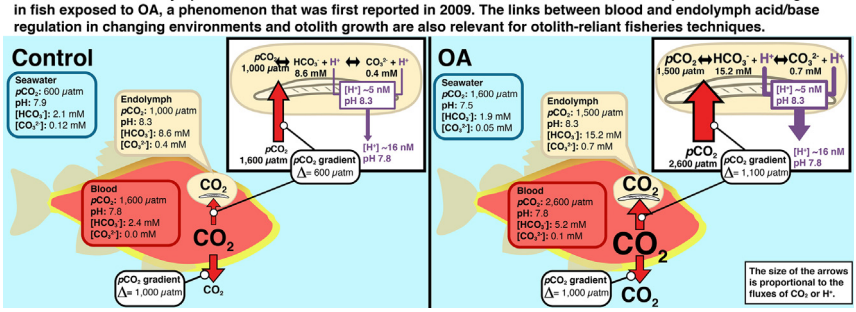
HIGHLIGHTS

- Rockfish regulated blood & endolymph pH despite ocean acidification (OA) exposure.
- Endolymph of OA-exposed fish had higher $[HCO_3^-]$, $[CO_3^{2-}]$, and $\Omega_{aragonite}$.
- Preexisting ATPase was sufficient for the increased H^+ removal.
- First evidence linking endolymph of OA-exposed fish favors otolith overgrowth.

GRAPHICAL ABSTRACT



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ABSTRACT

Over a decade ago, ocean acidification (OA) exposure was reported to induce otolith overgrowth in teleost fish. This phenomenon was subsequently confirmed in multiple species; however, the underlying physiological causes remain unknown. Here, we report that splitnose rockfish (*Sebastes diploproa)* exposed to ~1600 μatm pCO_2 (pH ~7.5) were able to fully regulated the pH of both blood and endolymph (the fluid that surrounds the otolith within the inner ear). However, while blood was regulated around pH 7.80, the endolymph was regulated around pH ~8.30. These different pH setpoints result in increased pCO_2 diffusion into the endolymph, which in turn leads to proportional increases in endolymph $[HCO_3^-]$ and $[CO_3^{2-}]$. Endolymph pH regulation despite the increased pCO_2 suggests enhanced H^+ removal. However, a lack of differences in inner ear bulk and cell-specific Na^+/K^+-ATPase and vacuolar type H^+-ATPase protein abundance localization pointed out to activation of preexisting ATPases, non-bicarbonate pH buffering, or both, as the mechanism for endolymph pH-regulation. These results provide the first direct evidence showcasing the acid-base chemistry of the endolymph of OA-exposed fish favors otolith overgrowth, and suggests that this phenomenon will be more pronounced in species that count with more robust blood and endolymph pH regulatory mechanisms.

1. Introduction

The inner ear of teleost fishes contains three pairs of otoliths that contribute to hearing and maintaining balance. Otoliths are comprised of calcium carbonate ($CaCO_3$) embedded within a protein matrix, and are biomineralized within an acellular fluid called the endolymph (Payan et al., 2004a). Otoliths are biomineralized in a successive ring pattern correlated with the fish growth rate (Campana and Neilson, 1985; Kalish, 1989; Pannella, 1971), which are used by scientists and fishery managers to estimate fish age and length (Campana, 2001; Campana and Thorrold, 2001), estimate recruitment, and set fishery-specific catch limits (Methot, 2015; Vitale et al., 2019).

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Originally, it was predicted that CO_2-induced ocean acidification (OA) would impair otolith biomineralization because the associated decreases in seawater pH and [CO_3^{2-}] hamper $CaCO_3$ precipitation (Ishimatsu et al., 2008). However, subsequent studies reported that fish exposed to OA developed enlarged otoliths (Bignami et al., 2013a, 2013b; Checkley et al., 2009; Faria et al., 2017; Hurst et al., 2012; Réveillac et al., 2015; Shen et al., 2016). These findings led to a broader awareness that otolith biomineralization is strongly linked to endolymph and blood chemistries, and to the hypothesis that biological regulation of endolymph pH could lead to increased [CO_3^{2-}] resulting in otolith overgrowth (Checkley et al., 2009). In addition, fish exposed to hypercapnia typically accumulate [HCO_3^-] in their plasma to compensate the respiratory acidosis; this could result in enhanced HCO_3^- flux into the endolymph and further contribute to otolith overgrowth (Heuer and Grosell, 2014). However, experimental support for these hypotheses is lacking, as there are no reports of endolymph acid-base parameters under OA-relevant conditions, and only a few studies have measured blood acid-base parameters in fish exposed to OA-relevant CO_2 levels (Esbaugh et al., 2012, 2016; Montgomery et al., 2019). This knowledge gap is in large part due to the disrupting effects of blood sampling by caudal puncture on the acid-base status of fish internal fluids and the challenge of blood vessel cannulation in small fish and species with convoluted dorsal aorta anatomy, coupled with the difficulty of collecting sufficient endolymph for analyses. Moreover, the cellular heterogeneity of the inner ear complicates the quantification of ionocyte-specific responses using standard molecular and biochemical assays on bulk tissue. As a result, the underlying acid-base and physiological causes of OA-induced otolith overgrowth remain unknown.

The chemistry of the endolymph is actively controlled by the inner ear epithelium to maintain acid-base conditions that promote biomineralization, namely, higher pH, [HCO_3^-], [CO_3^{2-}], and total CO_2 than the blood (Payan et al., 1999, 1997; Takagi, 2002; Takagi et al., 2005). This gradient is actively maintained by two types of ion-transporting cells ("ionocytes"): the Type-I ionocyte, which transports K^+ and Cl^- into the endolymph and removes H^+ powered by Na^+/K^+-ATPase (NKA) (Kwan et al., 2020; Mayer-Gostan et al., 1997; Payan et al., 1997; Takagi, 1997) and the Type-II ionocyte, which secretes HCO_3^- into the endolymph driven by V-type H^+-ATPase (VHA) (Kwan et al., 2020; Mayer-Gostan et al., 1997; Payan et al., 1997; Takagi, 1997; Tohse et al., 2004, 2006). However numerous other cells within the inner ear organ also express NKA and VHA, including the sensory hair cells and the endothelial cells that make up the blood vessels (Kwan et al., 2020; Mayer-Gostan et al., 1997; Shiao et al., 2005).

In the current study, splitnose rockfish (*Sebastes diploproa)* were exposed to ~1600 μatm CO_2 (pH ~7.5), a condition readily experienced in their natural habitat (Culberson and Pytkowicz, 1970; Love et al., 2002) and predicted for the surface ocean by the year 2300 (Goodwin et al., 2018). The OA exposure spanned three days, a duration previously documented to result in otolith overgrowth in fish larvae (Faria et al., 2017). Blood acid-base chemistry was measured after taken samples using a benzocaine-based anesthetic protocol that yields measurements comparable to those achieved using cannulation (Montgomery et al., 2019). Additionally, we took advantage of the large rockfish inner ear organ to collect sufficient endolymph for acid-base chemistry analysis, and inner ear tissue for quantification of NKA and VHA protein abundances. Finally, we performed immunohistochemical analyses on six inner ear cell types to explore potential cell-specific changes in protein expression patterns. This multidimensional approach allowed us to explore the mechanistic acid-base causes that underlie otolith overgrowth in fish exposed to OA.

2. Methods

2.1. Specimens

Juvenile splitnose rockfish (*S. diploproa*) were caught from drifting kelp paddies off the shores of La Jolla and raised in the Hubbs Experimental Aquarium (La Jolla, USA) in accordance to the permit (#SCP13227) issued by the California Department of Fish and Wildlife. Rockfish were raised for >2 years in a flow-through system with seawater continuously pumped from the Scripps Coastal Reserve, and were fed frozen market squids and food pellets (EWOS, Cargill Incorporated, Minneapolis, MN, USA). Average rockfish total length (12.33 ± 0.16 cm) and weight (49.11 ± 2.18 g) (N = 9) were not significantly different between treatments. All experiments were approved under the Institutional Animal Care and Use Committee protocol (#S10320) by the Scripps Institution of Oceanography, University of California San Diego animal care committee.

2.2. Experimental aquarium setup

Two header tanks were supplied with ambient seawater from the Scripps Coastal Reserve, one was not manipulated and was considered as the control condition. The other header tank was bubbled with CO_2 using a pH-stat system (IKS Aquastar, Karlsbad, Germany) to maintain a seawater pH ~7.5 and generate the OA condition. Temperature and pH were continuously monitored and recorded every 2 min using the IKS Aquastar system (Fig. S1). Discrete seawater samples were collected from header tanks at the beginning and end of each experiment, and analyzed for alkalinity (via titration with LabView software Version 2.9j; National Instruments, Austin, Texas, United States), pH (using the indicator dye purified m-cresol purple (Liu et al., 2011) in an Agilent 8453 spectrophotometer (Agilent, Santa Clara, CA, USA)), and salinity (by converting density measurements using Mettler Toledo DE-45 (Mettler-Toledo, Columbus, Ohio, United States)) by the Dickson Lab (Scripps Institution of Oceanography). The pH values from the discrete seawater samples were used to validate and back-correct the IKS pH measurements. Subsequently, the pH, alkalinity, and salinity values were used to calculate pCO_2 using CO2SYS (Lewis and Wallace, 1998). These analyses indicated control pH and pCO_2 levels of 7.89 ± 0.012 and 571.90 ± 4.88 μatm, respectively, which are typical for La Jolla, USA (Frieder et al., 2012; Hofmann et al., 2011; Takeshita et al., 2015). In contrast, pH and pCO_2 in the OA treatment were 7.49 ± 0.01 and 1591.56 ± 18.58 μatm, respectively (table S1).

Each header tank supplied water to three opaque 3-L experimental tanks at a flow rate of 0.3-L min^{-1}. Individual rockfish were acclimated within an experimental tank for 12 h, followed by a 72-h exposure to control or OA conditions. To ensure similar metabolic state among individuals, rockfish were not fed during the 48 h prior to the acclimations or during the experiment. Three separate experiments were conducted during March 2020, each time with three control and three OA-exposed fish. No mortality was observed.

2.3. Blood, endolymph, and inner ear sampling

Sampling and acid-base determinations were performed in a temperature-controlled room at 18 °C (i.e. same as that of seawater). Fish were anesthetized by stopping the seawater flow into the individual experimental tank and slowly adding benzocaine through to achieve a final concentration of 0.15 g/L. After fish lost equilibrium (~5 min), they were moved to a surgery table where the gills were irrigated with aeriated seawater from their respective treatment (control or OA) containing benzocaine (0.05 g/L) using a pump (Harter et al., 2021; Montgomery et al., 2019, 2022). Blood was drawn from the caudal vein using a heparinized syringe and pH was immediately measured using a microelectrode (Orion™ PerpHecT™ Ross™, ThermoFisher Scientific, Waltham, MA, USA). Next, blood was centrifuged for 1 min at 6000 ×g using a microcentrifuge (VWR Kinetic Energy 26 Joules, Radnor, PA, USA), and the resulting plasma was measured for total CO_2 (TCO_2) using a carbon dioxide analyzer (Corning 965, Ciba Corning Diagnostic, Halstead, Essex, United Kingdom). After blood sampling (N = 8–9), the fish was euthanized by spinal pithing, and the gills were quickly removed. Endolymph (N = 7–8) was drawn using a heparinized syringe from the ventral side of the skull, and pH and TCO_2 were measured as described above. CO_2 loss was minimized by measuring endolymph within 3 min after spinal pithing. Inner ear tissue was either flash frozen in liquid nitrogen and stored at −80 °C, or fixed in 4% paraformaldehyde (8 h at 4 °C), incubated in 50% ethanol (8 h at 4 °C), then stored in 70% ethanol until processing.

2.4. HCO_3^-, CO_3^{2-}, and pCO_2 calculation

Blood and endolymph pH and TCO_2 values were used to calculate $[HCO_3^-]$, $[CO_3^{2-}]$, and pCO_2 using the Henderson-Hasselbalch equation. The solubility coefficient of CO_2 (plasma: 0.0578 mmol l^{-1} $Torr^{-1}$; endolymph: 0.0853 mmol l^{-1} $Torr^{-1}$), ionic strength (plasma: 0.15 mol l^{-1}, endolymph: 0.18 mol l^{-1}), pK_1' (plasma: ~6.20, endolymph: ~6.16), and pK_2' (plasma: ~9.76, endolymph: ~9.71) were based upon (Boutilier et al., 1984) and (Takagi, 2002) for blood and endolymph, respectively. The $[Na^+]$ (plasma: 170 mmol l^{-1}, endolymph: 100 mmol l^{-1}) used for calculating pK_1' was based upon (Payan et al., 1997).

2.5. Antibodies

NKA was immunodetected using a monoclonal α5 mouse antibody raised against the α-subunit of chicken NKA (a5, Developmental Studies Hybridoma Bank, Iowa City, IA, USA; (Lebovitz et al., 1989)), whereas the β-subunit of VHA was immunodetected using a custom-made polyclonal rabbit antibody (epitope: AREEVPGRRGFPGYC; GenScript, Piscataway, USA). These antibodies have been previously used in the inner ear of the Pacific chub mackerel (*Scomber japonicus*; (Kwan et al., 2020)), and were validated here for splitnose rockfish (Fig. S2). Secondary antibodies goat anti-mouse HRP-linked secondary antibodies (Bio-Rad, Hercules, CA, USA) and goat anti-rabbit HRP-linked secondary antibodies (Bio-Rad) were used for immunoblotting.

2.6. Western Blotting and relative protein abundance analysis

Frozen inner ear samples were immersed in liquid nitrogen, pulverized using a handheld motorized homogenizer (Kimble®/Kontes, Dusseldorf, Germany), and suspended in ice-cold homogenization buffer containing protease inhibitors (250 mmol l^{-1} sucrose, 1 mmol l^{-1} EDTA, 30 mmol l^{-1} Tris, 10 mmol l^{-1} benzamidine hydrochloride hydrate, 1 mmol l^{-1} phenylmethanesulfonyl fluoride, 1 mmol l^{-1} dithiothreitol, pH 7.5). Samples were centrifuged at low speed (3000 ×*g*, 10 min, 4 °C) to remove debris, and the resulting supernatant was considered the crude homogenate. Total protein concentration in all fractions was determined by the Bradford assay (Bradford, 1976). Prior to SDS-electrophoresis, samples were mixed with an equal volume of 90% 2× Laemmli buffer and 10% β-mercaptoethanol, and heated at 70 °C for 5 min. Proteins (crude homogenate: 10 μg per lane; membrane-enriched fraction: 5 μg per lane) were loaded onto a 7.5% polyacrylamide mini gel (Bio-Rad, Hercules, CA, USA) – alternating between control and high CO_2 treatments to avoid possible gel lane effects. The gel ran at 200 V for 40 min, and the separated proteins were then transferred to a polyvinylidene difluoride (PVDF) membrane using a wet transfer cell (Bio-Rad) at 100 mAmps at 4 °C overnight. PVDF membranes were incubated in tris-buffered saline with 1% tween (TBS-T) with milk powder (0.1 g/mL) at RT for 1 h, then incubated with primary antibody (NKA: 10.5 ng/ml; VHA: 3 μg/ml) in blocking buffer at 4 °C overnight. On the following day, PVDF membranes were washed with TBS-T (three times; 10 min each), incubated in blocking buffer with their respective secondary antibodies (1:10,000) at RT for 1 h, and washed again with TBS-T (three times; 10 min each). Bands were made visible through addition of ECL Prime Western Blotting Detection Reagent (GE Healthcare, Waukesha, WI) and imaged and analyzed in a BioRad Universal III Hood using Image Lab software (version 6.0.1; BioRad). Following imaging, the PVDF membrane was incubated in Ponceau stain (10 min, room temperature) to estimate protein loading. Relative protein abundance (N = 6–8) were quantified using the Image Lab software (version 6.0.1; BioRad) and normalized by the protein content in each lane.

2.7. Whole-mount immunohistochemistry and confocal microscopy

Immunolabeling was performed based on the protocol described in Kwan et al., (2020) for tissue sections and optimized for whole tissues as follows. Fixed inner ear tissue was rehydrated in phosphate buffer saline + 0.1% tween (PBS-T) for 10 min. Autofluorescence was quenched by rinsing in ice-cold PBS-T with sodium borohydride (1.5 mg/mL; six times; 10 min each), followed by incubation in blocking buffer (PBS-T, 2% normal goat serum, 0.02% keyhole limpet hemocyanin) at room temperature for 1 h. Samples were incubated with blocking buffer containing primary antibodies (NKA: 40 ng/mL; VHA: 6 μg/mL) at 4 °C overnight. On the following day, samples were washed in PBS-T (three times at room temperature; 10 min each), and incubated with the fluorescent secondary antibodies (1:500) counterstained with DAPI (1 μg/mL) at room temperature for 1 h. Samples were washed again in PBS-T as before and stored at 4 °C until imaging.

Immunostained inner ear samples were immersed in PBS-T, mounted onto a depressed glass slide fitted with a glass cover slip (No. 1.5, 0.17 mm) and imaged using a Zeiss LSM800 inverted confocal microscope equipped with a Zeiss LD LCI Plan-Apochromat 40x/1.2 lmm Korr DIC M27 objective and Zeiss ZEN 2.6 blue edition software (Cambridge, United Kingdom). The following channels were used for imaging: VHA (excitation 493 nm with 1% laser power, emission 517 nm, detection 510–575 nm), NKA (excitation 577 nm at 1% laser power, emission 603 nm, detection 571–617 nm), and DAPI (excitation 353 nm at 0.7% laser power, emission 465 nm, detection 410–470 nm). *Z*-stacks (range: ~70–400 optical sections; thickness: ~0.27 μm per section) of the various inner ear cell types were visualized as maximum intensity projection, and through orthogonal cuts to capture fluorescent signal across the X-Z and Y-Z planes. Inner ear organs from four control and four OA-exposed rockfish were imaged.

2.8. Statistical analysis

Normality was tested using the Shapiro-Wilk normality test, and homogeneity was tested using the F-test. Datasets that failed to meet the assumptions of normality were log- (i.e. $[CO_3^{2-}]$, pH) or inverse-transformed (i.e. $[H^+]$). Acid-base parameters were analyzed using two-way analysis of variance (2-way ANOVA), with "CO_2 level" (control or OA) and "internal fluid" (blood or endolymph) as factors. If significant interaction effect was detected, subsequent Tukey honest significant difference (HSD) tests were used. NKA and VHA protein abundances were analyzed using two-tailed Student's *t*-tests. Values are reported as mean ± s.e.m., and an alpha of 0.05 was employed for all analyses. Statistical tests were performed using Prism (version 7.0a) and R (version 4.0.3; R Development Core Team, 2013).

3. Results and discussion

The difference in seawater pCO_2 between the control and OA-condition was ~1000 μatm, which induced an equivalent elevation in blood pCO_2 from 1603.25 ± 190.69 μatm in control fish to 2659.20 ± 223.87 μatm in OA-exposed fish (Fig. 1a). However, blood pH was fully regulated (control: 7.75 ± 0.03; OA: 7.85 ± 0.04) (Fig. 1b). As is typical for regulation of blood acidosis (Tresguerres and Hamilton, 2017), OA-exposed fish demonstrated a significant accumulation of HCO_3^- in blood plasma, from 2.37 ± 0.20 mM in control fish up to 5.16 ± 0.31 mM in OA-exposed fish (Fig. 1c). This response matches the magnitude of the hypercapnic stress according to classic Davenport acid-base physiology, as well as the three previous studies on blood acid-base chemistry in fish exposed to OA-relevant CO_2 levels (Esbaugh et al., 2012, 2016; Montgomery et al., 2019). In addition, the increased plasma TCO_2 at unchanged pH led to the tripling of plasma $[CO_3^{2-}]$ from ~0.02 to ~0.07 mM (Fig. 1d). These increases in blood $[HCO_3^-]$ and $[CO_3^{2-}]$ may contribute to the skeletal hypercalcification (Di Santo, 2019) and deformities (Pimentel et al., 2014) reported in some OA-exposed fishes.

The endolymph of control rockfish had higher TCO_2 compared to the blood (9.06 ± 0.38 vs 2.46 ± 0.20 mM; Fig. S3) and also a higher pH (8.32 ± 0.05 vs. 7.75 ± 0.03), resulting in lower pCO_2 (971.38 ± 120.70 vs. 1603.25 ± 190.69 μatm), higher $[HCO_3^-]$ (8.63 ± 0.35 vs. 2.37 ± 0.20 mM), and much higher $[CO_3^{2-}]$ (0.36 ± 0.04 vs 0.02 ± 0.01 mM) (Fig. 1a-d). Importantly, these measurements revealed higher pH and lower pCO_2, TCO_2, $[HCO_3^-]$ and $[CO_3^{2-}]$ compared to previous

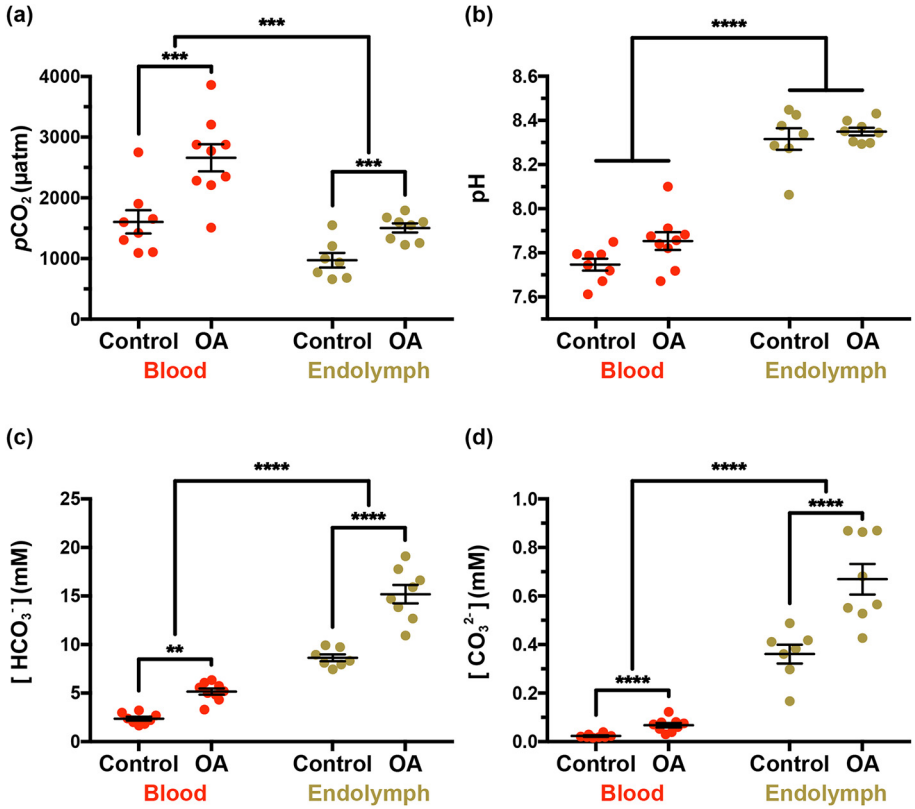

Fig. 1. Blood and endolymph acid-base parameters in control and OA-exposed rockfish. A) pCO_2, B) pH, C) $[HCO_3^-]$, and D) $[CO_3^{2-}]$. Data is presented as mean and s.e.m. for each group and the individual measurements are shown as red (blood) or beige (endolymph) points (N = 7–9). Statistical significance between fluids, and between treatments for a given fluid are indicated by the connecting lines and asterisks (2-way ANOVA, *$p < 0.05$, **$p < 0.005$, ***$p < 0.001$, ****$p < 0.0001$). Statistical details are reported in tables S3-S5, and TCO_2,$[CO_2]$ and $[H^+]$ are shown in Fig. S3.

studies that collected endolymph without previously anesthetizing the fish (Payan et al., 1999, 1997), and to others that used 2-phenoxyethanol as anesthetic but did not irrigate the gills during endolymph collection (Takagi, 2002; Takagi et al., 2005) (table S2). This finding highlights the crucial importance of sampling procedures for accurate acid-base measurements in fish physiological fluids. Indeed, fish struggling during handling and hypoxia due to gill collapse during emersion are known to greatly affect blood acid-base measurements, and our results indicate that these disturbances extend to the endolymph.

In rockfish exposed to OA, endolymph pCO_2 increased from 971.38 ± 120.70 to 1503.21 ± 73.72 µatm (Fig. 1a). Crucially, this ~500 µatm increase was half of that observed in the blood and therefore the pCO_2 difference between blood and endolymph increased from ~600 to ~1100 µatm, which is predicted to induce a proportional increase in CO_2 flux into the endolymph following Fick's law of diffusion. Endolymph TCO_2 in OA-exposed rockfish also nearly doubled (control: 9.06 ± 0.38 mM; OA = 15.96 ± 1.02 mM; Fig. S3) and, since pH remained unchanged at ~8.30 pH (Fig. 1b), it was reflected as increased $[HCO_3^-]$ (control: 8.63 ± 0.35 mM, OA: 15.19 ± 0.95 mM vs) (Fig. 1c) and $[CO_3^{2-}]$ (control: 0.36 ± 0.04 mM; OA 0.67 ± 0.06 mM) (Fig. 1d). Since aragonite saturation state ($\Omega_{aragonite}$) is directly proportional to $[CO_3^{2-}]$, it implies that biomineralization in the endolymph of OA-exposed fish is nearly twice more favorable than in that of control fish. To our knowledge, this is the first direct evidence that the acid-base chemistry in the endolymph of OA-exposed fish favors otolith overgrowth.

The increased pCO_2 diffusive rate into the endolymph and subsequent generation of H^+ as a result of CO_2 hydration and $CaCO_3$ biomineralization would be expected to induce a decrease in pH. Thus, the lack of change in endolymph pH in OA-exposed rockfish indicates robust pH regulation. Hence, we hypothesized that OA-exposed fish may have increased abundance of NKA and VHA, as these ATPases are proposed to provide the driving force for transepithelial H^+ and HCO_3^- transport across the inner ear epithelium (Kwan et al., 2020; Mayer-Gostan et al., 1997; Payan et al., 1997; Shiao et al., 2005). However, Western blotting on bulk inner ear tissue revealed no significant differences between control and OA-exposed fish (Fig. 2, table S6).

Next, we used immunocytochemistry and confocal microscopy to examine potential changes in NKA and VHA abundance or sub-cellular localization in specific inner ear epithelial cell types. The NKA and VHA immunostaining in rockfish inner ear epithelial cells generally matched

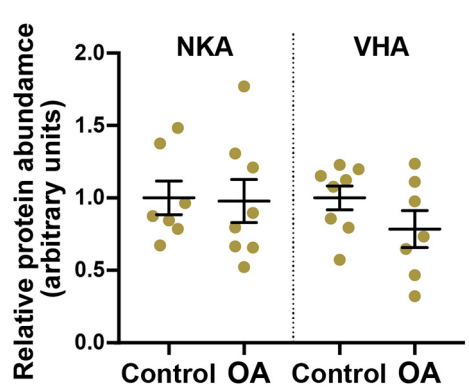

Fig. 2. Na^+/K^+-ATPase (NKA) and V-type H^+-ATPase (VHA) protein abundance in the inner ear organ of control and OA-exposed rockfish. Data is presented as mean and s.e.m. and the individual measurements are shown as beige points (N = 7–8). Relative protein abundance was calculated for each ATPase; NKA and VHA abundances are not comparable to each other. There were no significant differences for NKA (p = 0.9104) or VHA (p = 0.1695). Statistical details are reported in tables S6.

reports from other fish species (Kwan et al., 2020; Pisam et al., 1998; Shiao et al., 2005; Takagi, 1997) (Fig. 3; Fig. S4), and there were no apparent differences between control and OA-exposed fish in any cell type in terms of signal intensity of subcellular localization. The Type-I ionocytes are characterized by intense NKA signal in their highly infolded basolateral membrane and by a much fainter cytoplasmic VHA signal (Fig. 3a). These ionocytes are most abundant in the meshwork area, where they contact each other by their pseudopods giving the appearance of an interconnected matrix. The Type-II ionocytes are interspersed between the Type-I ionocytes in the meshwork area and have cytoplasmic VHA signal of comparable intensity to that in the Type-I ionocytes; however, they lack NKA signal (Fig. 3a). The sensory hair cells are in the macula; they express intense NKA signal in their basolateral membrane and very intense cytoplasmic VHA signal, which was especially concentrated towards their basal area consistent with synaptic vesicles (Fig. 3b). The supporting cells surround each sensory hair cell; they display faint cytoplasmic VHA signal and no detectable NKA signal (Fig. 3b). The granular cells flank the macula and have a characteristic columnar shape. These cells have faint NKA signal

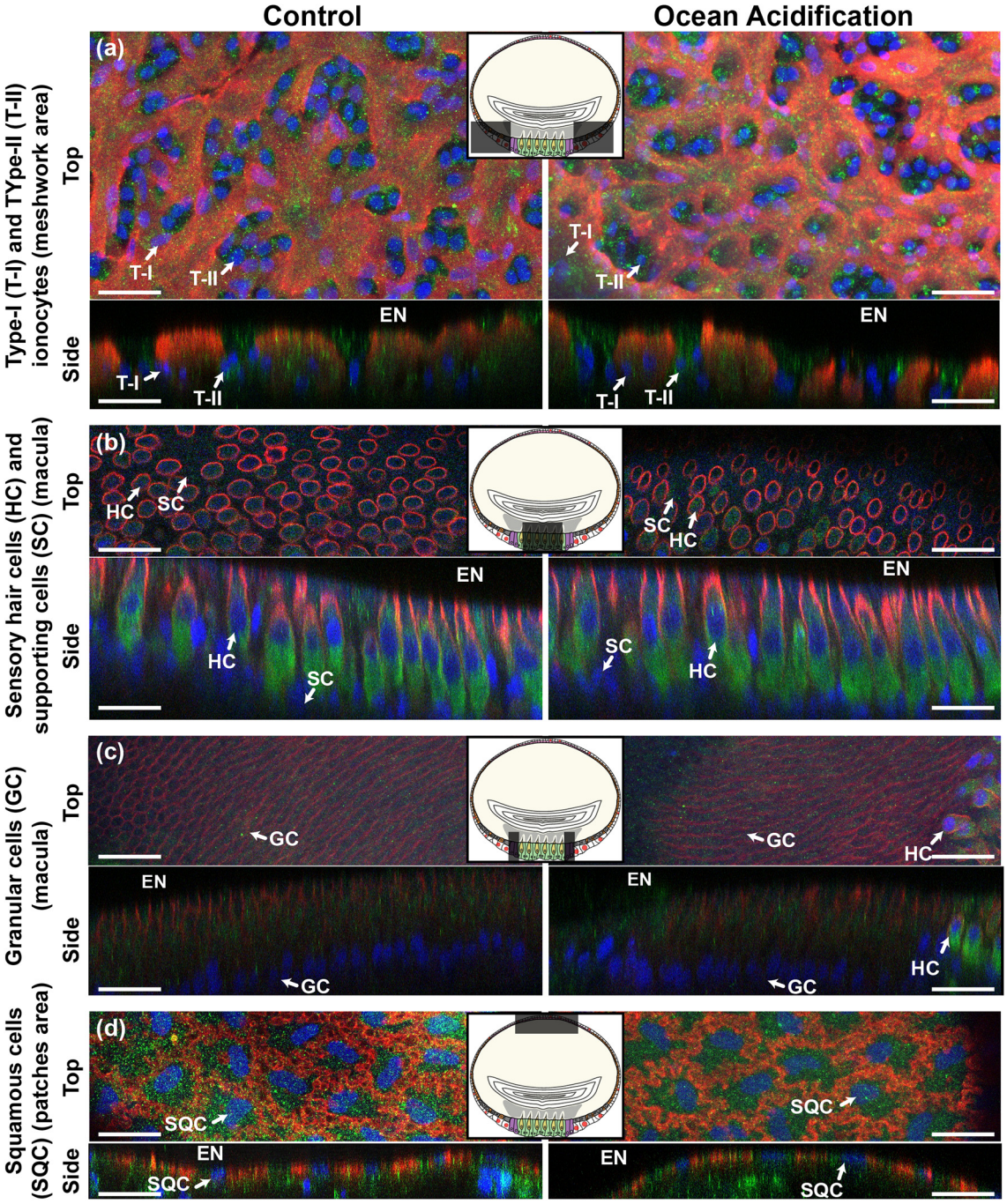

Fig. 3. Immunocytochemistry of the inner ear epithelium of control and OA-exposed rockfish. Na^+/K^+-ATPase is in red, V-type H^+-ATPase is in green, and nuclei are in blue. There were no apparent differences in NKA or VHA signal intensities or localization patterns between control and OA-exposed fish. (a) Type-I (T-I) and Type-II ionocytes (T-II), (b) sensory hair cells (HC) and supporting cells (SC), (c) granular cells (GC), and (d) squamous cells (SQC). The top view shows the X-Y plane in maximum projection, whereas the side view shows the X-Z or Y-Z plane using orthogonal cuts. EN = endolymph. Scale bar = 20 μm. Images are representative of inner ear from four control and four OA-exposed rockfish. The shaded boxes in the diagrams indicate the location of each cell type within the otolith sac. A larger diagram showcasing the heterogeneous cellular anatomy of the inner ear epithelium is provided in Fig. S4.

along their lateral plasma membrane and faint cytoplasmic VHA signal (Fig. 3c). Finally, the squamous cells are found in the patches area in the distal side of the epithelium; these cells are very thin and have NKA signal on their ribbon-like lateral membrane as well as faint cytoplasmic VHA signal (Fig. 3d). A summary of the NKA and VHA relative signal intensities in each cell type is reported in table S7.

The lack of apparent differences in NKA and VHA abundance and localization cellular patterns between control and OA-exposed fish indicates that preexisting levels of NKA and VHA were sufficient to mediate the endolymph pH regulation observed in our study. Overall, these findings are consistent with models suggesting that H^+ extrusion from the endolymph into the blood passively follows the transepithelial potential that is established by active K^+ excretion into the endolymph (Payan et al., 2004). And since the function of the sensory hair cells requires a high $[K^+]$ in the endolymph, modulation of inner ear transepithelial potential for the sole purpose of decreasing H^+ extrusion seems unlikely.

In our recent paper (Kwan et al., 2020), we proposed that HCO_3^- transport into the endolymph and H^+ removal could be upregulated by insertion of VHA into the basolateral membrane of Type-II ionocytes; however, we found no evidence for such mechanism in OA-exposed rockfish (Fig. 3a, *right panels*). Instead, upregulation of ATPase activity could have occurred via other post-translational modifications or by increased substrate availability (c.f. Kwan et al., 2021). The expression of carbonic anhydrases, ion exchangers, and other acid-base relevant proteins must be examined in future studies, ideally through an approach that includes cell-specific analyses. Lastly, a contribution of non-bicarbonate buffering to endolymph pH regulation cannot be ruled out; unfortunately, performing the required titrations are not trivial due to the small volume of this fluid.

4. Conclusions

Increased endolymph $[HCO_3^-]$ and $[CO_3^{2-}]$ provides a mechanistic explanation for otolith overgrowth in OA-exposed fish, a phenomenon that was first described over a decade ago (Checkley et al., 2009). The ultimate cause is an interplay between blood and endolymph acid-base regulation, which results in increased CO_2 flux into the endolymph coupled with endolymph pH regulation. As a result, the carbonate equilibria reactions shift to the right, promoting $[HCO_3^-]$ and $[CO_3^{2-}]$ accumulation bound to increase $\Omega_{aragonite}$, and thus promote biomineralization (Fig. 4). This implies that otolith overgrowth in response to OA will be more pronounced in fish species with more robust acid-base regulatory mechanisms; however, this hypothesis must be experimentally tested. Future studies should also investigate whether the fish inner ear epithelium can curb otolith overgrowth during prolonged OA exposure, if the long-term response requires changes in NKA and VHA protein abundance, and if species-specific differences exist. Potential mechanisms include a change in the endolymph pH setpoint, modulation of glycoprotein or Ca^{2+} secretion, and engagement of other compensatory mechanisms. Coupled with functional studies (e.g. Radford et al., 2021; Shen et al., 2016), this information will help predict whether the inner ear vestibular and auditory sensory systems of fish will be affected by OA. Furthermore, understanding the mechanisms responsible for otolith biomineralization and overgrowth during OA exposure can

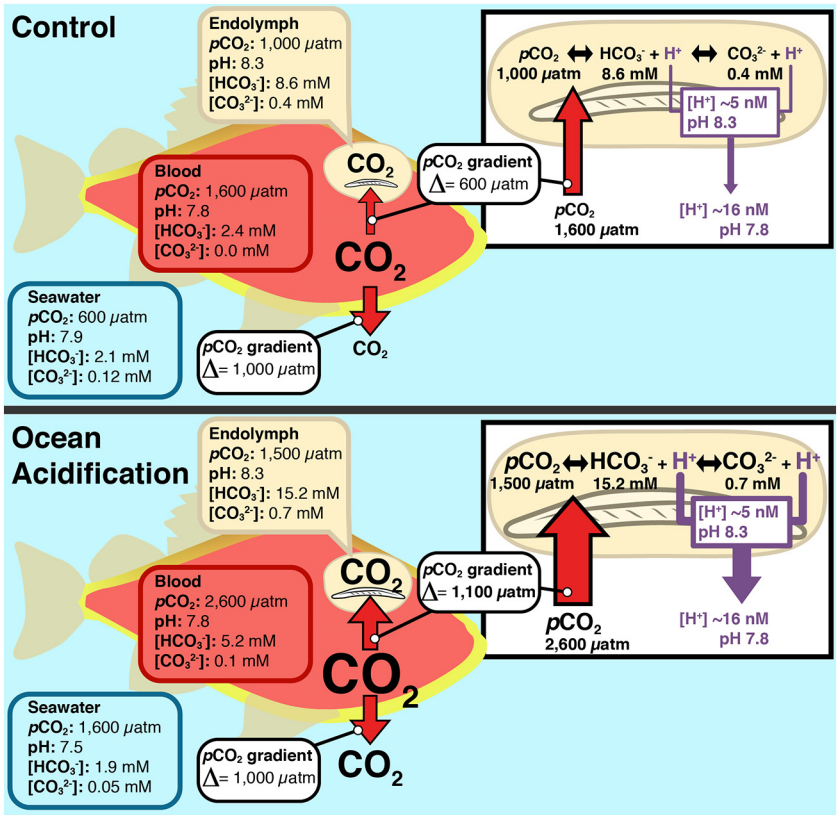

Fig. 4. Effect of blood and endolymph acid-base regulation on otolith overgrowth during exposure to ocean acidification. Under control conditions, metabolically produced CO_2 results in higher levels within the fish blood (~1600 µatm) than those in seawater (~600 µatm) and endolymph (~1000 µatm). As a result, blood CO_2 diffuses into seawater (Δ = ~1000 µatm) as it passes through the gills, and into the endolymph (Δ = ~600 µatm) as it passes through the inner ear. Under ocean acidification, the 1000 µatm increase in seawater pCO_2 (to ~1600 µatm) induces an equivalent increase in the blood (to ~2600 µatm), but a lesser increase in the endolymph (to ~1500 µatm). Thus, the pCO_2 diffusion gradient from the blood into seawater remain constant, but the pCO_2 diffusion gradient from the blood into the endolymph increases (Δ = ~1100 µatm). This process is driven by pH regulation from the endolymph by the inner ear epithelium, presumably by increased H^+ removal into the blood (although non-bicarbonate buffering cannot be ruled out). The increased CO_2 diffusion rate into the endolymph coupled with endolymph pH regulation results in the accumulation of $[HCO_3^-]$ and $[CO_3^{2-}]$, thereby increasing $\Omega_{aragonite}$ and promoting otolith calcification. The size of the arrows is proportional to the fluxes of CO_2 or H^+.

help improve the accuracy of otolith-reliant aging techniques in the future ocean.

CRediT authorship contribution statement

GTK and MT conceived and designed the experiments, analyzed the data, and wrote the manuscript. GTK executed the experiments. All authors gave final approval for publication.

Declaration of competing interest

No competing interests declared.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153690.

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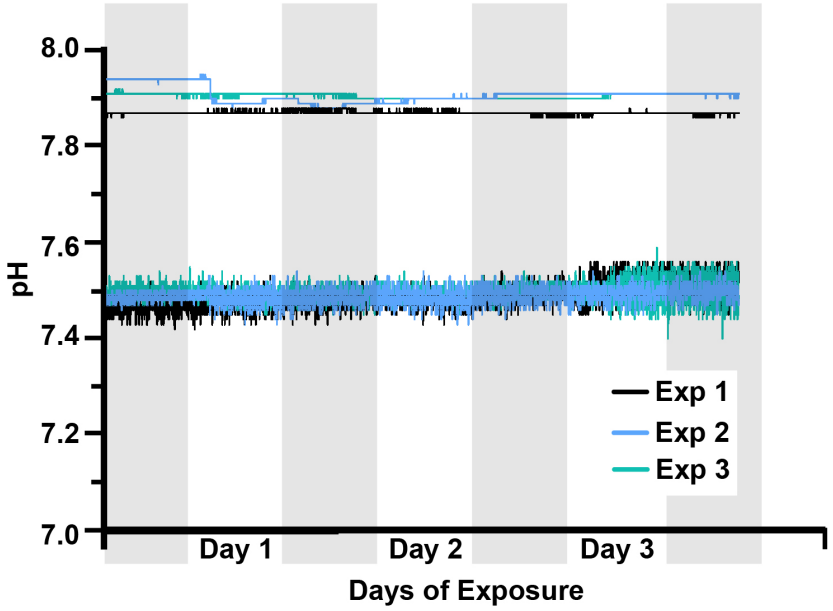

Figure S1: Seawater pH in the experimental header tanks, which was monitored and recorded every 2 minutes using an IKS Aquastar system (see Methods for more details).

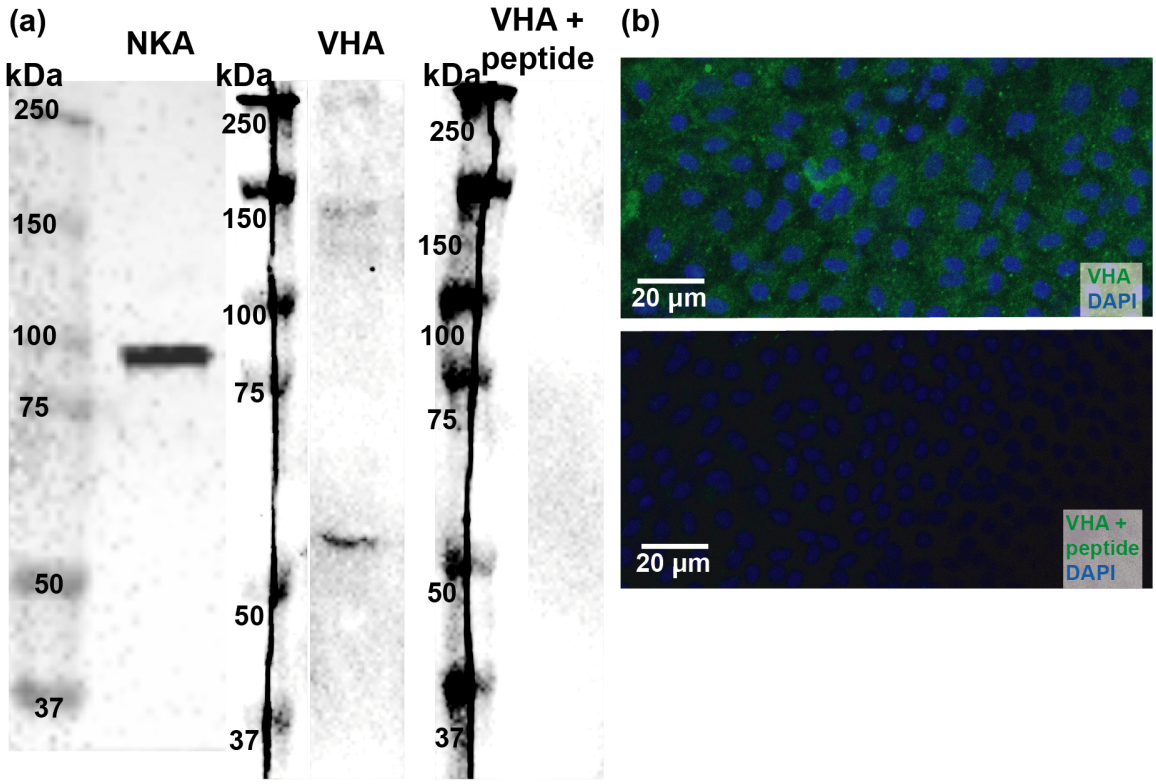

Figure S2: Validation of anti-Na^+/K^+-ATPase (NKA) and vacuolar-type H^+-ATPase (VHA) antibodies in rockfish inner ear. **(a)** Western blotting revealed single bands matching the predicted sizes of NKA at ~100 kDa, and VHA at ~55 kDa. The far-right lane shows a lack of VHA signal in the peptide preabsorption control (VHA + peptide), indicating antibody specificity. **(b)** Immunostaining of inner ear tissue showing VHA signal (green) and lack of signal in the peptide preabsorption control. Nuclei were stained with DAPI (blue). In both the Western blot and immunohistochemistry experiments, the anti-VHA antibodies were preincubated with excess antigen peptide (1:5 on a molar basis, overnight, 4°C) and then applied *in lieu* of the primary antibodies (see Methods for more details).

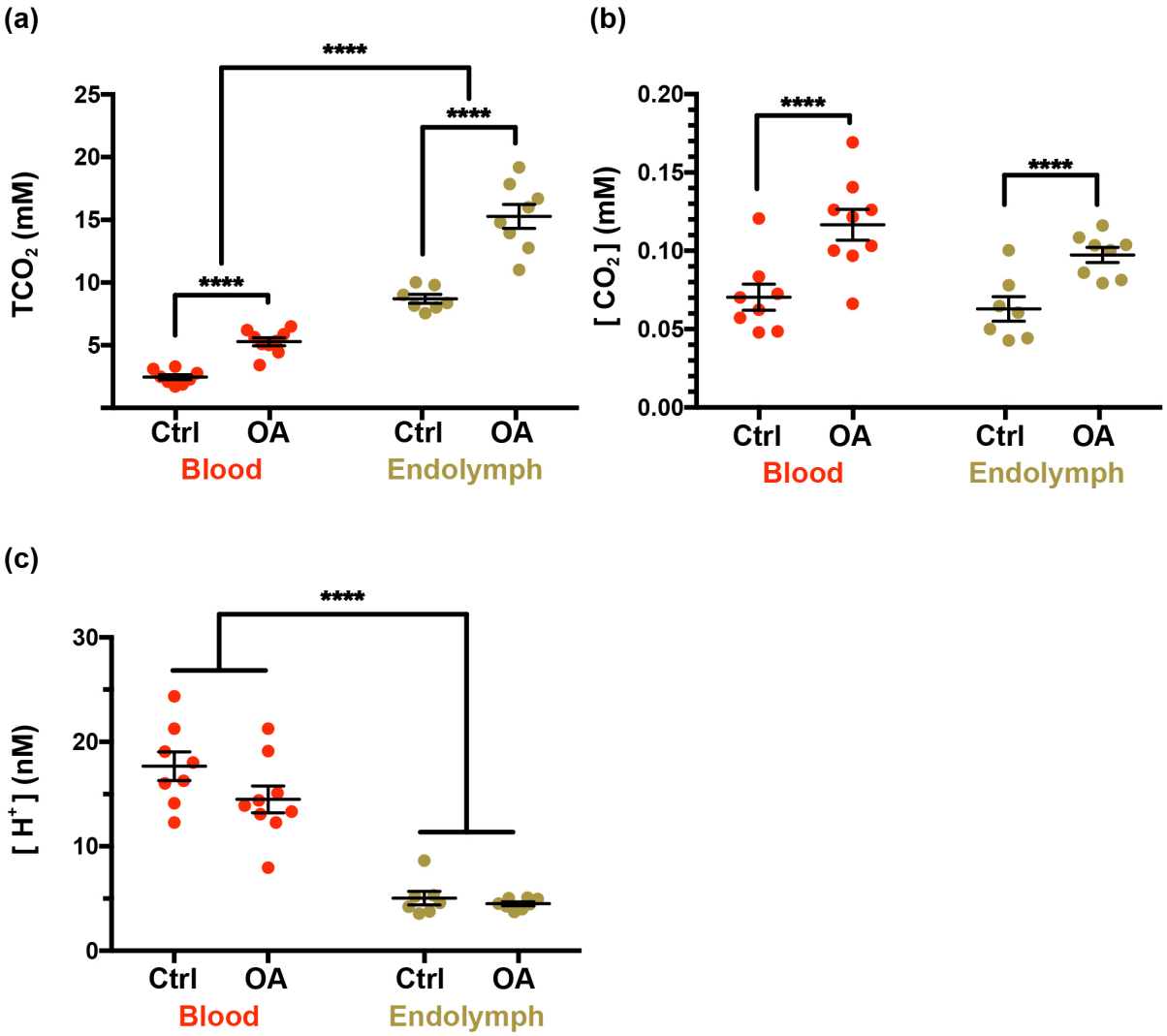

Figure S3: Blood and endolymph acid-base parameters in control and OA-exposed rockfish. **a)** [TCO_2], **b)** [CO_2], **c)** [H^+]. Data is presented as mean and s.e.m. for each group and the individual measurements are shown as red (blood) or beige (endolymph) points (N= 7-9). Statistical significance between fluids, and between treatments for a given fluid are indicated by the connecting lines and asterisks (2-way ANOVA, *p<0.05, **p<0.005, ***p<0.001, ****p<0.0001). Statistical details are reported in tables S3-S5.

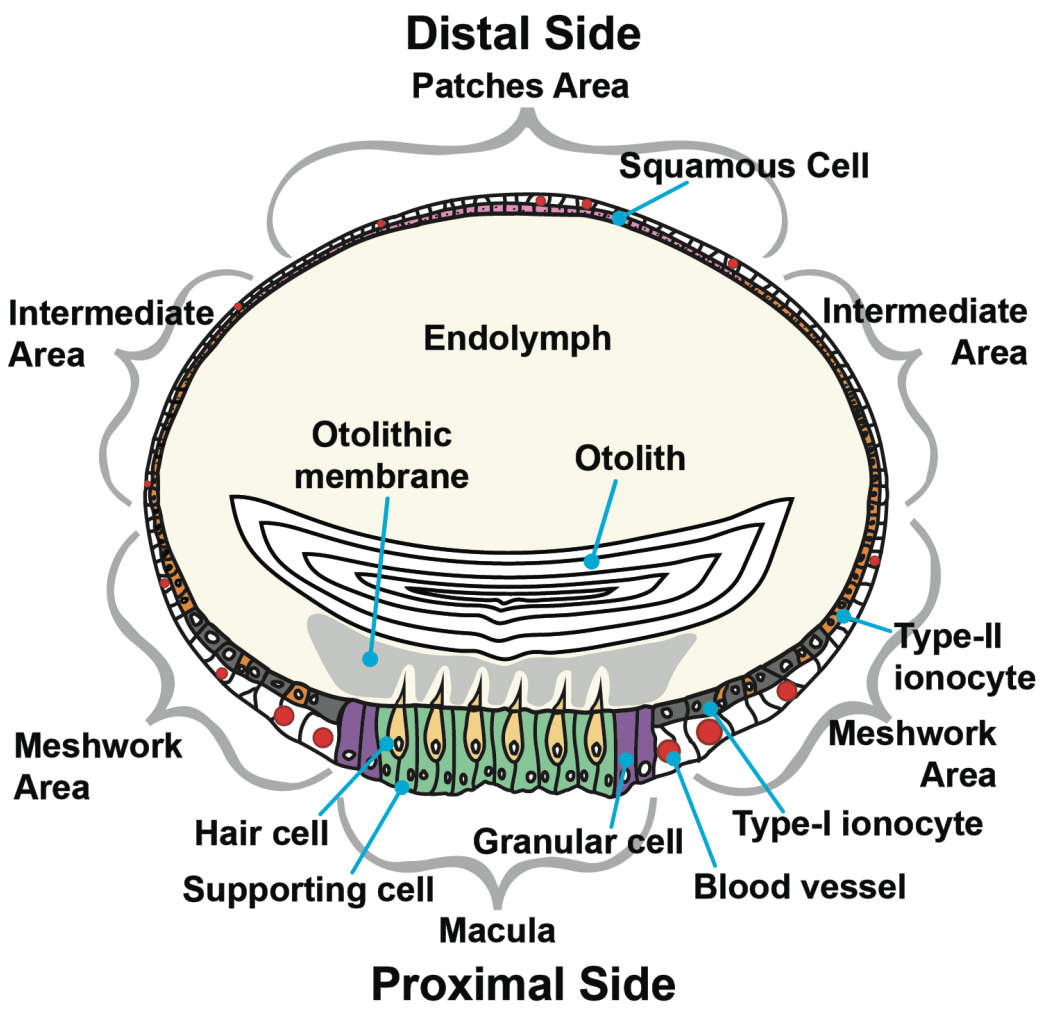

Figure S4: Cellular anatomy of the otolith sac inner ear epithelium. The otolith is biomineralized within the endolymph (beige). The sensory hair cells (yellow), supporting cells (green), and granular cells (purple) are found in the macula. The Type-I (dark grey) and Type-II ionocytes (orange) are predominantly present in the meshwork area. Type-II ionocytes make up the intermediate area, and the squamous cells (pink) are found in the patches area. Blood vessels (red) surround the organ, and are especially prevalent around the macula and meshwork areas.

Table S1: Seawater parameters of the control and ocean acidification treatments. *Asterisk* and bold font denote a significant difference (Student's T-test, α=0.05). Values are mean ± S.E.M calculated from pH recordings at 2-min intervals throughout the exposures (see Methods for details).

	Control	**Ocean Acidification**
pH	7.89 ± 0.01	**7.49 ± 0.01***
Alkalinity (µmol kgSW−1)	2,229.65 ± 1.62	2,230.33 ± 3.27
pCO_2 (µatm)	571.90 ± 4.88	**1,591.56 ± 18.58 ***
Salinity (ppt)	33.27 ± 0.04	33.27 ± 0.04
Temperature (°C)	15.830 ± 0.003	

Table S2: Comparison of endolymph acid-base values across studies. *Values were calculated using data provided in their study. ‡Values were estimated from charts provided in the study using *WebPlotDigitizer* (version 4.5; apps.automeris.io).

Study	**Payan *et al.* 1997**		**Takagi 2002**		**Takagi *et al.* 2005**		**Kwan & Tresguerres (this study)**	
Species	Rainbow trout (*O. mykiss*)	Turbot (*P. maximus*)	Rainbow trout (*O. mykiss*)	Rainbow trout (*O. mykiss*)	Rainbow trout (*O. mykiss*)	Rainbow trout (*O. mykiss*)	Splitnose rockfish (*S. diploproa*)	Splitnose rockfish (*S. diploproa*)
Anesthesia	*None reported*		0.1% 2-phenoxy-ethanol		0.1% 2-phenoxy-ethanol		0.05 g/L benzocaine	
Gill Irrigation	no		no		no		yes	
Treatment	None	None	1+ year old	2+ year old	Day	Night	Control	OA-exposed
pH	7.97 ± 0.045	*n/a*	7.90 ± 0.02	7.95 ± 0.03	7.73 ± 0.05‡	7.81 ± 0.04‡	8.32 ± 0.05	8.35 ± 0.02
TCO_2 (mM)	32.3 ± 2.60	17.2 ± 1.04	*n/a*	*n/a*	*n/a*	*n/a*	9.06 ± 0.38	15.96 ± 1.02
pCO_2 (µatm)	8,319 ± 525*	*n/a*	16,421 ± 1,013	11,078 ± 316	15,168 ± 850‡	12,838 ± 980‡	971.38 ± 120.70	1,503.21 ± 73.72
$[HCO_3^-]$ (mM)	31.76 ± 5.23*	*n/a*	44.6 ± 1.8	35.4 ± 2.3	27.5 ± 3.5‡	28.2 ± 3.1‡	8.63 ± 0.35	15.19 ± 0.95
$[CO_3^{2-}]$ (mM)	0.58 ± 0.23*	*n/a*	0.691 ± 0.039	0.673 ± 0.077	0.30 ± 0.07‡	0.36 ± 0.07‡	0.36 ± 0.04	0.67 ± 0.06

Table S3: Splitnose rockfish blood plasma and endolymph acid-base values following a 3-day exposure to control or ocean acidification (OA) conditions. Control = ~600 µatm pCO_2, pH ~7.9; OA = ~1,600 µatm pCO_2, pH ~7.5. Values are mean ± s.e.m.

	Blood Plasma		**Endolymph**	
	Control	**OA**	**Control**	**OA**
pCO_2 (µatm)	1,603.25 ± 190.69	2,659.20 ± 223.87	971.38 ± 120.70	1503.21 ± 73.72
$[CO_2]$ (mM)	0.07 ± 0.01	0.12 ± 0.01	0.06 ± 0.01	0.10 ± 0.00
$[H^+]$ (nM)	17.69 ± 1.38	14.50 ± 1.29	5.04 ± 0.65	4.50 ± 0.18
pH	7.75 ± 0.03	7.85 ± 0.04	8.32 ± 0.05	8.35 ± 0.02
$[HCO_3^-]$ (mM)	2.37 ± 0.20	5.16 ± 0.31	8.63 ± 0.35	15.19 ± 0.95
$[CO_3^{2-}]$ (mM)	0.02 ± 0.00	0.07 ± 0.01	0.36 ± 0.04	0.67 ± 0.06
TCO_2 (mM)	2.46 ± 0.20	5.34 ± 0.32	9.06 ± 0.38	15.96 ± 1.02
n	8	9	7	8

Table S4: Two-way analysis of variance (ANOVA; α=0.05) on the acid-base chemistry of splitnose rockfish internal fluids (blood, endolymph) after a 3-day exposure to control (~600 µatm pCO_2) or ocean acidification (~1,600 µatm pCO_2) condition. Bolded values denote significant difference.

		Df	Sum Sq	Mean Sq	F-ratio	*p*-value
***p*CO$_2$**	Fluid	1	6342574	6342574	27.07	**<0.0001**
	Treatment	1	5002441	5002441	21.35	**<0.0001**
	Fluid*Treatment	1	545068	545068	2.326	0.1384
	Residual	28	6561019	234322		
[CO$_2$]	Fluid	1	0.001429	0.001429	2.715	0.1106
	Treatment	1	0.01297	0.01297	24.64	**<0.0001**
	Fluid*Treatment	1	0.000282	0.0002815	0.53	0.4707
	Residual	28	0.01474	0.0005264		
[H$^+$]	Fluid	1	0.1857	0.1857	182.1	**<0.0001**
	Treatment	1	0.001289	0.001289	1.264	0.2705
	Fluid*Treatment	1	0.000038	0.000038	0.0373	0.8482
	Residual	28	0.02855	0.00102		
pH	Fluid	1	0.2289	0.2289	228.3	**<0.0001**
	Treatment	1	0.003157	0.003157	3.15	0.0868
	Fluid*Treatment	1	0.0006252	0.0006252	0.6237	0.4363
	Residual	28	0.02807	0.001002		
[HCO$_3^-$]	Fluid	1	526.8	526.8	225.5	**<0.0001**
	Treatment	1	173.1	173.1	74.09	**<0.0001**
	Fluid*Treatment	1	28.16	28.16	12.06	**0.0017**
	Residual	28	65.41	2.336		
[CO$_3^{2-}$]	Fluid	1	50.66	50.66	434.1	**<0.0001**
	Treatment	1	5.484	5.484	47	**<0.0001**
	Fluid*Treatment	1	0.3148	0.3148	2.698	0.1117
	Residual	28	3.267	0.1167		
TCO$_2$	Fluid	1	525.1	525.1	222.9	**<0.0001**
	Treatment	1	176.1	176.1	74.75	**<0.0001**
	Fluid*Treatment	1	27.99	27.99	11.88	**0.0018**
	Residual	28	65.97	2.356		

Table S5: Tukey HSD posthoc analysis (95% family-wise confidence level; α=0.05) following the two-way ANOVA analysis on the acid-base chemistry of splitnose rockfish internal fluids (blood, endolymph) after a 3-day exposure to control (ctrl; ~600 µatm pCO_2) or ocean acidification (OA; ~1,600 µatm pCO_2) condition. Bolded values denote significant differences.

	Treatment:Fluid	Difference	Lower Interval	Upper Interval	*Adjusted p*-value
[HCO_3^-]	Ctrl:Endo – Ctrl:Blood	6.263	4.104	8.423	**<0.0001**
	OA:Blood – Ctrl:Blood	2.786	0.7585	4.814	**0.0043**
	OA:Endo – Ctrl:Blood	12.82	10.73	14.9	**<0.0001**
	OA:Blood – Ctrl:Endo	-3.477	-5.58	-1.374	**0.0006**
	OA:Endo – Ctrl:Endo	6.554	4.394	8.714	**<0.0001**
	OA:Endo – OA:Blood	10.03	8.003	12.06	**<0.0001**
TCO_2	Ctrl:Endo – Ctrl:Blood	6.256	4.087	8.425	**<0.0001**
	OA:Blood – Ctrl:Blood	2.833	0.7963	4.869	**0.0038**
	OA:Endo – Ctrl:Blood	12.84	10.75	14.94	**<0.0001**
	OA:Blood – Ctrl:Endo	-3.423	-5.535	-1.311	**0.0007**
	OA:Endo – Ctrl:Endo	6.588	4.419	8.757	**<0.0001**
	OA:Endo – OA:Blood	10.01	7.975	12.05	**<0.0001**

Table S6: Na^+/K^+-ATPase (NKA) and V-type H^+-ATPase (VHA) protein abundance in the inner ear organ of control and OA-exposed rockfish. Values are mean ± s.e.m. There were no significant differences for NKA or VHA (Two-tailed t-test, α = 0.05).

Protein	Relative Protein Abundance	n	t-ratio	Degrees of freedom	*p*-value
NKA	Control: 1.00 ± 0.12	7	0.11728	13	0.9104
	OA: 0.98 ± 0.15	8			
VHA	Control: 1.00 ± 0.08	8	1.4182	13	0.1695
	OA: 0.78 ± 0.13	7			

Table S7: Relative comparison of Na^+/K^+-ATPase (NKA) and V-type H^+-ATPase (VHA) signal intensity and subcellular localization in rockfish inner ear epithelial cells. There were no apparent differences between control and ocean acidification-exposed rockfish.

Cell Type	NKA Signal	VHA Signal
Type-I Ionocyte	+++ Basolateral membrane infoldings	+ Cytoplasm
Type-II Ionocyte	-	+ Cytoplasm
Sensory Hair Cell	++ Basolateral membrane	+++ Cytoplasm (concentrated in the basal portion)
Supporting Cell	-	+ Cytoplasm
Granular Cell	+ Lateral membrane	+ Cytoplasm
Squamous Cell	++ Ribbon-like lateral membrane	+ Cytoplasm