Redox-sensitive transient receptor potential channels in oxygen sensing and adaptation

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Abstract Regulation of ion channels is central to the mechanisms that underlie immediate acute physiological responses to changes in the availability of molecular oxygen (O2). A group of cation-permeable channels that are formed by transient receptor potential (TRP) proteins have been characterized as exquisite sensors of redox reactive species and as efficient actuators of electric/ionic signals in vivo. In this review, we first discuss how redox-sensitive TRP channels such as TRPA1 have recently emerged as sensors of the relatively inert oxidant O2. With regard to the physiological significance of O2 sensor TRP channels, vagal TRPA1 channels are mainly discussed with respect to their role in respiratory regulation in comparison with canonical pathways in glomus cells of the carotid body, which is a well-established O2-sensing organ. TRPM7 channels are discussed regarding hypoxia-sensing function in ischemic cell death. Also, ubiquitous expression of TRPA1 and TRPM7 together with their physiological relevance in the body is examined. Finally, based upon these studies on TRP channels, we propose a hypothesis of “O2 remodeling.” The hypothesis is that cells detect deviation of O2 availability from appropriate levels via sensors and adjust local O2 environments in vivo by controlling supply and consumption of O2 via pathways comprising cellular signals and transcription factors downstream of sensors, which consequently optimize physiological functions. This new insight into O2 adaptation through ion channels, particularly TRPs, may foster a paradigm shift in our understanding in the biological significance of O2.

Keywords TRP channels · Oxygen · Hypoxia · Vagus · Carotid body

Introduction Molecular oxygen (O2) is an essential substrate for life, because of its role in the generation of adenosine triphosphate (ATP) which is a major source of energy in aerobic organisms. It is therefore fundamental that aerobic organisms sense and respond to hypoxia (low O2 environments), thus allowing them to adapt to variable habitats and physiological situations. Physiological responses to hypoxia can be classified into immediate acute (~s) and later (subacute to chronic) forms (~m to h). Later responses depend at least in part on hypoxia-inducible transcription factors (HIFs) [91, 112], which determine the expression of numerous gene-encoding enzymes, transporters, and growth factors. Immediate acute responses rely mainly on adaptive changes mediated by O2-regulated ion channels, which regulate cell excitability, contractility, and secretory activity. Respiratory and cardiovascular systems can adjust themselves rapidly to maintain O2 delivery to the most critical organs, such as the brain and heart. As early as 1868, Pflüger recognized that hypoxia stimulates respiration...
that there are different O₂-signaling mechanisms that respond
first identified redox-sensitive TRP channel, is activated
Ca²⁺ channels and exocytosis [115]. However, the exact chan-
hyperoxia) from normoxia in vivo [81, 101]. Given that
neuroepithelial bodies (NEBs) and aortic bodies (ABs) inner-
sensory neurons, the responses to mild hypoxia are attribut-
regulate biological and physiological processes [26].
redox reactive species also serve as signaling molecules that
ruption of cellular redox homeostasis by excessive production
of redox reactive species leads to oxidative damage to mem-
neutrophilic molecules. It was generally understood that the dis-
troph of non-CB chemoreceptors to detect deviation of O₂ availability (hypoxia and hyperoxia) from normoxia in vivo [81, 101]. Given that TRPA1 channels are predominantly expressed in vagal and sensory neurons, the responses to mild hypoxia are attribut-
able mainly to vagal nerves themselves or lung airway
epithelial bodies (NEBs) and aortic bodies (ABs) innerv-
vated by vagal nerves [115]. These findings further suggest
that there are different O₂-signaling mechanisms that respond to varying degrees of hypoxic stimulus. Thus, studies on the redox-sensitive TRP channels opened up a new avenue for studying O₂-sensing organs and the O₂ environment that is formed within our body.

What are redox-sensitive TRP channels?
The cellular redox status depends on a balance between the
levels of intracellular antioxidants and redox reactive species, including reactive oxygen and nitrogen species and other electrophilic molecules. It was generally understood that the dis-
ruption of cellular redox homeostasis by excessive production
of redox reactive species leads to oxidative damage to mem-
brane lipids, proteins, and DNA [15]. However, in the past
two decades, several lines of evidence have suggested that redox reactive species also serve as signaling molecules that regulate biological and physiological processes [26].

One particular group of TRP channels function as exquisite sensors of redox reactive species and as efficient actuators of electric and ionic signal in vivo [52]. The TRPM2 channel, the first identified redox-sensitive TRP channel, is activated indirectly by H₂O₂ through the production of nicotinamide adenine dinucleotide and its metabolites, ADP-ribose and cyclic ADP-ribose [35, 78]. Accumulated evidence indicates that TRPM2 mediates H₂O₂-activated Ca²⁺ influx that mediates cell death [35] and irradiation-activated Ca²⁺ influx that causes irreversible loss of salivary gland function [59]. TRPM2 also mediates H₂O₂-activated Ca²⁺ or cation influx that drives insulin secretion in pancreatic β-cells [104, 107]. Furthermore, studies using Trpm2 gene knockout (KO) mice have revealed that H₂O₂-activated Ca²⁺ influx through TRPM2 contributes to innate immune responses via chem-
oxine production in monocytes [119], neutrophil adhesion during myocardial ischemia/reperfusion injury [39], and NLRP3 inflammasome activation in macrophages [122].

In addition to the indirect redox-sensing mechanism that involves TRPM2, direct sensing through cysteine (Cys) modifi-
cation has emerged as a prominent mechanism underlying activation of various TRP channels [103]. Oxidative modific-
cations of Cys residues by H₂O₂, nitric oxide (NO), and reactive disulfides have been demonstrated for TRPC5 [120], which was originally identified from the mouse brain as a receptor activated Ca²⁺-permeable cation channel linked to phospholipase Cs [74, 80]. NO and reactive disulfides directly modify Cys residues (Cys553 and Cys558) located on the N-terminal side of the pore-forming region between S5 and S6 transmembrane helices via S-nitrosylation and disulfide ex-
change reactions, respectively, in mouse TRPC5. In vascular endothelial cells, TRPC5 activation induced by NO via nitrosylation enhances Ca²⁺ influx, which induces NO pro-
duction by endothelial type NO synthase (eNOS) [120]. This raises the possibility that TRPC5 mediates a positive feedback loop of NO production upon vasodilator stimulation in vascular endothelial cells [28, 120]. Interestingly, TRPC5 is also activated by the reducing agent dithiothreitol and extracellular-reduced thioredoxin [118]. The closest relatives of TRPC5 are TRPC1 and TRPC4, as well as thermosensor channels TRPV1, TRPV3, and TRPV4, which carry Cys res-
ides corresponding to Cys553 and Cys558 on TRPC5 protein [120]. Indeed, these channels are targets of nitrosylation that leads to channel activation. TRPV1 also shows sensitivity to phenylarsine oxide and allicin from garlic through covalent modification of Cys residues located in the C-terminal and N-terminal regions [12, 87].

More recently, the TRPA1 channel has been shown to open upon oxidative Cys modification by pungent compounds and inflammatory mediators [38, 62, 102]. Originally identified TRPA1 activators are pungent natural compounds that include cinnamaldehyde, allyl isothiocyanate, and α,β-unsaturated aldehydes from plants such as mustard, onion, cinnamon, and wasabi, and the pungent garlic compound allicin (these com-
ounds are potentially susceptible to the nucleophile attack at the sulphydryl group of Cys residues), cold temperature, re-
ceptor stimulation, and cannabinoids [5, 7, 47, 63, 97]. Later
examinations of various noxious compounds finally led to the understanding that electrophilic pungent compounds that covalently modify Cys residues through mechanisms such as Michael addition, are commonly potent activators of TRPA1 channels [38, 62].

Considering the distinct redox reactivity of each oxidizing chemical species, particular redox sensitivity of TRP channels should be quantified in terms of sensitivity to these species. This was attained through systematic comparison of the responses of redox-sensitive TRP channels with a congeneric series of reactive disulfides, which show different electron acceptor (oxidation) abilities indicated as redox potentials that are obtained using rotating disc electrode voltammetry [101]. TRP channel activity was correlated with redox potentials of reactive disulfide stimuli, revealing threshold redox potentials for respective TRPs (Fig. 1). Strikingly, among the TRPs tested, only TRPA1 responded to inert oxidants/electrophiles with a redox potential of −2950 mV. The redox potential of O2 (−2765 mV) is less negative than the threshold redox potential for TRPA1 (approximately −3400 mV) but is more negative than these for the other channels investigated, suggesting that TRPA1 is activated by O2 (a weak oxidant) to function as a hyperoxia sensor. Indeed, only TRPA1 responded to hyperoxic solutions prepared by bubbling with O2 gas in a concentration-dependent manner [101]. Thus, among TRP channels, TRPA1 has the highest oxidation sensitivity, which enables TRPA1 to respond to an inert oxidant such as O2.

**TRPA1 as an O2 sensor**

In higher animals, particularly mammals, the respiratory and cardiovascular systems must rapidly adjust themselves to maintain O2 delivery to the most critical organs, such as the brain and heart. In mammals, it is understood that the CBs detect changes in partial O2 pressure (PO2) through K+ channel activities in arterial blood [30, 71, 115]. Sensory and vagal afferent neurons, which project nerve endings throughout the body, have also been proposed to detect hypoxia in organs, such as the airway, lungs, and heart, under ischemia and other conditions of low O2 supply [17, 32, 41, 60]. However, the characteristics and mechanisms of hypoxia detection by non-CB chemoreceptors including sensory and vagal neurons, have yet to be fully defined [60]. Recently, a major advance in our understanding of the function of non-CB chemoreceptors came with the demonstration that the TRPA1 channel, which is expressed in non-CB chemoreceptors is capable of detecting changes in O2 availability in vivo [81, 101].

As described above, systematic evaluation of TRP channels using reactive disulfides with different redox potentials led to our finding that TRPA1 can sense O2 [101]. Notably, Cys oxidation is not the only mechanism that underlies O2 sensing in TRPA1 channels. Indeed, hypoxic solutions prepared by bubbling with N2 gas induce robust TRPA1 responses; TRPA1 activation shows an inverted bell-shaped O2-dependence curve with a minimum at PO2 of 137 mmHg (18 %), which is slightly below the atmospheric PO2 of 152 mmHg (20 %).

O2 sensing by TRPA1 is based upon disparate processes, such as proline (Pro) hydroxylation by Pro hydroxylases (PHDs) and direct oxidation of Cys residues [101] (Fig. 2). During normoxia, PHDs hydroxylate conserved Pro394 within the 10th ankyrin repeat domain of human TRPA1 to inhibit its activity. During hypoxia, the decrease in O2 concentration diminishes PHD activity, relieving TRPA1 from the inhibitory action of Pro hydroxylation to lead to its activation. This recovery of TRPA1 activation is likely dependent on the insertion of fresh, unmodified TRPA1 proteins into the plasma membrane or an unidentified dehydroxylation of modified proteins through an unidentified molecular mechanism. During hyperoxia, O2 activates TRPA1 by oxidizing Cys633, Cys856, or both. Cys633 and Cys856 are located within the 17th ankyrin repeat domain and the intracellular linker region between S4 and S5, respectively, in human TRPA1. TRPA1 can take at least two oxidized forms during hyperoxia: a relatively unstable oxidized state (state 1) readily reversed by glutathione and a relatively stable oxidized state (state 2). Sulfhydryl groups on the key Cys residues (Cys633 and Cys856) may be modified to sulfenic acid (S-OH) in state 1.

![Fig. 1 Threshold redox potentials for activation of redox-sensitive TRP channels](image-url)
and form disulfide bonds (S-S) in state 2. This oxidation mechanism overrides the inhibition by Pro hydroxylation to activate TRPA1.

In mice, exposure to hyperoxic (100 % O₂) or hypoxic (10, 13, and 15 % O₂) gas via a tracheal cannula significantly enhances discharges of afferents in the cervical vagal trunk and in the superior laryngeal vagal branch innervating the mucosa of the larynx, as shown by a multifiber neurogram. However, disruption of the Trpa1 gene abolishes the enhancement of nerve discharges by hyperoxia and mild hypoxia (15 % O₂) and delays that by severe hypoxia (10 and 13 % O₂) [101]. Notably, TRPA1 antagonism abolishes the respiratory responses to mild hypoxia (13 % O₂) but not to severe hypoxia (7 % O₂) in conscious mice [81]. These findings raise possibility that there are different O₂ signaling mechanisms that respond to varying degrees of hypoxic stimulus. In mild hypoxia, the respiratory responses appear to be critically dependent on TRPA1 channels, as TRPA1 antagonism abolishes the response. Given that TRPA1 channels are predominantly expressed in vagal and sensory neurons [68], it is possible that the responses to mild hypoxia are attributable mainly to non-CB chemoreceptors including vagal nerves, NEBs, and/or ABs in mice. Conversely, during severe hypoxia, the respiratory responses may be more dependent on hypoxia-sensitive K⁺ channels in the CBs, with little involvement of the TRPA1 system, in agreement with studies using Trpa1-deficient mice [101]. The finding of O₂ sensitivities of TRPA1 underscores the importance of non-CB chemosensitive mechanisms in hypoxic respiratory responses in mammals.

**TRPM7 as another O₂ sensor candidate among TRP channels**

TRPM7 is an important candidate O₂ sensor. This TRP channel is characterized by its unique “chance” structure comprising the kinase domain as well as the transmembrane ion channel pore permeable to cations such as Mg²⁺, Ni²⁺, Zn²⁺, and other trace metals [65, 67, 84]. Tymianski’s group originally demonstrated activation of TRPM7 by anoxic condition using cultured neurons subjected to oxygen-glucose deprivation [1]. ROS and RNS have been suggested to mediate this mode of TRPM7 activation. In our systematic evaluation of different redox-sensitive TRP channels, we also observed that TRPM7-like TRPA1 is activated by application of hypoxic solution prepared by bubbling N₂ gas [101]. Anoxia/hypoxia-induced activation of TRPM7 plays an important role in non-excitotoxic ischemic brain injury [99], in which large reductions in extracellular divalents, acidosis, and oxidative stress are induced [58, 94, 95]. All these conditions potentiate TRPM7 activity, although TRPM7 conducts only a few pA of inward currents under physiological pH levels, extracellular Ca²⁺ and Mg²⁺ concentrations, and low oxidative stress [53, 67, 84, 114]. The C-terminal kinase domain excised from the channel domain has been implicated in the cell death process [18, 54].

Wide expression of TRPM7 suggests its general biological importance shared by different types of cells [67, 84]. After it was reported that disruption of TRPM7 in DT-40 B cell lines affect their survival [67, 90], evidence has been accumulating
for the involvement of TRPM7 in proliferation and metastasis of various forms of cancer cells [33, 34, 45, 123]. TRPM7 also regulates a variety of basic cellular responses, such as cell adhesion [13, 72], polarization [89], migration [13, 113], and volume regulation [73]. Moreover, TRPM7 is essential for embryonic development before day 7.5 of embryogenesis and for T cell growth needed for thymopoiesis [46]. In regulating these cellular responses, particularly in proliferation, Mg$^{2+}$ permeation that controls cellular Mg$^{2+}$ homeostasis and downstream phosphoinositide 3-kinase is likely an important function of TRPM7 channels [67, 86, 90]. Thus, assuming that hypoxia-induced activation is the common feature shared by TRPM7 channels in different tissues and cell types, it is possible that decreases in local O$_2$ levels in vivo by changes in body architecture, during development, and changes in climate, can modulate TRPM7 function to modify ionic homeostasis and/or downstream signaling cascades.

**Table 1**  Expression of TRPA1 in neuronal cells and tissues, function, and method of detection, shown in chronological order

| Expressed in cell and tissue | Function (including suggested function) | Species | Method of detection | Reference | Year |
|-----------------------------|------------------------------------------|---------|---------------------|-----------|------|
| Dorsal root ganglion neurons | Noxious cold sensor, thermosensation       | Rat, mouse | Northern blotting, in situ hybridization, calcium imaging, electrophysiology | Story et al. [97] | 2003 |
| Sympathetic superior cervical ganglion neurons | Sole cold sensor, thermosensation | Murine | Calcium imaging | Smith et al. [96] | 2004 |
| Trigeminal neurons (C-fibers) | Nociception, sensory | Rat | In situ hybridization, immunohistochemistry | Kobayashi et al. [51] | 2005 |
| Dental primary afferents | Thermosensation | Rat | Immunohistochemistry, single-cell RT-PCR, whole-cell recordings | Park et al. [77] | 2006 |
| Geniculate ganglion | Somatosensory or gustatory function, nociception, thermosensing | Rat | RT-PCR, in situ hybridization | Katsura et al. [49] | 2006 |
| Primary sensory neurons | Mechanosensory transduction, nociception | Rat | Quantitative PCR, immunofluorescence staining, cystometry | Du et al. [20] | 2007 |
| Lung afferent fibers | Respiratory, nociception | Mouse | Single-cell RT-PCR, whole-cell patch-clamp recordings | Nassenstein et al. [70] | 2008 |
| Masticatory muscle afferent fibers | Craniofacial muscle nociception, mechanical hyperalgesia | Rat | Immunohistochemistry, behavioral studies | Ro et al. [83] | 2009 |
| Trigeminal sensory afferents, spinal dorsal horn, nodose, jugular and petrosal ganglia | Nociception | Rat | Electron microscopy, immunohistochemistry | Kim et al. [50] | 2010 |
| Inhibitory motor neurons of the intestine | Inhibition of spontaneous neurogenic contractions and transit of colon | Mouse | RT-PCR, immunofluorescence, calcium imaging | Poole et al. [82] | 2011 |
| Dura | Headache | Mouse | Immunohistochemistry | Huang et al. [42] | 2012 |
| Vestibular ganglia | Vestibular function, vertigo | Rat | RT-PCR, in situ hybridization, immunohistochemistry, calcium imaging | Kamakura et al. [48] | 2013 |
| Vagina epithelium, wall nerve fibers | Neurotransmission | Human | Immunohistochemistry, RT-PCR | Uckert et al. [108] | 2015 |
from the currently known TRPs, thus prompting it to be placed as a separate subfamily [44]. The group also observed that the TRPA1 gene expression was relatively low and difficult to detect with northern blot analysis and required more sensitive polymerase chain reaction (PCR) technology. Despite this, TRPA1 was detected in numerous tissues [44] and was confirmed later in subsequent studies (Tables 1 and 2).

The function of TRPA1 became evident 4 years later where TRPA1 was shown to mediate sensation of noxious and painful cold and to be expressed in the dorsal root ganglion (DRG) neurons. TRPA1 co-localizes with TRPV1 (a heat-sensing TRP channel) expressing sensory neurons rather than TRPM8-positive sensory neurons, indicating separate cold-sensing modalities [97]. This was particularly interesting as TRPM8 is different from TRPA1 in responding to mild cold temperatures as well as to different sets of organic compounds [97]. Since its discovery, TRPA1 has been reported in most sensory neurons targeting vital organs (see the non-extensive Table 1 below for TRPA1 expression in neuronal populations and nociception) [20, 40, 42, 48–51, 70, 77, 82, 83, 96, 97, 108]. To date, TRPA1 has been also detected in non-neuronal cells such as hair cells of the ear, urethra, skin, olfactory epithelium, dental pulp, uvea, vagina, and pulmonary epithelial cells, and this list is still growing (Table 2) [3, 4, 8, 9, 11, 14, 19, 22, 31, 55, 56, 64, 66, 69, 105, 106]. In 2004, Corey and colleagues proposed the idea that, TRPA1 may be involved in mechanosensation in the hair cell epithelia [14]. A follow-up study nearly half a decade later performed by the same group showed later however that TRPA1 KO mice exhibited normal vestibular function, normal startle reaction following loud auditory stimuli and normal hearing [55].

TRPM7 was first cloned from the rat brain library. Ryazanova and colleagues investigated deletion of the TRPM7 kinase domain in mice [85]. They showed that homozygous mice with TRPM7 lacking the protein kinase domain (denoted as TRPM7Δkinase) were embryonically lethal, Table 2  Expression of TRPA1 in non-neuronal cells and tissues, function, and method of detection, shown in chronological order

| Expressed in cell and tissue                  | Function (including suggested function)                                                                 | Species | Method of detection                                                                 | Reference          | Year  |
|-----------------------------------------------|----------------------------------------------------------------------------------------------------------|---------|------------------------------------------------------------------------------------|--------------------|-------|
| Hair cell of the ear                          | Hair cell transduction, mechanosensation (debated)                                                       | Zebrafish, mouse | In situ hybridization, siRNA                                                      | Corey et al. [14]  | 2004  |
| Urethra                                       | Tone of urethral preparations, afferent and efferent sensory signaling of the human outflow region      | Human   | Western blotting, immunohistochemistry, functional in vitro investigations        | Gratzke et al. [31]| 2009  |
| Skin                                          | Keratinocyte differentiation, inflammation                                                              | Human   | Quantitative PCR, microarray                                                     | Atoyan et al. [4]  | 2009  |
| Developing cochlea                            | Normal cochlear function                                                                                 | Mouse   | Quantitative PCR                                                                 | Asai et al. [3]    | 2010  |
| Olfactory epithelium                         | Olfactory chemosensation, Olfactory adaptation, olfactory–trigeminal interaction, olfactory epithelium fluid homeostasis. | Mouse   | Immunohistochemistry                                                             | Nakashimo et al. [69]| 2010  |
| Dental pulp fibroblasts                       | Thermosensation                                                                                         | Human   | RT-PCR, western blotting, immunohistochemistry                                   | Karim et al. [22] | 2011  |
| Lung fibroblasts and epithelial cells         | Pathogenesis of airway diseases                                                                          | Human   | Calcium imaging                                                                  | Mukhopadhyay et al. [66]| 2011  |
| Pancreatic beta cells                         | Insulin secretion                                                                                        | Rat     | Immunohistochemistry, RT-PCR, western blotting, calcium imaging                | Cao et al. [9]     | 2012  |
| Astrocytes in the superficial laminae of trigeminal caudal nucleus | Inflammation                                                                                          | Rat     | Immunoelectron microscopy                                                        | Lee et al. [56]    | 2012  |
| Olfactory bulb                                | Olfactory transduction                                                                                   | Mouse   | RT-PCR                                                                            | Dong et al. [19]   | 2012  |
| Pulmonary epithelial cells                    | Inflammation                                                                                           | Human, Porcine | Immunohistochemistry                                                              | Bucht et al. [8] | 2013  |
| Peridontal ligament cells                     | Mechanoreception                                                                                        | Human   | DNA microarray                                                                   | Tsutsumi et al. [106]| 2013  |
| Odontoblasts                                  | Sensing membrane stretching, low-temperature stimulation                                                | Rat     | Immunohistochemistry                                                              | Tsumura et al. [105]| 2013  |
| Digestive system, enteroendocrine cells       | Secretion possibly to aid digestion                                                                      | Mouse   | In situ hybridization, Immunofluorescence staining                               | Cho et al. [11]    | 2014  |
| Uvea                                          | Thermosensation                                                                                        | Human   | Quantitative PCR, calcium imaging                                                | Mergler et al. [64]| 2014  |
| Expressed in cell and tissue | Function (including suggested function) | Species | Method of detection | Reference | Year |
|-----------------------------|-----------------------------------------|---------|---------------------|-----------|------|
| Heart, brain, spleen, lung, liver, skeletal muscle and kidney | Calcium channel, serine-threonine kinase | Mouse | Electrophysiology, northern blotting | Runnels et al. [84] | 2001 |
| Cortical neurons | Magnesium homeostasis, excitotoxicity | Mouse | Electrophysiology, radioisotope techniques | Aarts et al. [1] | 2003 |
| Vascular smooth muscle cells | Mg$^{2+}$ homeostasis | Rat, Mouse, Human | Biochemical, genetic and pharmacological tools | He et al. [36] | 2005 |
| Liver (hepatocytes) | Cell proliferation | Zebrafish, human | RT-PCR, immunocytochemistry, patch-clamp recordings, calcium imaging | Boustany et al. [21], and Elizondo et al. [23] | 2008, 2005 |
| Heart, pituitary, bone, adipose tissue | ND | Human | RT-PCR | Fonfría et al. [27] | 2006 |
| Epithelial cells | Stretch- and swell-sensitive ion channel, cell volume regulation | Human | Single channel recordings, RT-PCR | Numata et al. [73] | 2007 |
| Prostate | ND | Rat | RT-PCR | Wang et al. [111] | 2007 |
| Human lung mast cells (HLMCs), human mast cell lines (LAD2 and HMC-1) | Release of proinflammatory mediators, cell survival | Human | Electrophysiology, RT-PCR | Wykes et al. [117] | 2007 |
| Hippocampal neurons (CA1 neurons) | Excitotoxicity, Ca$^{2+}$ paradox | Mouse | Electrophysiology | Wei et al. [114] | 2007 |
| Rumen epithelial cells | Magnesium transport pathways | Ovine | RT-PCR, western blotting, flow cytometry, immunocytochemistry, magnesium imaging | Schwegel et al. [92] | 2008 |
| Human osteoblast-like cells (MG-63, SaOS and U2-OS cells) | Cell proliferation | Human | Cell proliferation, PCR, calcium and magnesium imaging | Abed et al. [2] | 2009 |
| Bone-marrow derived mesenchymal stem cells | Cell survival | Mouse | RT-PCR, immunocytochemistry, electrophysiology | Cheng et al. [10] | 2010 |
| Urothelial cells | Polymodal sensing | Mouse | RT-PCR, immunocytochemistry, patch-clamp recordings, calcium imaging | Evensets et al. [25] | 2010 |
| Retina (cone outer segments) | Magnesium homeostasis | Mouse | RT-PCR, northern blotting, in situ hybridization | Gilliam and Wendsel [29] | 2011 |
| Atrial myocytes | Fibrogenesis | Human | Whole-cell patch-clamp recordings, RT-PCR, western blotting | Zhang et al. [121] | 2012 |
| Trigeminal neurons, dorsal root ganglion neurons | Cell proliferation, organ development, Mg$^{2+}$ homeostasis | Mouse | Quantitative PCR | Vandewauw et al. [110] | 2013 |
| Endometrial stromal cells | Cell proliferation | Human | Quantitative PCR, Immunocytochemistry, calcium imaging, whole-cell patch-clamp recordings | De Clercq et al. [16] | 2015 |

ND not determined
while TRPM7Δkinase heterozygous mice showed impaired magnesium homeostasis. TRPM7Δkinase heterozygous mice showed low magnesium concentration in the plasma, erythrocytes, and bones. Magnesium impairment was further demonstrated with data obtained from mice fed a poor magnesium diet. Mice with TRPM7Δkinase showed clamping, tremor, and seizures consistent with impairment in magnesium homeostasis. To elucidate the complete functional profile of the TRPM channel family, Fonfria and colleagues analyzed TRPM7 temporal channel tissue distribution by quantitative PCR \[27\]. Their study revealed TRPM7 expression in the brain, pituitary, heart, lung, liver, fetal liver, skeletal muscle, stomach, intestine, spleen, macrophages, adipose, pancreas, prostate, placenta, cartilage, bone marrow, and bone. Highest expression was in the pituitary, heart, adipose, and bone, and lowest expression was in cartilage, liver, and bone marrow \[27\]. Subsequent studies employing various techniques with varying sensitivity confirmed the findings (Table 3) \[1, 2, 6, 10, 16, 21, 23, 25, 27, 29, 36, 73, 84, 92, 110, 111, 114, 117, 121\]. Thus, TRPA1 and TRPM7 have been shown to be ubiquitous in many tissues and cells. Since the function of these channels was shown to be tissue specific, the spatial and temporal expressions of these channels are important clues for the ever growing list of functions.

**What is the significance of the ubiquity of O2 sensor TRP channels in the body?**

It is important to address the primary significance of O2-sensing TRP channels that are ubiquitously expressed in the body. We suggest that these O2 sensors play key roles in the molecular mechanisms which underlie the O2-sensing ability of chemoreceptor (or chemoreceptor-like) cells localized ubiquitously in a variety of tissues and organs. It is possible that TRP O2 sensors detect local O2 availability and contribute to fine tuning of local O2 levels, which cannot be done by the CB alone, in the respective organs and tissues and in their subareas. Information of detected local O2 availablility (partial pressure) may be transmitted through neurons, as discussed above and/or humoral factors to control O2 delivery to peripheral organs and tissues. Interestingly, TRPA1 acts as sensors for not only hypoxia but also for hyperoxia, suggesting that at least TRPA1 and other redox-sensitive TRP channels also transmit negative signals to suppress excessive O2 delivery responsible for harmful ROS production. These TRP channels may even contribute to a mechanism that maintains O2 availability of certain organs/tissues and their subareas at hypoxic levels compared with the atmospheric O2 level. It has indeed been reported that hypoxic levels are important in maintaining cellular conditions of certain types of cells in vivo \[24, 75, 76, 98\].

The many lines of experimental evidence thus far have led us to propose the concept of “O2 remodeling” (Fig. 3). In O2 remodeling, O2-sensing chemoreceptors detect deviation of O2 availability and transmit this information to neurons and/or humoral factors, such as vascular endothelial growth factor \[57, 93\] to control O2 delivery. Also, according to the types, location, and condition (including O2 availability itself) of the tissues in the body, mitochondrial O2 consumption \[88\] is regulated by mechanisms such as the Pasteur effect, which switches O2 dependence of ATP production \[109\]. In the mechanism underlying O2 remodeling, O2 sensor TRP channels and redox-sensitive TRP channels play important roles, together with signaling cascades controlled by HIF/PHD \[91, 112\] and also by polysulfide redox factors \[43\]. Compared with the roles of HIF/PHD, those of TRP channels in controlling O2-triggered signaling cascades via signals of ions such as \(\text{Ca}^{2+}\) are still very elusive. As a readout of the signaling mechanism, O2 availability is adjusted to optimal levels, which enable sufficient cellular O2 supply for the activity and function of corresponding organs and tissues and at the same time, minimized production of excessive ROS and cellular conditions of tissues in the body, mitochondrial O2 consumption is regulated by mechanisms such as the Pasteur effect, which switches O2 dependence of ATP production.
damage. It is interesting to speculate that such “active” (not passive) optimization by O2 remodeling leads to the formation of a local O2 environment, in which population of cells behave as a unit for homeostasis that is responsible for the regulation of metabolism and development of organs and tissues in aerobic organisms, including as human beings (Fig. 4). We should note that TRPA1 and TRPM7 are not necessarily associated with control of O2 supply in all organs and tissues, considering their well-known ability to detect substances other than O2. However, we still consider it reasonable to expect modification by changes in O2 availability for cellular responses via these TRP channels activated by these other triggers.

Conclusion

Identification of O2-sensing TRP channels opens a new area of oxygen physiology. In particular, wide tissue expression of O2-sensing TRPA1 and TRPM7 channels is indicative of “acute” O2-sensing capacity in diverse types of cells, tissues, and organs. This constitutes a considerable departure from the classical concept of respiratory physiology ascribing the powerful hypoxic chemoreflex solely to CB chemoreceptor excitation [81, 100]. In the case of TRPA1, hyperoxia-induced activation has been shown through the quantitative characterization of oxidation sensitivity of redox-sensitive TRP channels. The O2-sensing mechanisms involving TRPA1 and other oxidation-sensitive mechanisms may be important for maintaining O2 availability at certain hypoxic levels to avoid unnecessary and excessive production of ROS. In this review, we have suggested that “O2 remodeling,” in which cells comprising organs and tissues actively form a local in vivo O2 environment optimal for their function in the body, emerges as a new central concept for oxygen biology. This concept may allow us to systematically understand numerous physiological phenomena affected by O2 availability in aerobic organisms. In studying O2 remodeling, it is a tantalizing prospect to discover whether O2-sensing TRP channels are involved in the mechanisms underlying ‘chronic’ forms of hypoxic adaptation. Breakthrough studies on the time-dependent aspects (acute vs. chronic), as well as the concentration-dependent aspects (hypoxic vs. hyperoxic) of O2 remodeling would eventually result in a paradigm shift in our understanding of the biology of O2.

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