

Research article

## Immunocytochemical evidence for co-expression of Type III IP<sub>3</sub> receptor with signaling components of bitter taste transduction

Tod R Clapp\*<sup>1</sup>, Leslie M Stone<sup>1</sup>, Robert F Margolskee<sup>2</sup> and Sue C Kinnamon<sup>1</sup>

Address: <sup>1</sup>Department of Anatomy and Neurobiology, Colorado State University, Fort Collins, CO 80523 and the Rocky Mountain Taste and Smell Center, University of Colorado Health Sciences Center, Denver, CO 80262, USA and <sup>2</sup>Howard Hughes Medical Institute and Department of Physiology and Biophysics, Mount Sinai School of Medicine of New York University, Box 1677, 1425 Madison Avenue, New York, NY 10029, USA

E-mail: Tod R Clapp\* - [tlapp@cvmb.colostate.edu](mailto:tlapp@cvmb.colostate.edu); Leslie M Stone - [lstone@lamar.colostate.edu](mailto:lstone@lamar.colostate.edu);

Robert F Margolskee - [bob@inka.mssm.edu](mailto:bob@inka.mssm.edu); Sue C Kinnamon - [scknina@lamar.colostate.edu](mailto:scknina@lamar.colostate.edu)

\*Corresponding author

Published: 23 April 2001

Received: 23 March 2001

*BMC Neuroscience* 2001, 2:6

Accepted: 23 April 2001

This article is available from: <http://www.biomedcentral.com/1471-2202/2/6>

(c) 2001 Clapp et al, licensee BioMed Central Ltd.

### Abstract

**Background:** Taste receptor cells are responsible for transducing chemical stimuli into electrical signals that lead to the sense of taste. An important second messenger in taste transduction is IP<sub>3</sub>, which is involved in both bitter and sweet transduction pathways. Several components of the bitter transduction pathway have been identified, including the T2R/TRB taste receptors, phospholipase C β<sub>2</sub>, and the G protein subunits α-gustducin, β<sub>3</sub>, and γ<sub>13</sub>. However, the identity of the IP<sub>3</sub> receptor subtype in this pathway is not known. In the present study we used immunocytochemistry on rodent taste tissue to identify the IP<sub>3</sub> receptors expressed in taste cells and to examine taste bud expression patterns for IP<sub>3</sub>R3.

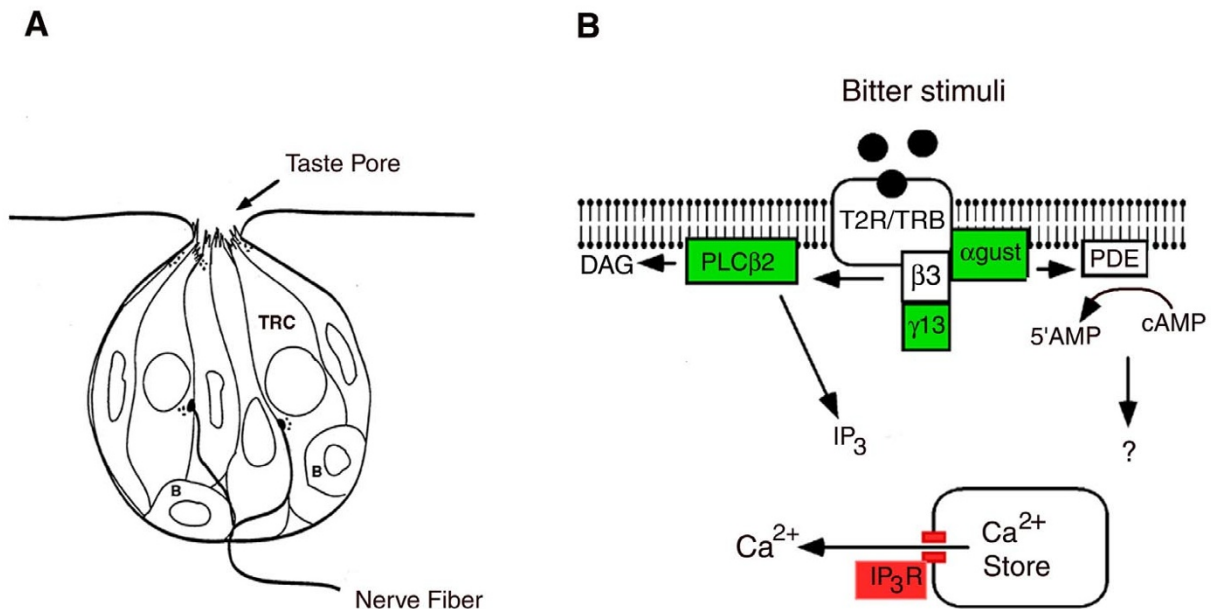
**Results:** Antibodies against Type I, II, and III IP<sub>3</sub> receptors were tested on sections of rat and mouse circumvallate papillae. Robust cytoplasmic labeling for the Type III IP<sub>3</sub> receptor (IP<sub>3</sub>R3) was found in a large subset of taste cells in both species. In contrast, little or no immunoreactivity was seen with antibodies against the Type I or Type II IP<sub>3</sub> receptors. To investigate the potential role of IP<sub>3</sub>R3 in bitter taste transduction, we used double-label immunocytochemistry to determine whether IP<sub>3</sub>R3 is expressed in the same subset of cells expressing other bitter signaling components. IP<sub>3</sub>R3 immunoreactive taste cells were also immunoreactive for PLCβ<sub>2</sub> and γ<sub>13</sub>. Alpha-gustducin immunoreactivity was present in a subset of IP<sub>3</sub>R3, PLCβ<sub>2</sub>, and γ<sub>13</sub> positive cells.

**Conclusions:** IP<sub>3</sub>R3 is the dominant form of the IP<sub>3</sub> receptor expressed in taste cells and our data suggest it plays an important role in bitter taste transduction.

### Background

Taste receptor cells are specialized epithelial cells, which are organized into discrete endorgans called taste buds. Typical taste buds contain 50-100 polarized taste cells, which extend from the basal lamina to the taste pore, where apical microvilli protrude into the oral cavity. The basolateral membrane forms chemical synapses with

primary gustatory neurons (Fig. 1A). In mammals, lingual taste buds are housed in connective tissue structures called papillae. Fungiform papillae are located on the anterior two-thirds of the tongue and typically contain 1-2 taste buds each. Vallate and foliate papillae are found on the posterior tongue and house several hundred taste buds each. Taste transduction begins when



**Figure 1**

Diagrammatic representation of a rodent taste bud and important components of the bitter transduction pathway. (A) A typical taste bud consists of 50-100 taste receptor cells (TRCs) that extend from the basal lamina to the taste pore. Taste stimuli interact with taste receptors on the apical membrane, while nerve fibers form chemical synapses with the basolateral membrane. Basal cells (labeled B) along the margin of the taste bud are proliferative cells that give rise to taste receptor cells. (B) Bitter stimuli interact with T2R/TRB receptors located on the apical membrane. These receptors couple to a heterotrimeric G protein consisting of  $\alpha$ -gustducin,  $\beta 3$ , and  $\gamma 13$ . Alpha gustducin activates phosphodiesterase (PDE), causing decreases in intracellular cAMP, while  $\beta 3\gamma 13$  activates phospholipase C  $\beta 2$  (PLC $\beta 2$ ) to produce the second messengers inositol 1,4,5 trisphosphate (IP $_3$ ) and diacylglycerol (DAG). The IP $_3$  binds to receptors located on smooth endoplasmic reticulum, causing a release of Ca $^{2+}$  into the cytosol. The purpose of this study was to identify the IP $_3$  receptor isotype that is expressed in taste cells.

sapid stimuli interact with the apical membrane of taste cells, usually resulting in taste cell depolarization, calcium influx, and transmitter release onto gustatory afferent neurons. Simple stimuli, such as salts and acids depolarize taste cells by direct interaction with apical ion channels. In contrast, complex stimuli, such as sugars, amino acids, and most bitter compounds bind to G protein coupled receptors, initiating intracellular signaling cascades that culminate in Ca $^{2+}$  influx or release of Ca $^{2+}$  from intracellular stores [1-3].

Inositol 1,4,5-trisphosphate (IP $_3$ ) is an important second messenger in both bitter and sweet taste transduction. In both pathways, activation of taste receptors stimulates a G protein-coupled cascade resulting in activation of phospholipase C (PLC), which cleaves phosphoinositol biphosphate (PIP $_2$ ) to produce the second messengers IP $_3$  and diacylglycerol (DAG). The soluble messenger IP $_3$  binds to receptors located on calcium store membranes, causing release of calcium into the cytosol, while DAG remains in the membrane, where it can activate downstream effectors. While little is known about the role of IP $_3$  in sweet taste transduction, considerable data indi-

cate that IP $_3$  plays an important role in bitter transduction. The first evidence for the involvement of IP $_3$  in bitter transduction was obtained by Akabas et al. [4], who used Ca $^{2+}$  imaging to show that the bitter stimulus denatonium causes release of Ca $^{2+}$  from intracellular stores. More recently, biochemical measurements have shown that several bitter compounds elevate IP $_3$  in taste tissue [5-8].

Other studies, however, suggested that a decrease in cAMP, rather than an increase in IP $_3$ , mediated bitter transduction. In 1992, a chemosensory specific G protein,  $\alpha$ -gustducin, was identified in a subset of taste cells [9]. Alpha-gustducin, which is closely related to the rod and cone transducins, activates PDE to reduce intracellular levels of cAMP [13]. Evidence for gustducin's role in bitter taste came from knockout studies, in which a targeted deletion of  $\alpha$ -gustducin resulted in mice with a reduced sensitivity for bitter compounds [10]. More recently, a variety of bitter compounds have been shown to activate gustducin in biochemical assays [11, 12], causing a decrease in intracellular cAMP levels via activation of PDE [13]. It is now known that individual bitter recep-

tors modulate both the IP<sub>3</sub> and cAMP pathways (Fig. 1B). Bitter compounds bind to a family of G protein-coupled receptors called the T2R [14, 15] or TRB [16] receptors, which activate a heterotrimeric G protein consisting of  $\alpha$ -gustducin and a  $\beta\gamma$  complex containing  $\beta_3$  [17] and  $\gamma_{13}$  [8]. Alpha-gustducin activates PDE to decrease intracellular levels of cAMP [13], while its  $\beta\gamma$  partners stimulate PLC $\beta_2$  to produce IP<sub>3</sub> and DAG [18].

Although it is clear that IP<sub>3</sub> binds to receptors located on intracellular Ca<sup>2+</sup> stores, the specific identity of IP<sub>3</sub> receptors in taste cells is not known. There are at least 3 known isotypes of IP<sub>3</sub> receptors encoded by different genes [19]. Each protein product is about 300 Kda. Four subunits assemble to form a functional channel. Both homomultimeres and heteromultimeres have been reported [19]. The N terminus of each subunit houses the IP<sub>3</sub> binding domain while the C terminus anchors the protein to the membrane, is involved in the formation of the tetrameric protein, and forms the Ca<sup>2+</sup> pore region. The general structure of each isoform is similar, however they differ in primary sequence, distribution, regulation, and IP<sub>3</sub> affinity [19].

In this study we used immunocytochemical methods to determine which IP<sub>3</sub>R isoform is expressed in taste cells and to examine the expression patterns of IP<sub>3</sub> receptors relative to other proteins known to be important for taste transduction. We report that the Type III IP<sub>3</sub> receptor is the dominant isotype expressed in rodent taste cells and that it is primarily found in the same subset of taste cells as other known signaling components of bitter transduction. A preliminary account of this work was published in abstract form [20].

## Results

### IP<sub>3</sub> Receptor Isoforms

Forty micron thick rat sections containing circumvallate papillae were exposed to either anti-IP<sub>3</sub>R1, anti-IP<sub>3</sub>R2, or anti-IP<sub>3</sub>R3 antibodies and appropriate secondary antibodies. Laser scanning confocal microscopy of the resultant sections was used to examine the distribution of IP<sub>3</sub> receptor immunoreactivity in rat circumvallate taste buds. Labeling for IP<sub>3</sub>R1 and IP<sub>3</sub>R2 was negligible (Figs. 2A, B). In contrast, immunoreactivity to IP<sub>3</sub>R3 was robust and present in a large subset of taste cells (Fig. 2C). Generally, immunoreactivity extended throughout the cytoplasm of labeled cells. Immunoreactivity was found only in taste buds and was not present in the lingual epithelium surrounding taste buds. Primarily intragemmal taste cells were labeled, proliferative basal cells of the taste buds did not appear to be labeled. In addition, gustatory nerve fibers did not appear to be labeled. Controls in which the primary antibody was omitted showed no specific labeling (Fig. 2D).

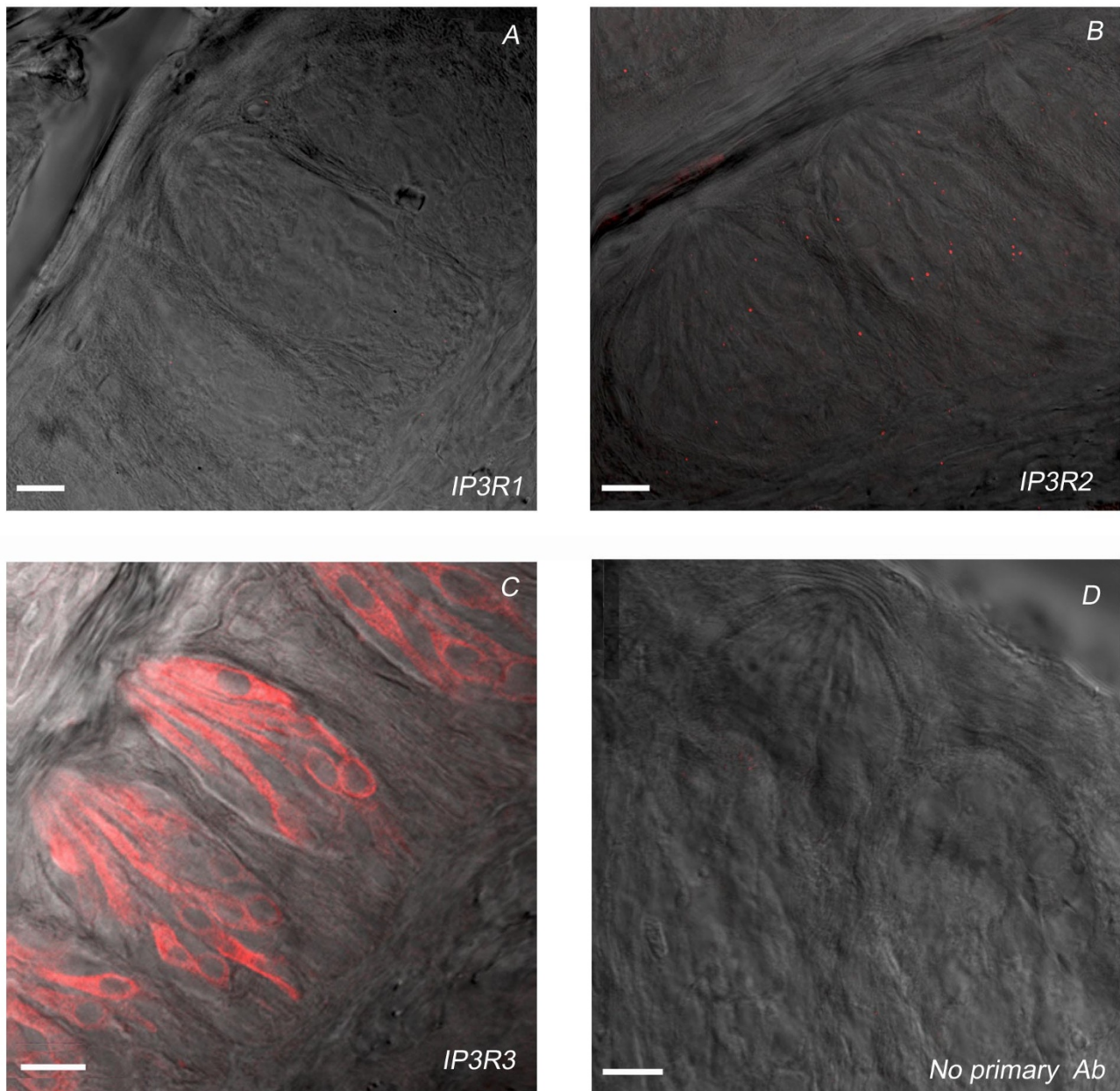
### Co-expression of IP<sub>3</sub>R3 with known bitter signaling components

To determine if IP<sub>3</sub>R3 could be involved in bitter taste transduction, we performed double-label immunocytochemistry with antibodies to IP<sub>3</sub>R3 and components of the bitter signaling pathway. For most experiments, mouse as well as rat tissues were examined. Exposure of tissue to antibodies against  $\alpha$ -gustducin and IP<sub>3</sub>R3 showed that all  $\alpha$ -gustducin immunoreactive (IR) cells were also immunoreactive for IP<sub>3</sub>R3, however, a subset of IP<sub>3</sub>R3-IR taste cells lacked  $\alpha$ -gustducin-IR (Fig. 3). Further analysis with antibodies to other signaling components of the bitter transduction pathway are shown in Figs. 4-5. Immunoreactivity for PLC $\beta_2$  and IP<sub>3</sub>R3 showed nearly complete coincidence of labeling (Fig. 4). Immunoreactivity for PLC $\beta_2$  extended throughout the cytoplasm, as did immunoreactivity for IP<sub>3</sub>R3. However, some taste cells appeared to differ in the degree of labeling for each antibody, with some cells showing more intense label for IP<sub>3</sub>R3 and others for PLC $\beta_2$ . We also compared IP<sub>3</sub>R3 IR with  $\gamma_{13}$  IR in rat and mouse circumvallate taste buds. As shown in Fig. 5, nearly complete colocalization was again observed for both antigens. Results from PLC $\beta_2$  and  $\gamma_{13}$  double label experiments were similar for mouse and rat taste buds. Taken together, these immunocytochemical data indicate that IP<sub>3</sub>R3 is the predominant isoform of IP<sub>3</sub> receptor expressed in taste cells, and that it is found in the same subset of taste cells as other components known to be involved with bitter taste transduction.

## Discussion

IP<sub>3</sub>R3 is heavily expressed in a large subset of vallate taste cells of both mouse and rat, suggesting that IP<sub>3</sub>R3 plays a similar role in both species. IP<sub>3</sub>R3 appears to be located throughout the cytoplasm of taste cells, consistent with its expected location on the smooth endoplasmic membrane [21]. In other cells, IP<sub>3</sub> receptors have also been found on the plasma membrane [19], but because of heavy cytoplasmic labeling, we were unable to resolve whether it was also located on the plasma membrane. One caveat is that antigen retrieval was necessary to observe IP<sub>3</sub>R3 labeling. However, using this method with  $\alpha$ -gustducin, PLC $\beta_2$ , and  $\gamma_{13}$  antibodies did not alter their immunoreactivities; similar results were obtained with and without antigen retrieval. Thus, we do not believe that antigen retrieval compromised our interpretation of the results.

Taste cells expressing IP<sub>3</sub>R3 have an elongate, bipolar morphology, suggestive of Type II taste cells [22]. Indeed, a subset of the IP<sub>3</sub>R3 immunoreactive taste cells is also immunoreactive for  $\alpha$ -gustducin, which has been identified exclusively in Type II cells [23]. However, whether IP<sub>3</sub>R3 is expressed exclusively in Type II cells



### Figure 2

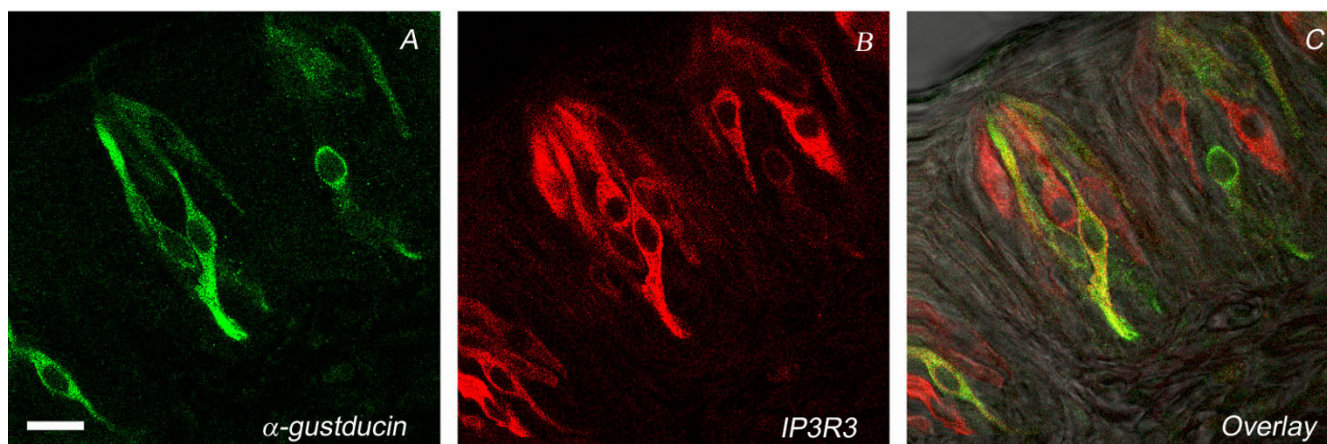
Laser scanning confocal micrographs (LCSMs) of rat circumvallate taste buds labeled with antibodies against the three isoforms of the IP<sub>3</sub> receptor. (A). IP<sub>3</sub>R1 immunoreactivity (IR), (B) IP<sub>3</sub>R2 IR, (C) IP<sub>3</sub>R3 IR, (D) no primary antibody control for IP<sub>3</sub>R3. The scale bar in each figure represents 10 μm.

awaits further investigation. It is noteworthy that a subset of taste cells does not express IP<sub>3</sub> receptors. This raises the question as to whether these cells have intracellular Ca<sup>2+</sup> release mechanisms. Ryanodine receptors also mediate release of Ca<sup>2+</sup> from intracellular stores, however a previous study showed no effect of ry-

anodine on bitter taste responses in *Necturus* taste cells [24].

IP<sub>3</sub>R3 immunoreactivity was expressed in the same subset of taste cells as PLCβ2 and γ13, and by inference from other data, β3 [8]. Antibodies against these proteins have been shown to inhibit IP<sub>3</sub> formation to bitter compounds





**Figure 3**  
 LCSMs of rat circumvallate taste buds double labeled with antibodies against  $\alpha$ -gustducin (green) and IP<sub>3</sub>R3 (red). Panel C shows an overlay of A and B with the differential interference contrast image to enhance visualization of individual taste cells. Scale bar is 10  $\mu$ m. Note that all  $\alpha$ -gustducin IR taste cells are also IP<sub>3</sub>R3 IR, however not all IP<sub>3</sub>R3 IR cells are  $\alpha$ -gustducin IR.

in taste cells [8, 17, 18], suggesting that they are important components of the bitter-stimulated IP<sub>3</sub> pathway. It is of interest that only a subset of IP<sub>3</sub>R3 IR cells express  $\alpha$ -gustducin, a G protein known to be involved with bitter transduction. These data suggest that alpha subunit(s) in addition to  $\alpha$ -gustducin must be involved with the IP<sub>3</sub> signaling pathway in  $\alpha$ -gustducin negative cells. Several G protein alpha subunits have been identified in taste cells, and are potential candidates for this role. These include  $\alpha$ -transducin [25], G $\alpha$ i-2, G $\alpha$ i-3, G $\alpha$ s [26], and G $\alpha$ 15 and G $\alpha$ q [27]. Further experiments will be required to identify the additional alpha subunits that couple to this pathway, and the receptors that activate these G proteins.

In addition to its role in bitter transduction, IP<sub>3</sub> is involved in the transduction of artificial sweeteners [28]. Interestingly, mice lacking  $\alpha$ -gustducin are compromised in the detection of sweet compounds as well as bitter compounds, suggesting that sweet receptors may also couple to  $\alpha$ -gustducin [10]. Approximately two-thirds of the  $\alpha$ -gustducin positive vallate taste cells express T2R/TRB receptors [15]. It is possible that the remaining  $\alpha$ -gustducin positive vallate taste cells express receptors for synthetic sweeteners, and that they couple to the IP<sub>3</sub> signaling pathway. Thus, IP<sub>3</sub>R3 may be involved with sweet as well as bitter taste transduction.

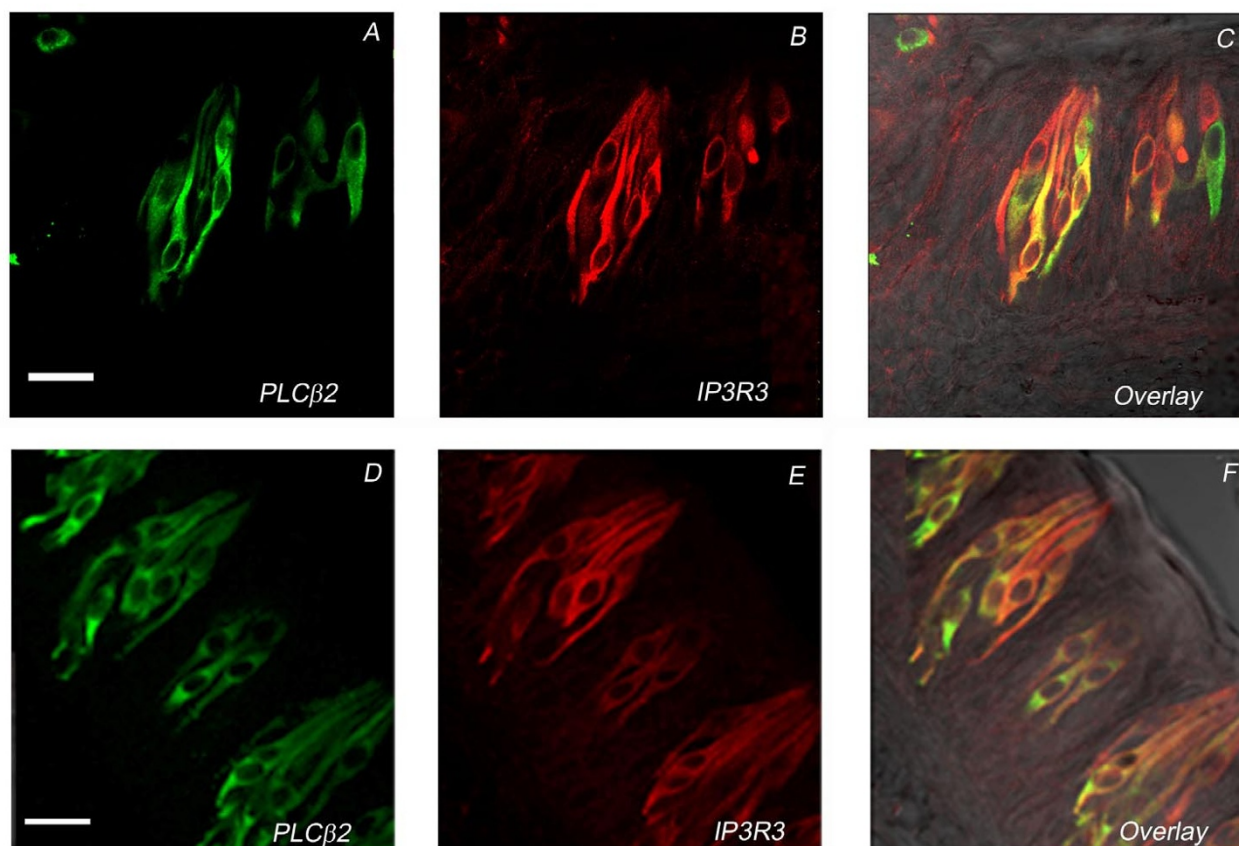
IP<sub>3</sub>R3 is widely expressed in cells in a variety of tissues including adult pancreatic islets, kidney, gastrointestinal tract, salivary glands, and brain [29, 30]. Many of these cell types, including taste cells, are polarized, where Ca<sup>2+</sup> signals are initiated on the apical membrane and must propagate long intracellular distances. IP<sub>3</sub>R3 is particu-

larly well suited for this function, since it is the only IP<sub>3</sub> receptor isotype that is not inhibited at high Ca<sup>2+</sup> concentrations [31]. In fact, under certain conditions, Ca<sup>2+</sup> can stimulate IP<sub>3</sub>R3, making it a likely candidate for participation in the propagation of Ca<sup>2+</sup> oscillations. In taste cells Ca<sup>2+</sup> oscillations have been observed in response to bitter stimuli (T. Ogura and S.C. Kinnamon, unpub. observations), and it's likely that IP<sub>3</sub>R3 participates in these Ca<sup>2+</sup> oscillations.

Another interesting feature of IP<sub>3</sub>R3 is that cAMP-dependent phosphorylation can inhibit its activity in pancreatic acinar cells [32, 33]. In these cells, cAMP-dependent phosphorylation decreases Ca<sup>2+</sup> release from intracellular stores and slows the frequency of Ca<sup>2+</sup> oscillations. These data suggest a possible role for  $\alpha$ -gustducin in bitter taste transduction. Specifically, activation of  $\alpha$ -gustducin, which decreases intracellular cAMP by activation of PDE [11], may lead to a decrease in the cAMP-dependent phosphorylation of IP<sub>3</sub>R3. This would disrupt the negative control of the receptor and potentiate the Ca<sup>2+</sup> response. Interestingly, G $\alpha$ i-2, another alpha subunit heavily expressed in taste cells [26], also functions to decrease intracellular levels of cAMP and may lead to regulation of IP<sub>3</sub>R3. Further experiments will be necessary to clarify the role of these alpha subunits in regulation of the IP<sub>3</sub> pathway in taste cells.

### Conclusions

The principal finding in this study is the identification of IP<sub>3</sub>R3 as the dominant isoform of the IP<sub>3</sub> receptor in taste cells. IP<sub>3</sub> has been shown to be an important second messenger in both bitter and sweet taste transduction, and IP<sub>3</sub>R3 likely mediates the Ca<sup>2+</sup> release from intrac-

**Figure 4**

LCSMs of rodent circumvallate taste buds double labeled with antibodies against PLC $\beta$ 2 (green) and IP $_3$ R3 (red). Panels A-C are from mouse; D-F are from rat. Panels C and F represent the overlay, as described for Figure 3. Scale bar is 20  $\mu$ m. Note almost complete co-localization of IP $_3$ R3 IR and PLC $\beta$ 2 IR.

ellular stores in response to IP $_3$ . In bitter taste transduction, many signaling components have been identified, and IP $_3$ R3 is co-expressed in the same taste cells (Fig. 6). Bitter stimuli bind to T2R/TRB taste receptors coupled to a heterotrimeric G protein complex consisting of  $\alpha$ -gustducin and its partners,  $\beta$ 3 and  $\gamma$ 13. Alpha gustducin activates PDE, causing decreases in intracellular cAMP, while its  $\beta\gamma$  partners stimulate PLC $\beta$ 2 to produce IP $_3$  and DAG. IP $_3$  subsequently binds to IP $_3$ R3, causing increases in cytosolic Ca $^{2+}$ , due to release from intracellular stores (Fig. 1B). The unique properties of IP $_3$ R3, including its regulation by Ca $^{2+}$  and cAMP dependent kinases, are consistent with known characteristics of bitter signaling in taste cells.

## Materials and Methods

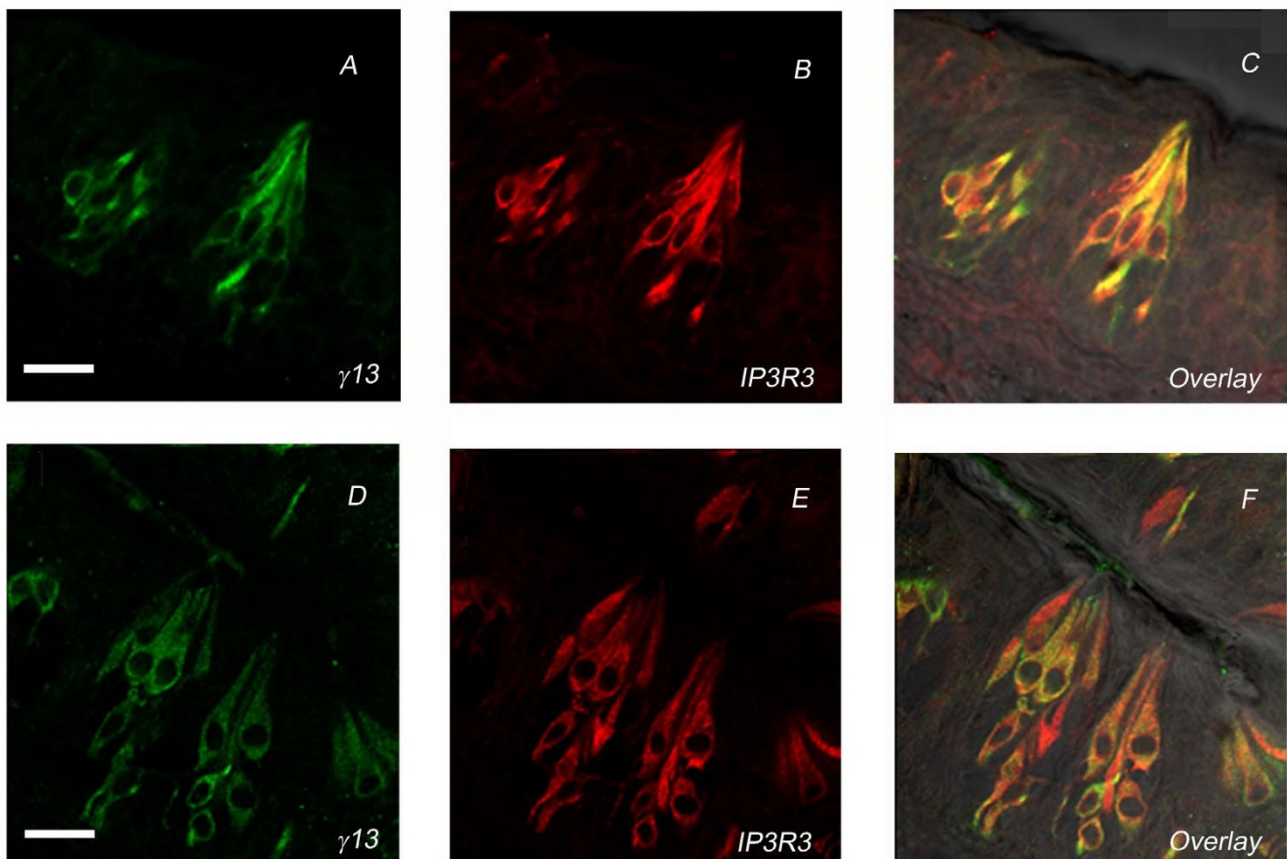
### Animals

Adult male Sprague Dawley Rats and adult C57/B1 male or female mice were obtained from Charles River Laboratories (Wilmington, MA). Animals were cared for in

compliance with the Colorado State University Animal Care and Use Committee.

### Tissue preparation

Rats or mice were deeply anesthetized by intraperitoneal injections of Sodium Pentobarbitol, 40 mg/Kg (Veterinary Laboratories, Inc., Lenexa, KS). Following anesthesia animals were injected intracardially with heparin (Elkins-Sinn, Inc., Cherry Hill, NJ) and 1% sodium nitrate. Rats were perfused with 80 ml of 4% paraformaldehyde and mice with 30 ml. Following perfusion tongues were removed and immediately placed into fresh 4% paraformaldehyde (Electron Microscopy Sciences, Ft. Washington, PA) in 0.1 M phosphate buffer for approximately twenty minutes. Tongues were then put into a 20% sucrose solution in 0.1 M phosphate buffer overnight for cryoprotection. Forty micron sections were cut on a Leitz 1729 digital Kryostat and collected in 0.1 M phosphate buffered saline (PBS, pH7.2). Following sectioning, the slices were washed in PBS three times for ten



**Figure 5**

LCsMs of rodent circumvallate taste buds double labeled with antibodies against  $\gamma$ 13 (green) and IP<sub>3</sub>R3 (red). Panels A-C are from mouse; D-F are from rat. Panels C and F represent the overlay as described for Figs. 3-4. Scale bar is 20  $\mu$ m. Note nearly complete co-localization of IP<sub>3</sub>R3 IR and  $\gamma$ 13 IR.

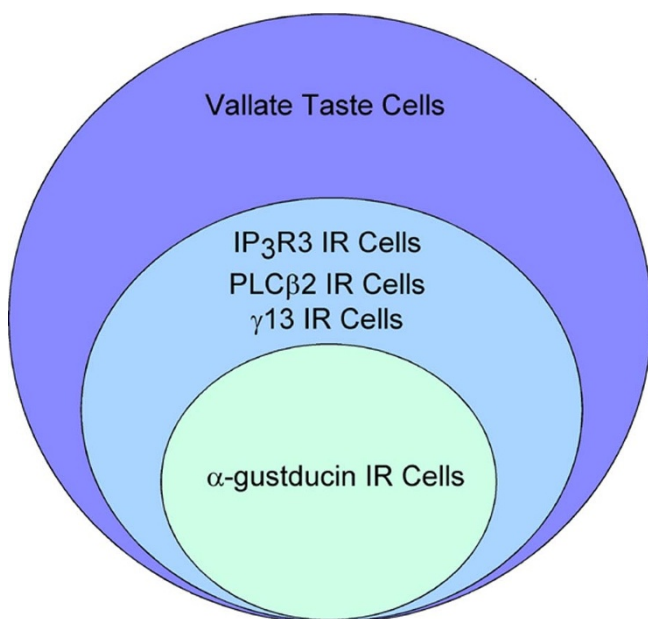
minutes each at room temperature. Antigen retrieval was performed by placing sections into a 10 mM sodium citrate solution at 80°C for 30 minutes. This was done to help disrupt protein cross-bridges formed by formalin fixation and expose antigen binding sites. In some experiments the incubation time in sodium citrate was reduced to 5 minutes, and labeling was still apparent. All sections were incubated in blocking solution for 1-2 hours at room temperature. Blocking solution contained 0.3% Triton X-100, 1% normal goat serum, and 1% bovine serum albumin in 0.1 M PBS. All chemicals were purchased from Sigma Chemical Corporation (St. Louis, MO) unless otherwise noted.

#### Antibodies

Polyclonal antibodies raised in rabbit against the sequence N<sub>1829</sub>KKKDDEVDRDAPSRKKAKE<sub>1848</sub> near the COOH-terminal domain of human IP<sub>3</sub>R1 were purchased from Affinity Bioreagents, Inc. (Golden, CO, cat

#PA1-901). Polyclonal antibodies raised in rabbit against a synthetic peptide with a sequence derived from the cytoplasmic, NH<sub>2</sub>-terminal domain of the rat IP<sub>3</sub>R2 protein (E<sub>317</sub>LNPDYRDAQNEGKTVRD<sub>334</sub>), were also purchased from Affinity Bioreagents, Inc. (Golden, CO, cat #PA1-904). Monoclonal mouse anti-IP<sub>3</sub>R3 was purchased from Transduction laboratories (Lexington, KY, cat #131220). Monoclonal mouse anti-IP<sub>3</sub>R3 recognizes the peptide sequence 22-230. Rabbit anti- $\alpha$ -gustducin (cat #SC-395) directed against a peptide fragment containing amino acids 93-113 of  $\alpha$ -gustducin; and rabbit anti-PLC $\beta$ 2 (cat #SC206) were obtained from Santa Cruz laboratories (Santa Cruz, CA). Rabbit anti- $\gamma$ 13 was prepared as described previously [8]. All secondary antibodies were purchased from Jackson ImmunoResearch Laboratories, Inc. (West Grove, PA). These included: Rhodamine Red X anti-rabbit (# 111-295-045), Rhodamine Red X anti-mouse (# 115-295-146), Cy-5 anti-mouse (# 115-175-146), Fluorescein (FITC) anti-rabbit (# 711-





**Figure 6**

Qualitative representation of the co-expression patterns of IP<sub>3</sub>R3, α-gustducin, PLCβ2, and γ13 in circumvallate taste buds.

095-152). Cy-5 anti mouse antibodies were tested on mouse tissue prior to these experiments to insure no background labeling.

#### Single label Immunocytochemistry

Sections from rat circumvallate papillae were incubated with primary antibodies overnight at 4°C. Controls in which the primary antibodies were excluded were included in each experiment. The primary antibodies rabbit anti-IP<sub>3</sub>R1 and rabbit anti-IP<sub>3</sub>R2 were diluted to 1:100 in blocking solution. Mouse anti-IP<sub>3</sub>R3 was used at 1:50 in blocking solution. Following overnight incubation in primary antibodies, sections were washed three times for ten minutes each in PBS at room temperature. Rabbit anti-IP<sub>3</sub>R1, rabbit anti-IP<sub>3</sub>R2, and no primary antibody control sections were then incubated with the secondary antibody Rhodamine Red X anti-rabbit (1:100 in blocking solution) at room temperature for two hours. Mouse anti-IP<sub>3</sub>R3 labeled sections, were incubated in Rhodamine anti-mouse. Following incubation with secondary antibodies, sections were washed three times for ten minutes in PBS and mounted on RITE-ON micro slides (Becton, Dickinson and Company, Portsmouth, NH) using Fluoromount-G (Southern Biotechnology Associates, Inc., Birmingham, AL, cat# 0100-01) and coverslipped (VWR Scientific, Media, PA). Slides were stored at 4°C.

#### Double Label Immunocytochemistry

Double-labeled experiments involved incubations with two primary antibodies and subsequent incubation with appropriate secondary antibodies. Rabbit anti-α-gustducin was used at 1:500 in blocking solution. Both rabbit anti-PLCβ2 and rabbit anti-γ13 were used at 1:1000 in blocking solution. Following incubation with primary antibodies, sections were washed in PBS three times for ten minutes each. Both rabbit anti-IP<sub>3</sub>R1 and rabbit anti-IP<sub>3</sub>R2 labeled sections were then treated with Rhodamine Red X anti rabbit antibodies (1:100). For IP<sub>3</sub>R3 double-labeled sections, Cy-5 anti-mouse secondary antibodies were applied. Rabbit anti-α-gustducin was visualized using FITC anti-rabbit (1:100) secondary antibodies. Both rabbit anti-PLCβ2 and rabbit anti-γ13 were labeled with FITC anti rabbit (1:100). Incubations with secondary antibodies were done at room temperature for two hours. Sections were then washed in PBS three times for ten minutes each, mounted using flouromount-6, and coverslipped.

#### Imaging

Lingual sections were viewed with an Olympus Fluoview laser scanning confocal microscope. Sequential scanning techniques were used for some double-label experiments and showed no differences from simultaneous scans. There is no overlap between the excitation and emission spectra for the FITC and Cy5 secondary antibodies used in the double label experiments. Images were captured with an Olympus FVX-IHRT Fluoview Confocal Laser Scanning Microscope. Lasers included Argon 488 nm, HeNe 543 nm, and HeNe 622. Fluoview software was used for data acquisition. Images were processed and printed using Photoshop 6.0 software.

#### Acknowledgements

We thank Dr. Vince Dionne for the initial motivation for this study, and Ms. Barbel Böttger for the suggestion of using antigen retrieval. We also thank Dr. Kathryn Medler for technical advice and Dr. Tom Finger for comments on the manuscript. RFM is an Associate Investigator of the Howard Hughes Medical institute. This study was supported by NIH grants DC00244 and DC00766 to SCK and DC03155 to RFM.

**Note added in proof:** Similar results were obtained by Miyoshi et al. and appear in the current issue of *Chemical Senses* (*Chem Senses* 26:259-265, 2001).

#### References

1. Lindemann B: **Taste reception.** *Physiol Rev* 1996, **76**:718-766
2. Gilbertson TA, Damak S, Margolskee RF: **The molecular physiology of taste transduction.** *Curr Opin Neurobiol* 2000, **10**:519-527
3. Glendinning JI, Chaudhari N, Kinnamon SC: **Taste transduction and molecular biology.** In: *The Neurobiology of Taste and Smell* (Edited by Finger TE, Silver WL, Restrepo D.) 2nd ed. New York: Wiley-Liss; 2000, 315-351
4. Akabas MH, Dodd J, Al-Awqati Q: **A bitter substance induces a rise in intracellular calcium in a subpopulation of rat taste cells.** *Science* 1988, **242**:1047-1050
5. Hwang PM, Verma A, Bredt DS, Snyder SH: **Localization of phosphatidylinositol signaling components in rat taste cells: role in bitter taste transduction.** *Proc Natl Acad Sci USA* 1990, **87**:7395-7399



6. Spielman AI, Huque T, Nagai H, Whitney G, Brand JG: **Generation of inositol phosphates in bitter taste transduction.** *Physiol Behav* 1994, **56**:1149-1155
7. Spielman AI, Nagai H, Sunavala G, Dasso M, Breer H, Boekhoff I, Huque T, Whitney G, Brand JG: **Rapid kinetics of second messenger production in bitter taste.** *Am J Physiol* 1996, **270**:C926-931
8. Huang L, Shanker YG, Dubauskaite J, Zheng JZ, Yan W, Rosenzweig S, Spielman AI, Max M, Margolskee RF: **Ggamma13 colocalizes with gustducin in taste receptor cells and mediates IP3 responses to bitter denatonium.** *Nat Neurosci* 1999, **2**:1055-1062
9. McLaughlin SK, McKinnon PJ, Margolskee RF: **Gustducin is a taste-cell-specific G protein closely related to the transducins.** *Nature* 1992, **357**:563-569
10. Wong GT, Gannon KS, Margolskee RF: **Transduction of bitter and sweet taste by gustducin.** *Nature* 1996, **381**:796-800
11. Ruiz-Avila L, McLaughlin SK, Wildman D, McKinnon PJ, Robichon A, Spickofsky N, Margolskee RF: **Coupling of bitter receptor to phosphodiesterase through gustducin in taste receptor cells.** *Nature* 1995, **376**:80-85
12. Ming D, Ruiz-Avila L, Margolskee RF: **Characterization and solubilization of bitter-responsive receptors that couple to gustducin.** *Proc Natl Acad Sci USA* 1998, **95**:8933-8938
13. Yan W, Sunavala G, Rosenzweig S, Dasso M, Brand JG, Spielman AI: **Bitter taste transduced by PLC-beta(2)-dependent rise in IP(3) and alpha-gustducin-dependent fall in cyclic nucleotides.** *Am J Physiol Cell Physiol* 2001, **280**:C742-751
14. Chandrashekar J, Mueller KL, Hoon MA, Adler E, Feng L, Guo W, Zuker CS, Ryba NJ: **T2Rs function as bitter taste receptors.** *Cell* 2000, **100**:703-711
15. Adler E, Hoon MA, Mueller KL, Chandrashekar J, Ryba NJ, Zuker CS: **A novel family of mammalian taste receptors.** *Cell* 2000, **100**:693-702
16. Matsunami H, Montmayeur JP, Buck LB: **A family of candidate taste receptors in human and mouse.** *Nature* 2000, **404**:601-604
17. Rossler P, Boekhoff I, Tareilus E, Beck S, Breer H, Freitag J: **G protein betagamma complexes in circumvallate taste cells involved in bitter transduction.** *Chem Senses* 2000, **25**:413-421
18. Rossler P, Kroner C, Freitag J, Noe J, Breer H: **Identification of a phospholipase C beta subtype in rat taste cells.** *Eur J Cell Biol* 1998, **77**:253-261
19. Patel S, Joseph SK, Thomas AP: **Molecular properties of inositol 1,4,5-trisphosphate receptors.** *Cell Calcium* 1999, **25**:247-264
20. Clapp TR, Stone LM, Kinnamon SC: **Type III IP3 receptors are in rat taste cells.** *Chem Senses* 2000, **25**:624-625
21. Otsu H, Yamamoto A, Maeda N, Mikoshiha K, Tashiro Y: **Immunogold localization of inositol 1,4,5-trisphosphate (InsP3) receptor in mouse cerebellar Purkinje cells using three monoclonal antibodies.** *Cell Struct Funct* 1990, **15**:163-173
22. Pumplin DW, Yu C, Smith DV: **Light and dark cells of rat vallate taste buds are morphologically distinct cell types.** *J Comp Neurol* 1997, **378**:389-410
23. Yang R, Tabata S, Crowley HH, Margolskee RF, Kinnamon JC: **Ultrastructural localization of gustducin immunoreactivity in microvilli of type II taste cells in the rat.** *J Comp Neurol* 2000, **425**:139-151
24. Ogura T, Mackay-Sim A, Kinnamon SC: **Bitter taste transduction of denatonium in the mudpuppy *Necturus maculosus*.** *J Neurosci* 1997, **17**:3580-3587
25. McLaughlin SK, McKinnon PJ, Robichon A, Spickofsky N, Margolskee RF: **Gustducin and transducin: a tale of two G proteins.** *Ciba Found Symp* 1993, **179**:186-196
26. Kusakabe Y, Yasuoka A, Asano-Miyoshi M, Iwabuchi K, Matsumoto I, Arai S, Emori Y, Abe K: **Comprehensive study on G protein alpha-subunits in taste bud cells, with special reference to the occurrence of Galpha2 as a major Galpha species.** *Chem Senses* 2000, **25**:525-531
27. Kusakabe Y, Yamaguchi E, Tanemura K, Kameyama K, Chiba N, Arai S, Emori Y, Abe K: **Identification of two alpha-subunit species of GTP-binding proteins, Galpha15 and Galphaq, expressed in rat taste buds.** *Biochim Biophys Acta* 1998, **1403**:265-272
28. Bernhardt SJ, Naim M, Zehavi U, Lindernann B: **Changes in IP3 and cytosolic Ca2+ in response to sugars and non-sugar sweeteners in transduction of sweet taste in the rat.** *J Physiol* 1996, **490**:325-336
29. Blondel O, Takeda J, Janssen H, Seino S, Bell GI: **Sequence and functional characterization of a third inositol trisphosphate receptor subtype, IP3R-3, expressed in pancreatic islets, kidney, gastrointestinal tract, and other tissues.** *J Biol Chem* 1993, **268**:11356-11363
30. De Smedt H, Missiaen L, Parys JB, Henning RH, Sienaert I, Vanlingen S, Gijssens A, Himpens B, Casteels R: **Isoform diversity of the inositol trisphosphate receptor in cell types of mouse origin.** *Biochem J* 1997, **322**:575-583
31. Hagar RE, Burgstahler AD, Nathanson MH, Ehrlich BE: **Type III InsP3 receptor channel stays open in the presence of increased calcium.** *Nature* 1998, **396**:81-84
32. Giovannucci DR, Sneyd J, Groblewski GE, Yule DI: **Modulation of InsP3 receptor properties by phosphorylation: targeting of PKA to InsP3 receptors shapes oscillatory calcium signals in pancreatic acinar cells.** *J Korean Med Sci* 2000, **15 Suppl**:S55-56
33. Giovannucci DR, Groblewski GE, Sneyd J, Yule DI: **Targeted phosphorylation of inositol 1,4,5-trisphosphate receptors selectively inhibits localized Ca2+ release and shapes oscillatory Ca2+ signals.** *J Biol Chem* 2000, **275**:33704-33711

Publish with **BioMedcentral** and every scientist can read your work free of charge

"BioMedcentral will be the most significant development for disseminating the results of biomedical research in our lifetime."

Paul Nurse, Director-General, Imperial Cancer Research Fund

Publish with **BMC** and your research papers will be:

- available free of charge to the entire biomedical community
- peer reviewed and published immediately upon acceptance
- cited in PubMed and archived on PubMed Central
- yours - you keep the copyright

Submit your manuscript here:

<http://www.biomedcentral.com/manuscript/>



BioMedcentral.com

[editorial@biomedcentral.com](mailto:editorial@biomedcentral.com)