



CO₂ per se activates carbon dioxide receptors

Pingxi Xu, Xiaolan Wen¹, Walter S. Leal*

Department of Molecular and Cellular Biology, University of California-Davis, Davis, CA, 95616, USA

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ABSTRACT

Carbon dioxide has been used in traps for more than six decades to monitor mosquito populations and help make informed vector management decisions. CO₂ is sensed by gustatory receptors (GRs) housed in neurons in the maxillary palps. CO₂-sensitive GRs have been identified from the vinegar fly and mosquitoes, but it remains to be resolved whether these receptors respond to CO₂ or bicarbonate. As opposed to the vinegar fly, mosquitoes have three GR subunits, but it is assumed that subunits GR1 and GR3 form functional receptors. In our attempt to identify the chemical species that bind these receptors, we discovered that GR2 and GR3 are essential for receptor function and that GR1 appears to function as a modulator. While *Xenopus* oocytes coexpressing *Culex quinquefasciatus* subunits CquiGR1/3 and CquiGR1/2 were not activated, CquiGR2/3 gave robust responses to sodium bicarbonate. Interestingly, CquiGR1/2/3-coexpressing oocytes gave significantly lower responses. That the ternary combination is markedly less sensitive than the GR2/GR3 combination was also observed with orthologs from the yellow fever and the malaria mosquito. By comparing responses of CquiGR2/CquiGR3-coexpressing oocytes to sodium bicarbonate samples (with or without acidification) and measuring the concentration of aqueous CO₂, we showed that there is a direct correlation between dissolved CO₂ and receptor response. We then concluded that subunits GR2 and GR3 are essential for these carbon dioxide-sensitive receptors and that they are activated by CO₂ per se, not bicarbonate.

1. Introduction

Carbon dioxide is the oldest known and the most powerful mosquito attractant (Van Thiel and Weurman, 1947). It has been widely used for decades for trapping host-seeking female mosquitoes (Reeves, 1951, 1953) to monitoring populations and to assist in integrated vector management programs. In addition to being an attractant sensu stricto, CO₂ gates mosquito perception of other sensory modalities (Gillies, 1980; Liu and Vosshall, 2019; McMeniman et al., 2014). In the vinegar fly, *Drosophila melanogaster*, CO₂ elicits through different pathways attraction and aversion behaviors (van Breugel et al., 2018). Mosquitoes sense CO₂ with olfactory receptor neurons (ORNs) (Grant et al., 1995; Majeed et al., 2017; Syed and Leal, 2007) housed in peg sensilla (= capitata pegs) in the maxillary palps (McIver and Charlton, 1970). It has been unambiguously demonstrated that CO₂ is sensed by the gustatory receptors DmelGR21a and DmelGR63a, housed in antennal neuron ab1C of the vinegar fly (Jones et al., 2007; Kwon et al., 2007; Suh et al., 2004), but it remains to be resolved whether carbon dioxide receptors are activated by CO₂ per se or bicarbonate (Jones et al., 2007; Kwon et al., 2007; Ning et al., 2016; Xu and Anderson, 2015).

Mosquitoes have three closely related homologs of DmelGR21a and

DmelGR63a (Robertson and Kent, 2009), GR1, GR2, and GR3. Because they were identified before the new nomenclature for these GR genes was proposed (Robertson and Kent, 2009), GR1-3 in the malaria mosquito, *Anopheles gambiae*, are still named AgamGR22, AgamGR23, and AgamGR24, respectively (Hill et al., 2002). While it has been clearly demonstrated that GR3 is essential for CO₂ reception in the yellow fever mosquito, *Aedes aegypti* (McMeniman et al., 2014), it is not yet known whether GR1 and GR2 are functionally redundant (McMeniman et al., 2014). While no response to CO₂ was recorded when both AgamGR22 and AgamGR24 (one copy of each) were coexpressed in the empty neuron system of the vinegar fly (Hallem et al., 2004), by increasing the dosage of both transgenes by two-fold led to significant response (Lu et al., 2007). Additionally, flies carrying one copy of each of the three subunits showed a significant response to CO₂, albeit not as strong as responses recorded from the flies carrying two-fold of AgamGR22 and 24 (Lu et al., 2007). Thus, AgamGR23 was implicated in CO₂ reception in the malaria mosquito, but its role was not clarified. On the other hand, by using RNAi combined with behavioral measurements, it has been suggested that AaegGR2 had no role in CO₂ reception by the yellow fever mosquito (Erdelyan et al., 2012). In summary, it remains to be determined whether all three GR subunits are functionally

* Corresponding author.

E-mail address: wsleal@ucdavis.edu (W.S. Leal).

¹ Current address: School of Preclinical Medicine, Guangxi Medical University, Nanning, 530021, China.

required for CO₂ detection in mosquitoes or whether GR1 and GR2 are functionally redundant (McMeniman et al., 2014).

We envisioned that having a functional carbon dioxide-detecting system in an aqueous environment as in the *Xenopus* oocyte recording system would allow us to address with the Le Chatelier's principle the long-standing question whether carbon dioxide receptors are activated by CO₂ per se or by bicarbonate (Jones et al., 2007; Kwon et al., 2007; Ning et al., 2016; Xu and Anderson, 2015). Because dissolved CO₂ forms an equilibrium with bicarbonate in water ($\text{CO}_2(\text{aq}) \rightleftharpoons \text{H}^+ + \text{HCO}_3^-$), a shift of the equilibrium towards dissolved CO₂ would increase a receptor response if CO₂ per se binds carbon dioxide receptors, whereas a reduced response would indicate activation by bicarbonate. Here, we show that CO₂ per se, not bicarbonate, activates the receptors. While preparing to address this question, we discovered that the gustatory receptor CquiGR2 from the southern house mosquito, *Culex quinquefasciatus*, is essential for function, whereas CquiGR1 appears to be a modulator. Additionally, we show a similar GR1 effect in the *Ae. aegypti* and *An. gambiae* CO₂-sensing system. Specifically, CO₂ elicited weaker responses in the ternary receptor systems than in the respective binary counterparts devoid of GR1 (GR22 in the case of the malaria mosquito receptors).

2. Material and methods

2.1. RNA extraction, DNA synthesis, and cloning

Three hundred pairs of palps from 4- to 6-d-old female *Culex* mosquitoes were dissected under a stereomicroscope (Zeiss, Stemi DR 1663) and collected in 75% (vol/vol) ethanol diluted in diethylpyr-carbonate (DEPC)-treated water on ice. The samples were centrifuged, and ethanol was removed before total RNA was extracted using TRIzol reagent (Invitrogen). cDNA was synthesized from 1 µg of total RNA using GoScript™ Reverse Transcription kit according to the manufacturer's instructions (Promega). For *An. gambiae* and *Ae. aegypti*, gene sequences of AgamGR22, 23, 24 and AaegGR1, 2, 3 from Genbank were synthesized by GenScript USA Inc. (Piscataway, NJ). Full-length gene-specific cloning primers were designed based on the sequences from Genbank and added 15-bp In-Fusion cloning adapters.

CqGR1-Fw GATCAATCCCCGGGaccATGATTACAGTCAGATGGA GGACG
 CqGR1-Rv CAAGCTTGCTCTAGACTATTGTGGGTTCTGTTTGGCCG.
 CqGR2-Fw GATCAATCCCCGGGaccATGGTCATCAAGACAGTGA CTTTGAC
 CqGR2-Rv CAAGCTTGCTCTAGATTAGTGAGCGTGAGCTTTCTGTA AATTCTC.
 CqGR3-Fw GATCAATCCCCGGGaccATGAGCATATTTCCGGATACT CTGCG
 CqGR3-Rv CAAGCTTGCTCTAGATCAATGCGCTGCGTGC.
 AgGR22-Fw GATCAATCCCCGGGaccATGATTACACACAGATGG AAG
 AgGR22-Rv CAAGCTTGCTCTAGATTAGGTGTTCACTTTGTCTGC.
 AgGR23-Fw GATCAATCCCCGGGaccATGGTTATCAAGGAAAGTG AGTTC
 AgGR23-Rv CAAGCTTGCTCTAGATTACTGTTGTGTAGCAGCTTA ACA.
 AgGR24-Fw GATCAATCCCCGGGaccATGAGTCTCTACTTCAACG CGG.
 AgGR24-Rv CAAGCTTGCTCTAGACTAAGAATGAGACGAATTACTG TGC.
 AaGR1-Fw GATCAATCCCCGGGaccATGATTACAGCCAGATGG AAG
 AaGR1-Rv CAAGCTTGCTCTAGACTAGTTCTCCTTCAGCTTAGTT AGA.
 AaGR2-Fw GATCAATCCCCGGGaccATGGTCATCAAAGACAGTG AGT
 AaGR2-Rv CAAGCTTGCTCTAGACTATCCCTTATGACTGTGCTTG

ATT.

AaGR3-Fw GATCAATCCCCGGGaccATGAATCTCAACCAAGACC CCA
 AaGR3-Rv CAAGCTTGCTCTAGACTACTCGCGATATGAACCCGTC ATA.

Adapter sequences are underlined, and lower case acc is Kozak consensus. PCR products were purified by Monarch® DNA Gel Extraction Kit (NEBioLab) and directly inserted to linearized destination vector-pGEMHE by In-Fusion reaction (Clontech). The colonies were picked, and vectors were extracted using Monarch® Plasmid Miniprep Kit. Inserts were submitted to DNA Sequencing Facility, UC Berkeley for verification of sequences.

2.2. Oocytes preparations and two-electrode voltage clamp recordings

The vectors carrying GR genes were linearized with restriction endonuclease *NheI*, except for AgamGR22, which was cut by *SphI*. The linearized vectors with gene inserts were used as templates to transcribe capped cRNAs with poly(A) using an mMMESSAGE mMACHINE T7 kit (Ambion) following the manufacturer's protocol. The cRNAs were dissolved in RNase-free water and adjusted at a concentration of 200 µg/mL by UV spectrophotometry (NanoDrop™ Lite Spectrophotometer, ThermoFisher). 9.2 nl of each cRNA samples were microinjected into stage V or VI *Xenopus* oocytes (purchased from EcoCyte Bioscience, Austin, TX). Then injected oocytes were incubated at 18 °C for 3–7 days in modified Barth's solution [in mM: 88 NaCl, 1 KCl, 2.4 NaHCO₃, 0.82 MgSO₄, 0.33 Ca(NO₃)₂, 0.41 CaCl₂, 10 HEPES, pH 7.4] supplemented with 10 µg/mL of gentamycin, 10 µg/mL of streptomycin, and 1.8 mM sodium pyruvate. For two-electrode voltage clamp (TEVC) recordings, as previously done (Xu et al., 2019), oocytes were placed in a perfusion chamber and challenged with test compounds. Compound-induced currents were amplified with an OC-725C amplifier (Warner Instruments, Hamden, CT), the voltage held at –80 mV, low-pass filtered at 50 Hz and digitized at 1 kHz. Data acquisition and analysis were carried out with Digidata 1440 A and pClamp10 software (Molecular Devices, LLC, Sunnyvale, CA).

2.3. Sample preparations and CO₂ measurement

Sodium chloride (Fisher Scientific, > 99%) and sodium bicarbonate (Sigma-Aldrich, 99.7%) were used to prepare fresh samples by dissolving the appropriate amounts of these salts in perfusion Ringer buffer (NaCl 96 mM, KCl 2 mM, CaCl₂ 1.8 mM, MgCl₂ 1 mM, HEPES 5 mM, pH 7.6) to make 0.5 M solutions. Then, the desired concentrations were prepared by diluting with perfusion Ringer buffer. CO₂ samples were prepared by bubbling MediPure™ CO₂ (Praxair, Danbury, CT) directly into perfusion buffer for 5 s, and subsequently adjusting the pH.

The concentration of dissolved CO₂, ie, CO₂ (aq), was calculated by equation (1):

$$[\text{CO}_2(\text{aq})] = \frac{10^{\text{pK}_{\text{overall}} - \text{pH}} \times [\text{HCO}_3^-]_{\text{nominal}}}{1 + 10^{\text{pK}_{\text{overall}} - \text{pH}}} \quad (1)$$

K_{overall}, which is sometimes referred to as K_a, is a constant, which incorporates the constant of hydrolysis of CO₂ and the first dissociation constant of carbonic acid, K_{a1}, ie, K_{overall} = K_h × K_{a1}. pKa is 6.3 (<https://pubchem.ncbi.nlm.nih.gov/compound/Sodium-bicarbonate#section=pKa>). The molar concentration of dissolved CO₂ is, therefore, related to the pH of the solution and the nominal concentration of sodium bicarbonate. Thus, the concentration of dissolved CO₂ in a 10 mM NaHCO₃ solution at pH 7.73 is approximately 0.358 mM or 15.76 ppm. At pH 7.32, the calculated concentration of dissolved CO₂ is 0.872 mM or 38.36 ppm.

pH and carbon dioxide were measured with an Orion Star™ A214 pH/ISE Benchtop Meter (ThermoFisher Scientific, Waltham, MA 02451). A carbon dioxide electrode was used for CO₂ measurements. The internal filling solution of this electrode is separated from the

sample solution with a gas-permeable membrane. CO₂ dissolved in a sample solution diffuses through this membrane until an equilibrium between CO₂ in the electrode filling and the sample solution is reached. The influx of CO₂ causes a change in hydrogen ion concentration in the electrode filling solution, which is measured by a sensing element behind the membrane. The system was calibrated before measurements with freshly prepared 22, 55 and 110 ppm solutions. Standard solutions were sealed with parafilm before measurements. To minimize losses of carbon dioxide during measurements, we used 50 mL Falcon tubes to house sample solutions. A hole was opened in the tube cap, and the electrode was inserted and kept in place with two O-ring seals below and two O-ring seals on the top of the cap. Then the cap was sealed with Teflon tapes and finally covered with electrical tape. Fifty milliliter Falcon tubes housing test samples were attached to the electrode and fastened tightly. The concentrations of dissolved CO₂ in bicarbonate solutions were measured by preparing 10, 25, 50, 100, 150, 200, 250, and 300 mM solutions in perfusion Ringer buffer, with four replicates for each sample. To compare the concentrations of dissolved CO₂ without adjustment and after acidification, 7 mL aliquots of 10 mM sodium bicarbonate buffers were prepared in pairs. One of the two aliquots in a pair was used to determine CO₂ concentration without pH change. To the other pair, 150 µl of 0.1 N HCl was added and immediately used for CO₂ measurement, and then the pH was recorded. To compare oocyte response, samples were similarly prepared by using smaller aliquots (700 µl) in V-vials. In this case, 0.1 N HCl was injected through the Teflon liner of the open-top caps. After that, an aliquot was collected to be applied to the *Xenopus* oocyte recording system, and the remainder was used for pH measurement.

2.4. Statistical analysis and graphical preparations

Prism 8.2.0 from GraphPad Software (La Jolla, CA) was used for both statistical analysis and graphical preparations. A dataset that passed the Shapiro-Wilk normality test was analyzed by *t*-test; otherwise, data were analyzed by Wilcoxon matched-pairs signed-rank test. All data are presented as mean ± SEM.

3. Results and discussion

3.1. *Cx. quinquefasciatus* gustatory receptor GR2/GR3 is sensitive to carbon dioxide

We cloned three gustatory receptors from the southern house mosquito, specifically CquiGR1 (VectorBase, CPIJ006622), CquiGR2 (GenBak, MN428502), and CquiGR3 (MN428503), which are likely to be involved in CO₂ reception. Initially, we coexpressed combinations of these three GRs in the *Xenopus laevis* oocytes and recorded their responses to sodium bicarbonate. Of note, the application of sodium bicarbonate increases the sodium concentration in the perfusion Ringer, thus causing inward currents through endogenous oocyte channels due to an increase in the extracellular concentration of Na⁺ (Fig. 1A, Fig. S1). We, therefore, applied equivalent doses of NaCl and NaHCO₃ in all experiments to control for the Na⁺ response. Equal responses to NaCl and NaHCO₃ at the same dose, as in the case of naked oocytes (Fig. 1A), indicate that the currents were generated by Na⁺ ions. Surprisingly, oocytes coexpressing CquiGR1 and CquiGR3 did not respond to bicarbonate as the response to sodium bicarbonate did not differ from the response to sodium chloride (Fig. 1B, Fig. S1). A lack of specific response to sodium bicarbonate was also observed with CquiGR1/CquiGR2-coexpressing oocytes (Fig. 1C, Fig. S1). By contrast, CquiGR2/CquiGR3-expressing oocytes gave robust dose-dependent responses to sodium bicarbonate (Figs. 1D and 2, Fig. S1). Although it is not surprising that injections of sodium chloride generated dose-dependent currents, they were significantly smaller (*t*-test, *P* = 0.0008) than those generated by sodium bicarbonate at the same dose (Fig. 2).

We then compared CquiGR2/CquiGR3 and CquiGR1/CquiGR2/

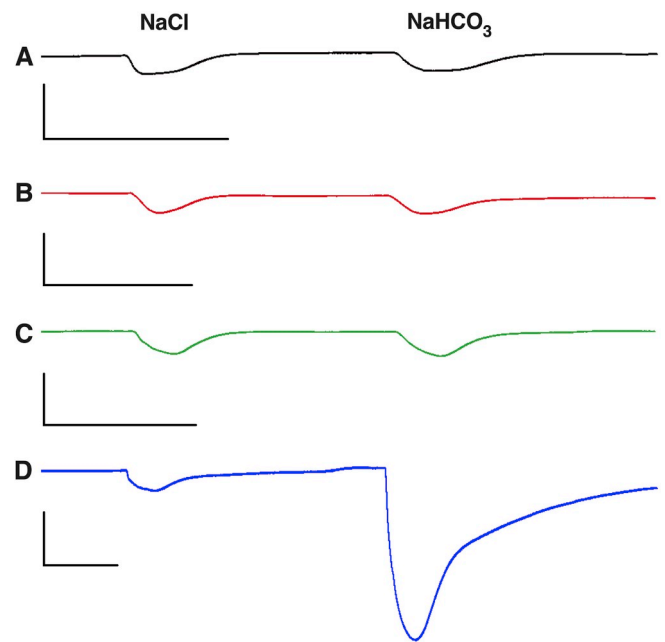


Fig. 1. Responses of Oocytes to Sodium Chloride and Sodium Bicarbonate Representative traces obtained with the following types of oocytes from the same batch and age: (A) Intact (naked) *Xenopus* oocytes. (B) Oocyte coexpressing CquiGR1 and CquiGR3 (C) Oocyte coexpressing CquiGR1 and CquiGR2 (D) Oocyte coexpressing CquiGR2 and CquiGR3. All scales are 200 nA and 0.5 min. Oocytes were first challenged with 200 mM NaCl and then 200 mM NaHCO₃.

CquiGR3 (Fig. 3). The ternary receptor system showed a remarkably lower (*t*-test, *P* = 0.0320) response to sodium bicarbonate than the binary receptor (Fig. 3).

Next, we examined whether variants of CquiGR1 would have different effects. We cloned five CquiGR1 variants, one of them showed an amino acid sequence identical to the sequence appearing in VectorBase (CPIJ 006622). We named this variant the wild type form. Three other variants differed in one amino acid residue each, specifically CquiGR1K456 N (GenBank, MN418391), CquiGR1M365 V (MN418394), and CquiGR1L246 F (MN418393). Lastly, one variant differed in two amino acid residues, ie, CquiGR1D143G; R434K (MN418392). We then expressed variants along with CquiGR2 + CquiGR3 in the *Xenopus* oocyte recording system and compared their responses to those obtained with CquiGR2/CquiGR3-coexpressing oocytes when stimulated with the same dose of sodium bicarbonate (Fig. S2). None of the five ternary receptor systems showed a stronger response than those recorded from CquiGR2/CquiGR3-coexpressing oocytes (Fig. 4). Responses recorded from CquiGR1D143G; R434K were not significantly different from those measured from the binary receptor system (*n* = 4, unpaired *t*-test, *P* = 0.0710). All other variants, including the wild type, generated significantly lower responses than those recorded from CquiGR2/CquiGR3-coexpressing oocytes (Fig. 4). These findings suggest that CquiGR1 may modulate the receptor system response to sodium bicarbonate.

3.2. Gustatory receptors are activated by carbon dioxide per se, not bicarbonate

To address this question, we used a carbon dioxide electrode, which was designed to measure the total amount of dissolved carbon dioxide in solution. The solution in the internal filling of the electrode is separated from the analytical sample by a CO₂ permeable membrane. Typically, a carbon dioxide buffer is added to the analytical sample to lower the pH to 4.8–5.2 thus shifting the CO₂/bicarbonate equilibrium (CO₂(aq) ⇌ H⁺ + HCO₃⁻) towards free CO₂. Carbon dioxide diffuses

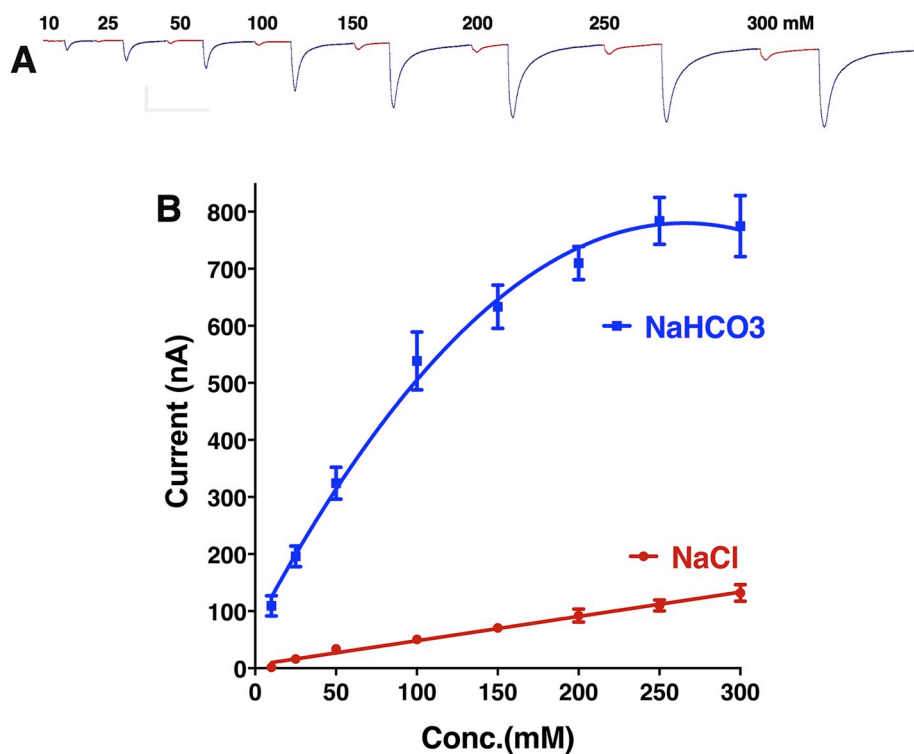


Fig. 2. Responses of CquiGR2 + CquiGR3-co-expressing oocytes to sodium chloride and sodium bicarbonate

(A) Representative trace from a single oocyte preparation stimulated with increasing doses (10–300 mM) of the two compounds. For clarity, responses to sodium chloride and sodium bicarbonate were colored red and blue, respectively. (B) Concentration-dependent curves obtained with five different oocytes coexpressing CquiGR2 and CquiGR3. Data are presented as mean ± SEM. Some error bars for NaCl curve do not appear, because they are shorter than the size of the symbol. From left to right: 0.81, 2.59, 3.24, 5.35, 6.92, 11.24, 9.59, and 14.42. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

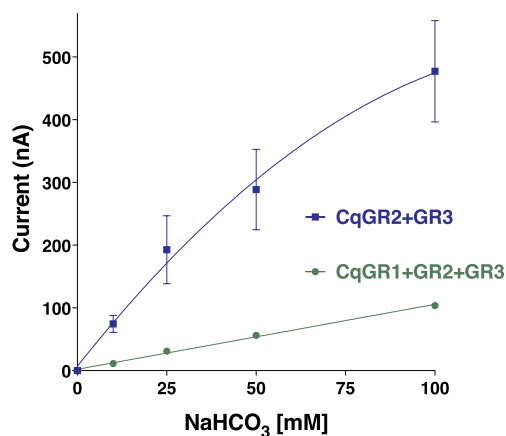


Fig. 3. Comparative concentration-dependent curves for oocytes co-expressing either two or three functional subunits

Results were obtained with four oocytes coexpressing CquiGR2 and CquiGR3 and four oocytes coexpressing the three GRs. For simplicity, in figures, we use two-letter symbols for proteins as opposed to four-letter symbols (eg, Cq = Cqui) used elsewhere. Data are presented as mean ± SEM. Error bars for the green curve do not appear because they are shorter than the size of the symbol. From left to right: 0, 0.63, 3.24, 1.65, and 3.84. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

through the membrane, and an equilibrium is reached between the concentration of CO₂ in the analyte and the internal filling. The increase of CO₂ in the internal filling causes an increase in hydrogen ion concentration, which is ultimately measured by the pH electrode. To measure the actual (equilibrium concentration) rather than the total concentration of carbon dioxide, we used this electrode in a sealed system and without the carbon dioxide buffer. To calibrate our measurement system, we compared the calculated concentrations of CO₂ in sodium bicarbonate buffers with those obtained by direct measurements with the carbon dioxide electrode (Fig. 5). The results showed a faithful relationship (two-tailed *t*-test, *P* = 0.1037) between calculated

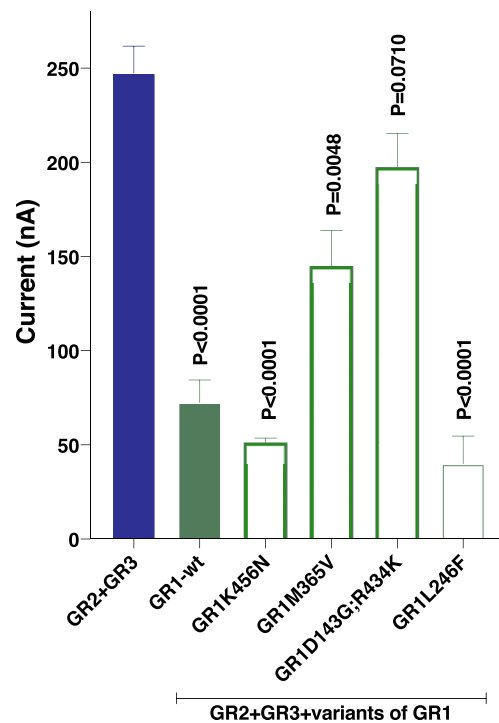


Fig. 4. Effect of different variants of CquiGR1 on the response of CquiGR2 + CquiGR3-co-expressing oocytes

All experiments were performed with four replicates with oocytes from the same batch coexpressing either CquiGR2 + CquiGR3 or CquiGR2 + CquiGR3 plus one of the CquiGR1 variants (K456N, M365V, D143G; R434K, and L246F). The clone with sequence identical to that in VectorBase (CJPI 006622) was named wild type (wt). Responses recorded from CquiGR2 + CquiGR3-co-expressing oocytes and those recorded from oocytes coexpressing CquiGR2 + CquiGR3 plus one CquiGR1 variant after stimulus with 200 mM sodium bicarbonate (n = 4) were compared by unpaired *t*-test. *P* values are presented on the top of each variant column. Data are presented as mean ± SEM.

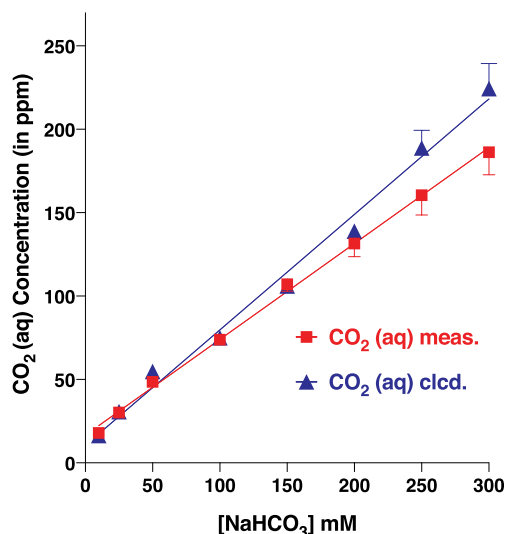


Fig. 5. CO₂ concentrations in solutions of sodium bicarbonate prepared in Ringer buffer

The calculated concentrations based on the final pH of each preparation ($n = 4$) are shown in red. The actual concentration of CO₂ in each solution was measured with a CO₂ Ion Selective Electrode. Data are presented as mean \pm SEM. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and measured CO₂ concentrations (Fig. 5). We then used this system to measure the concentrations of dissolved CO₂ in samples obtained by bubbling CO₂ in perfusion Ringer buffer. The higher the concentration of CO₂, the larger the currents recorded from CquiGR2/CquiGR3-co-expressing oocytes (Fig. S3). Of note, currents recorded from sodium bicarbonate is the summation of carbon dioxide and Na⁺ responses. Although we adjusted the pH of the tested bubbled CO₂ samples (Fig. S3) to rule out the possible effect of hydrogen ion concentrations on oocyte responses, these recordings did not unambiguously determine whether the receptor system is responding to carbon dioxide per se or bicarbonate.

The next experiment further examined the possible role of pH on recorded currents. We injected Ringer and 50 mM sodium chloride samples with their pH adjusted to that of the perfusion Ringer buffer, as

well as to 7, 6.5, 6, and 5.5. To make certain that the CquiGR2/CquiGR3-co-expressing oocyte system was functional throughout the tests, we injected Ringer, sodium chloride, and sodium bicarbonate at the beginning and the end of each run (Fig. S4). These experiments ($n = 6$) further demonstrated that hydrogen ion concentration at the pH range of 7.94 to 5.5 had little or no effect on sodium bicarbonate-elicited response (Fig. S4).

Having developed tools to measure the amount of free carbon dioxide in solution, CO₂ (aq), and demonstrated that pH change had minimal or no effect on oocyte responses, we next tested whether shifting the equilibrium of CO₂/bicarbonate buffers would cause an increase or a decrease in the receptor response. We prepared in duplicates aliquots of 10 mM sodium bicarbonate buffers and placed them in sealed V-vials with Teflon liner, open-top caps. One of the experimenters took a sample from one of a pair of vials, applied to a CquiGR2/CquiGR3-co-expressing oocyte, and recorded the elicited current. Meanwhile, the other experimenter injected an aliquot of 0.1 N HCl to the second pair of the same sample, vortexed, and provided the sample to the other experimenter to apply immediately to the oocyte preparation (Fig. S5). The pairs of unadjusted and pH adjusted samples were kept sealed until their pH values were recorded. As expected, the initial pH was nearly the same (pH = 7.73) because they were aliquots from the same 10 mM sodium bicarbonate sample. The final pH of the tested samples was 7.39 ± 0.05 .

Quantification of the recorded currents from paired samples showed a significant increase (two-tailed *t*-test, $n = 12$, $p = 0.0005$) in the lower pH samples (Fig. 6A). Similar experiments were performed to measure the actual concentration of dissolved CO₂ in paired samples with initial and lowered pH. The initial and final pH values of these samples ($n = 4$) were 7.73 and 7.32 ± 0.03 , respectively. As expected, the quantification of CO₂ (aq) showed an increase in dissolved CO₂ at lower pH (Fig. 6B). The measured CO₂ concentrations in the samples without adjustment (pH_{initial}) and with pH adjusted (pH_{lowered}) were 17.90 ± 1.55 ppm and 32.40 ± 2.40 ppm, whereas the calculated CO₂ concentrations were approximately 15.8 and 38.4 ppm, respectively. An increase in dissolved CO₂ concentration by lowering pH is predicted by Le Chatelier's Principle, given that an increase in H⁺ concentration shifts the equilibrium towards CO₂ (aq). Because the increased oocyte response (Fig. 6A) resulted from the increase of in situ CO₂ concentration (Fig. 6B), we concluded that CO₂ per se, not bicarbonate, activates the *Cx. quinquefasciatus* gustatory receptor system

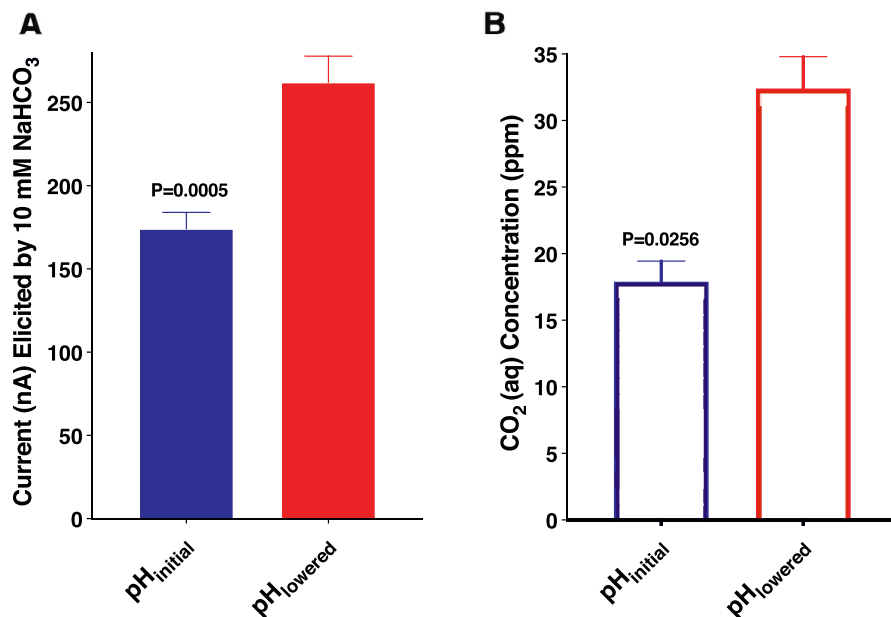


Fig. 6. Effect of pH on the oocyte response and the concentrations of CO₂ in solution

(A) Responses of CquiGR2 + CquiGR3-expressing oocytes to 10 mM of sodium bicarbonate without acidification and after acidification ($n = 12$). The final pH (pH_{lowered}) of the sodium bicarbonate buffer was 7.39 ± 0.05 . (B) Quantification of CO₂ in sodium bicarbonate samples ($n = 4$) without and after pH adjustment (acidification) as measured with a CO₂ Ion Selective Electrode. After acidification (pH_{lowered}), the pH of the sodium bicarbonate samples was 7.32 ± 0.03 . Data are presented as mean \pm SEM.

when expressed in *Xenopus* oocytes. It has also been reported that the BAG neurons of the nematode *Caenorhabditis elegans* are activated by molecular CO₂, although they can be activated by acid stimuli (Smith et al., 2013). We found no evidence for the activation of the *Culex* mosquito GR system by hydrogen ions.

3.3. *CquiGR1* orthologs in *An. gambiae* and *Ae. aegypti* are putative modulators

Given the unexpected results that *CquiGR1* was not necessary for receptor function, but rather attenuated the responses of the *CquiGR2/CquiGR3* receptor system to CO₂, we asked whether this would be a common feature of mosquito biology. We prepared oocytes to coexpress the three GR subunits from the malaria mosquito, specifically *AgamGR22*, *AgamGR23*, and *AgamGR24*. Using the same batch of oocytes, we prepared a binary combination of these receptors devoid of *AgamGR22*, ie, *AgamGR23/AgamGR24*-expressing oocytes. Then we compared the responses of these oocytes to the same concentrations of sodium chloride and sodium bicarbonate. Specifically, we challenged each oocyte preparation of the same age and the same batch of oocytes with 50, 100, 200, and 300 mM solutions of NaCl and NaHCO₃. *AgamGR23/AgamGR24*-coexpressing oocytes gave stronger, concentration-dependent responses to sodium bicarbonate (Fig. 7A) than the oocytes coexpressing a ternary receptor system, *AgamGR22/AgamGR23/AgamGR24* (Fig. 7B). These experiments were replicated with another batch of oocytes (Fig. 7C and D). These results suggest that the *CquiGR1* ortholog from the malaria mosquito, ie, *AgamGR22*, functions as a modulator.

Next, we prepared oocytes coexpressing the equivalent binary and ternary receptor systems with GRs from the yellow fever mosquito. Specifically, we compared the responses of *AeagGR2/AeagGR3*-coexpressing oocytes to oocytes of the same batch and the same age that coexpressed *AeagGR1*, *AeagGR2*, and *AeagGR3*. Again, the receptor system devoid of *AeagGR1* generated stronger, dose-dependent

responses to bicarbonate (Fig. S6A) than the ternary system (Fig. S6B), thus implicating *AeagGR1* in a modulatory role.

3.4. Overall conclusions

Our research plans to address a long-standing question regarding CO₂ reception led to unexpected results. Because it has been well-established in the literature that the reception of CO₂ in the vinegar fly antennae is mediated by *DmelGR21a* and *DmelGR63a* (Jones et al., 2007; Kwon et al., 2007; Suh et al., 2004), it has been assumed that CO₂ is detected by GR1 + GR3 in mosquitoes. This notion has been supported by RNAi-based experimental data suggesting that GR2 was not involved in CO₂ reception in *Ae. aegypti* (and *Cx. quinquefasciatus*) (Erdelyan et al., 2012). On the other hand, *AgamGR23*, the *CquiGR2* ortholog from the malaria mosquito *An. gambiae*, was implicated in CO₂ response (Lu et al., 2007), but the role of *AgamGR22* is yet to be unraveled. Our findings suggest that the three subunits might be involved, with GR1 (GR22 in the case of *An. gambiae*) being a putative modulator. Future studies will determine whether GR2 (or GR23) knock out mosquitoes are indeed insensitive to CO₂, whereas GR1 (or GR22) lines will allow us to get a better understanding of the mechanism(s) of modulation. It is conceivable that only the reception of CO₂ at high doses might be different in GR1 (or GR22) knock out mosquitoes. With a functional carbon dioxide-detecting receptor system in an aqueous environment, we applied a fundamental principle in chemistry to interrogate which of two species in equilibrium (CO₂ or HCO₃⁻) might activate the receptors. We compared receptor responses as well as CO₂ concentrations in paired samples without acidification and after acidification and showed that an increase in the concentrations of dissolved CO₂ was associated with an increase in receptor response. We then concluded that CO₂ per se, neither HCO₃⁻ nor protons, activates the carbon dioxide-detecting system in mosquitoes.

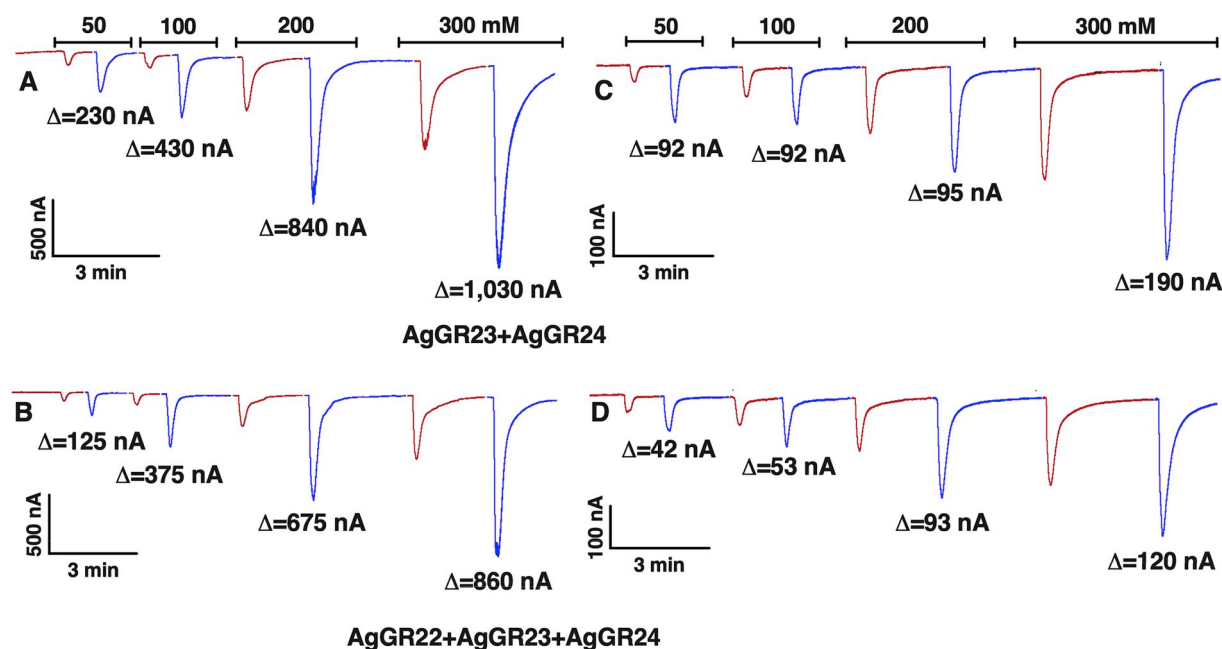


Fig. 7. Responses of *An. gambiae* GRs-expressing oocytes to sodium chloride and sodium bicarbonate

(A) Trace obtained with an oocyte coexpressing *AgamGR23* and *AgamGR24*. (B) Responses of another oocyte (from the same batch) co-expressing the three GRs from *An. gambiae*, *GR22*, *GR23*, and *GR24*. (C) Replication of experiment in (A), but using a different batch of oocytes. (D) Replication of the experiment in (B) with the same batch of oocytes used in (C). Δ values represent responses to sodium bicarbonate subtracted from responses to sodium chloride at the same concentration. In a third replication with a different batch of oocytes the Δ values recorded from a *GR23 + GR24*-coexpressing oocyte stimulated with 50, 100, 200, and 300 mM were 120, 225, 250, and 780 nA, whereas the respective values recorded from an oocyte from the same batch and coexpressing *GR22 + GR23 + GR24* were 23, 89, 193, and 270 nA.

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Author contributions

P.X., X.W., and W.S.L. performed research; W.S.L. designed research; P.X. and W.S.L. analyzed the data; W.S.L. wrote the paper; all authors read and approved the final manuscript.

Competing financial interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ibmb.2019.103284>.

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