State-dependent and site-directed photodynamic transformation of HCN2 channel by singlet oxygen

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Singlet oxygen (1O2), which is generated through metabolic reactions and oxidizes numerous biological molecules, has been a useful tool in basic research and clinical practice. However, its role as a signaling factor, as well as a mechanistic understanding of the oxidation process, remains poorly understood. Here, we show that hyperpolarization-activated, cAMP-gated (HCN) channels—which conduct the hyperpolarization-activated current (Ih) and the voltage-insensitive instantaneous current (Iinst)—and contribute to diverse physiological functions including learning and memory, cardiac pacemaking, and the sensation of pain—are subject to modification by 1O2. To increase the site specificity of 1O2 generation, we used fluorescein-conjugated cAMP, which specifically binds to HCN channels, or a chimeric channel in which an in-frame 1O2 generator (SOG) protein was fused to the HCN C terminus. Millisecond laser pulses reduced Ih current amplitude, slowed channel deactivation, and enhanced Iinst current. The modification of HCN channel function is a photodynamic process that involves 1O2, as supported by the dependence on dissolved oxygen in solutions, the inhibitory effect by a 1O2 scavenger, and the results with the HCN2-SOG fusion protein. Intriguingly, 1O2 modification of the HCN2 channel is state dependent: laser pulses applied to open channels mainly slow down deactivation and increase Iinst, whereas for the closed channels, 1O2 modification mainly reduced Ih amplitude. We identified a histidine residue (H434 in S6) near the activation gate in the pore critical for 1O2 modulation of HCN function. Alanine replacement of H434 abolished the delay in channel deactivation and the generation of Iinst induced by photodynamic modification. Our study provides new insights into the instantaneous current conducted by HCN channels, showing that modifications to the region close to the intracellular gate underlie the expression of Iinst and establishes a well-defined model for studying 1O2 modifications at the molecular level.

INTRODUCTION

Molecular oxygen has three different electron configurations: the triplet ground state (3Σ), and the first and second singlet excited states (1Δ and 1Σ) (Kochevar, 2004; Ogilby, 2010). Singlet oxygen (1O2) mainly refers to the 1Δ state because of its longer lifetime compared with the 1Σ state. 1O2 is highly reactive and oxidizes a wide range of biomolecules including DNA, proteins, and unsaturated lipids. Among the 20 amino acids, 1O2 mainly reacts with histidine, cysteine, methionine, tyrosine, and tryptophan (Gracanin et al., 2009). Histidine is an effective quencher of 1O2 and the major target of 1O2 oxidation. Under physiological conditions, 1O2 can be generated through metabolic reactions and functions as a signaling factor, such as in plants and stimulated neutrophils and macrophages (Steinbeck et al., 1992; Triantaphylides and Havaux, 2009). Native compounds including flavins and NADH/NADPH inside the cell can function as photodynamic processes, can lead to excessive oxidation of biomolecules and even cell necrosis. Photosensitization or photodynamic processes require three key elements: photosensitizer, oxygen, and light (Fig. S1) (DeRosa and Crutchley, 2002). Actually, many photo-excitable molecules used in basic research, such as FITC and fluorescent proteins, are effective photosensitizers and can produce 1O2 upon excitation.

Two unique features of 1O2 are its short lifetime (µs) and its short working distance (nm), which make it effective in eliminating the function of specific proteins and cells with high temporal and spatial precision. In chromophore-assisted light inactivation, a fluorophore-tagged antibody recognizes and forms a complex with the target protein. Upon light excitation, an excessive...
amount of \(^1\)O\(_2\) is generated and inactivates the function of the protein in close proximity (Liao et al., 1994; Tour et al., 2003). Similarly in photodynamic therapy (PDT), light is guided to the target tissue to excite the pre-administered drugs (photosensitizers) to produce \(^1\)O\(_2\), which eventually leads to the death of the target cells through a combination of apoptosis, necrosis, and acutely triggered local immune responses. The major advantage of PDT is the minimal side effects. PDT is a procedure approved by the US Food and Drug Administration for treating cancer and some other diseases (Agostinis et al., 2011).

However, in contrast to its application potential and physiological significance, little is known about \(^1\)O\(_2\)-mediated modification of biomacromolecules at the molecular level. Previous studies on \(^1\)O\(_2\) mainly relied on cell and tissue preparations in the presence of complex intracellular signaling pathways. Numerous factors make \(^1\)O\(_2\) a challenging research target: the volatile chemical nature of \(^1\)O\(_2\); the wide range of target molecules; and the heterogeneous distributions of oxygen, photosensitizers, and quenchers (Schweitzer and Schmidt, 2003; Skovsen et al., 2005; Latch and McNeill, 2006; Pedersen et al., 2011). Isolated reports have addressed the effects of \(^1\)O\(_2\) modification of channel and transporter proteins (Valenzeno and Tarr, 1991; Eisenman et al., 2007, 2009). Most of these studies used whole-cell preparations and applied nonspecific photosensitizers, such as rose bengal, to generate \(^1\)O\(_2\). Thus, interactions between \(^1\)O\(_2\) and lipid membranes or other membrane-affiliated elements could not be completely ruled out. Notably, all those studies required a long duration of light exposure—up to minutes or even longer—to produce observable effects, in contrast to the short lifetime of \(^1\)O\(_2\) (\(\mu\)s). A well-defined and sensitive working model for studying \(^1\)O\(_2\) modification is needed.

Here we report that hyperpolarization-activated, cAMP-gated (HCN) channels are sensitive to modification by photochemically generated \(^1\)O\(_2\). HCN channels are involved in physiological functions including cardiac pacemaking, sensation of pain, learning, and memory (Robinson and Siegelbaum, 2003; Biel et al., 2009). HCN channels are tetrameric. Each subunit contains a transmembrane domain of six \(\alpha\) helices (S1–S6), homologous to that of voltage-gated potassium channels, and the cyclic nucleotide-binding domain (CNBD) in the C terminus of the channel (Robinson and Siegelbaum, 2003; Biel et al., 2009). In the transmembrane domain, S4 contains multiple positively charged residues and functions as the voltage sensor for membrane hyperpolarization. Intracellular cAMP directly binds to the channel and increases current amplitude, shifts channel opening to less negative potentials, and slows down channel deactivation. cAMP-dependent gating in HCN channels contributes to the storage of working memory in the prefrontal cortex, the maintenance of heart rate at the resting level, and the sensation of pain (Nolan et al., 2003; Wang et al., 2007; Baruscotti et al., 2011). In addition to the hyperpolarization-activated current (I\(_h\)), HCN channels also conduct the voltage-insensitive instantaneous current (I\(_\text{inst}\)), although its molecular nature is not clear (Proenza et al., 2002; Mistrik et al., 2006; Proenza and Yellen, 2006). It was reported that I\(_h\) and I\(_\text{inst}\) could be conducted by two distinct populations of HCN channels that are not in rapid equilibrium (Proenza and Yellen, 2006).

The dual regulation of HCN channels by voltage and ligand provides a unique opportunity to study \(^1\)O\(_2\) modification of membrane proteins. In our previous studies, we have used fluorescent cAMP analogues as a reporter to address the dynamic interaction between cAMP and the whole channel (Wu et al., 2011, 2012). Using 8-NBD-cAMP as the marker, we discovered that channels in the open state have an increased binding affinity for cAMP, and residues near the activation gate in S6 remotely control ligand binding. During these studies we noticed that applying high concentrations of fluorescein-cAMP (8-fluor-cAMP or FITC-cAMP) resulted in interesting changes to HCN function. Following this lead, we identified \(^1\)O\(_2\) as the central player. Intriguingly, \(^1\)O\(_2\) modification of the HCN channel is state dependent and depends on a critical histidine residue near the activation gate.

**MATERIALS AND METHODS**

**Functional expression of HCN channels in Xenopus laevis oocytes**

The DNA plasmid containing the sequence of WT mouse HCN2 (mHCN2) channel was provided by S. Siegelbaum (Columbia University, New York, NY). The HCN2-SOG and HCN2-EGFP constructs were made by inserting the DNA sequence encoding \(^1\)O\(_2\) generator (SOG) or EGFP at the C terminus of the CNBD through the BamHI cut site, flanked by the CNBD and the downstream sequence of the mHCN2 channel (Figs. S2 and S3). The H434A mutation was introduced by a two-step PCR method. DNA plasmids were linearized by SphI and purified by phenol-chloroform extraction. mMessage machine (Ambion) was used to make cRNA. 40–50 ng cRNA was injected into each oocyte at stage VI. Injected cells were cultured between 16 and 18°C for 2–4 d before experiments.

**Electrophysiology and optical setup**

We used symmetrical solutions during patch-clamp recording in the inside-out configuration. The solution contained 110 mM KCl, 1 mM EDTA, and 10 mM HEPES, pH 7.4 adjusted by KOH. To measure ion selectivity, K\(^+\) ions in the bath solution, which faced the intracellular side of the channel, were replaced by Na\(^+\). All experiments were performed at room temperature. Current traces were amplified by a patch-clamp amplifier (model 2400; A-M Systems) and digitized by a Digidata 1440 (Axon Instruments). Voltage-clamp and laser-pulse protocols are illustrated in the figures. Typically the membrane potential was held at −40 mV. Hyperpolarizing voltage steps were applied every 15 s.

We calculated the percentage of I\(_\text{inst}\) based on the following equation:

\[
I_{\text{inst}}(\%) = \frac{I_{\text{inst}} - I_{\text{inst}}^{0}}{I_{\text{MAX}}^{0}} \times 100
\]
where $I_{\text{inst}}$ is the instantaneous current measured just after the hyperpolarizing voltage step, $i$ is the stimulation index (episode number), $I_{\text{inst}}$ is the instantaneous current before laser treatment, and $I_{\text{peak}}$ is the peak current measured near the end of the hyperpolarizing voltage step before laser treatment and includes both $I_{\text{h}}$ and $I_{\text{inst}}$. We used a single-exponential equation to fit the tail current measured at $-40$ mV. Leak current was not subtracted from the recordings. To determine the $V_{1/2}$ values, a series of hyperpolarizing voltage steps was applied to activate the channel. Tail currents were measured at $-40$ mV, and the amplitudes were fitted with the Boltzmann equation.

The ratio of permeability for Na$^+$ and K$^+$ ions was calculated based on the value of the reversal potential and the Goldman–Hodgkin–Katz equation:

$$\frac{P_{Na}}{P_{K}} = \frac{F E_{REV}}{[Na]_o - \exp \frac{E_{REV}}{RT} \cdot [Na]_i} \frac{\exp \frac{E_{REV}}{RT} \cdot [K]_o}{[K]_i - \exp \frac{E_{REV}}{RT} \cdot [K]_i},$$

where $E_{REV}$ represents the reversal potential, and $[X]_o$ and $[X]_i$ represent the ion concentrations in the pipette and in the bath, respectively.

The setup was based upon a microscope (IX71; Olympus) equipped with a 100× oil-immersion objective (NA 1.25; Olympus Plan). A 473- or a 532-nm diode-pumped, solid-state laser was used as the excitation light source. The following filter set was used to collect the fluorescence signal from FITC, EGFP, and
Modification of HCN channel by singlet oxygen laser light source, the CCD camera exposure time, and the amplifier for patch-clamp recording were synchronized by transistor–transistor logic signals. Fluorescence images were analyzed with ImageJ software (Schneider et al., 2012). The TurboReg program

Figure 2. Photodynamic transformation slows down channel deactivation and enhances voltage-insensitive $I_{\text{inst}}$. (A) Current traces before (black; no. 3 in B) and after (blue; no. 7 in B) laser treatments. Arrow indicates $I_{\text{inst}}$. Gray arrows point out close-up view over the current traces during channel deactivation. (B) Percentage of $I_{\text{inst}}$ (top) or time constant of channel deactivation (bottom) versus episode number. Laser pulses (filled blue triangle) were given every 15 s after the third episode. FITC-cAMP, $n = 19$; cAMP, $n = 7$. *, P < 0.05.

Figure 3. Photochemically generated $I_{\text{inst}}$ has key biophysical features of canonical HCN channel. (A) Voltage protocol (top) and current traces for measuring $pK^{+}/pNa^{+}$ of $I_{h}$ current. (B) I-V curves of $I_{h}$ current. (C) Voltage protocols (top) and current traces of $I_{\text{inst}}$. (D) I-V curves of $I_{\text{inst}}$. (E) ZD7288 and Cs$^{+}$ interact with different regions in the HCN pore. (F) $I_{\text{inst}}$ was generated by applying laser pulses (nos. 3–5). 60 µM ZD7288 was added to the bath solution after number 9. (G) 2 mM Cs$^{+}$ was added to the pipette solution. A voltage step to $+60$ mV released the Cs$^{+}$ block. Current traces: black, control; blue, after three laser pulses. Current traces in A–C were measured in the absence of ligands (cAMP or FITC-cAMP). 0.5 µM FITC-cAMP was present in F and G.
To prevent the interference from intracellular signal transduction pathways, we used a cell-free system and studied the channels expressed on a membrane patch held within the patch-clamp recording pipette in the inside-out configuration. To increase the spatial specificity of the photodynamic transformation, we used FITC-cAMP that specifically binds to the HCN channel on the cell membrane as the photosensitizer. Using uninjected oocytes as a negative control, we confirmed the specific interaction between FITC-cAMP and HCN channels (Fig. 1 A).

In the presence of 0.5 µM FITC-cAMP, a series of laser pulses applied during channel activation (473 nm, 100 msec, 1 pulse/episode) introduced significant functional changes in the mHCN2 channel (Fig. 1 B). Laser pulses significantly reduced the amplitude of the Ih current, slowed down channel deactivation, and enhanced the voltage-insensitive component (Iinst). First, we asked whether the changes in Ih after laser treatment are related to Ih rundown, which is a known phenomenon and reflected in both the reduction in current amplitude and the negative shift in the channel activation (I-V) curve. As a negative control, the same concentration of cAMP was applied to the patch. During the 3-min recording period, the reduction in Ih was minimal and less than ~10% with laser pulses (Fig. 1, C and D, green trace). In contrast, Ih was reduced by ~40% in the presence of FITC-cAMP and with laser pulses. Without laser treatment, applying FITC-cAMP led to a reduction in Ih, which was probably caused by the excitation of the fluorophore by ambient light. Further

**Results**

Photodynamic transformation of the mHCN2 channel

We performed experiments on a setup that enables simultaneous electrical recording of channel activity and optical detection of associated fluorescence signals (Wu et al., 2011). To prevent the interference from intracellular signal transduction pathways, we used a cell-free system and studied the channels expressed on a membrane patch held within the patch-clamp recording pipette in the inside-out configuration. To increase the spatial specificity of the photodynamic transformation, we used FITC-cAMP that specifically binds to the HCN channel on the cell membrane as the photosensitizer. Using uninjected oocytes as a negative control, we confirmed the specific interaction between FITC-cAMP and HCN channels (Fig. 1 A).

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![Figure 4](http://www.jgp.org/cgi/content/full/jgp.201311112/DC1)
control experiments involving two other constructs were performed under different conditions (Fig. S4). Collectively, these results suggest that the photodynamic transformation of HCN channels is an active process and distinct from their rundown. Moreover, we studied hyperpolarization-dependent channel activation by measuring the I-V curve (Fig. 1 E). After adding FITC-cAMP to the bath, we collected an I-V curve as the first control and then applied two to four laser pulses before collecting the second I-V curve. Compared with the I-V curves collected without laser treatment, the photodynamic process decreased the maximal current amplitude and slightly shifted the I-V curve toward negative potentials (Fig. 1, F and G). Notably, for an HCN channel with a slow gating kinetics, it is known that the duration of voltage command affects the I-V curve and slight slowdown in activation could lead to a negative shift in $V_{1/2}$.

To quantify the changes in the amplitude of I$_{\text{inst}}$ and the kinetics of channel deactivation, we calculated the percentage of I$_{\text{inst}}$ in the total current and measured the time constant of channel deactivation (Fig. 2). The slowdown in channel deactivation occurred immediately after the delivery of the first laser pulse and reached a plateau after four to six pulses, whereas I$_{\text{inst}}$ did not reach a plateau (Fig. S5). The “use-dependent” increase in I$_{\text{inst}}$ could be related to the fact that after laser treatment the channel closed so slowly that a substantial amount of channels remained open, even until the next voltage stimulation step.

To confirm that the I$_{\text{inst}}$ after laser treatment was carried by HCN channels but not related to nonspecific damage to the membrane patch, we characterized the biophysical properties of I$_{\text{inst}}$ and compared them with those of the I$_{\text{h}}$ current (Fig. 3). We started from ion selectivity because HCN channels have a distinctive mixed conductivity for K$^+$ and Na$^+$ ions. The ratio of permeability to K and Na is $\approx$3:1. We first measured the relative permeability of the I$_{\text{h}}$ conductance as a positive control. We separately applied solutions containing either K$^+$ or Na$^+$ to the intracellular side (Fig. 3 A). Based on the reversal potential, we determined $P_k/P_{Na}$ of the I$_{\text{h}}$ conductance to be $3.61 \pm 0.21$ ($n = 3$; Fig. 3 B). Next, we applied the photodynamic procedure to transform the channel and then determined $P_k/P_{Na}$ to be $3.03 \pm 0.22$ ($n = 7$), which is not significantly different from that of I$_{\text{h}}$ (one-way ANOVA) (Fig. 3, C and D). To further address the biophysical nature of I$_{\text{inst}}$, we asked whether I$_{\text{inst}}$ could be...
with EGFP. FITC is known to have a higher quantum yield for generating $^{1}$O$_2$ (3 vs. 0.4%) (DeRosa and Crutchley, 2002; Jiménez-Banzo et al., 2008). To test the involvement of $^{1}$O$_2$, we applied 0.1 µM rose bengal, a widely used photosensitizer (Fig. S9), or 10 mM of free FITC to the intracellular side of the patch and indeed obtained similar observations. Then we asked whether the photodynamic process was sensitive to oxygen. We degassed the solutions used in the recordings and separately purged them with pure nitrogen or pure oxygen (Fig. 4, A and B). Impressively, removing oxygen from the solution effectively abolished the photochemical transformation of HCN function whereas, in contrast, the solutions purged with oxygen exaggerated the transformation effects. We also tested Trolox C, a known $^{1}$O$_2$ quencher (Ohara et al., 2009). As expected, 0.5 mM Trolox C (under normal air) suppressed the increases in $\tau_{\text{deactivation}}$ and $I_{\text{inst}}$ (Fig. 4, C and D).

To further study the involvement of $^{1}$O$_2$, we engineered the recently developed mini-SOG protein to the C terminus of the HCN channel (Fig. 5, A and B). Mini-SOG was developed from the light, oxygen, voltage (LOV) domain of a plant protein. Mutations were introduced to increase the quantum yield of $^{1}$O$_2$ (up to 47%, 20 times higher than that of ReAsh, a previously developed genetically targetable SOG) (Shu et al., 2011; Qi et al., 2012). In the absence of exogenous photosensitizers, light illumination of the HCN2-SOG channel reproduced the observations on the HCN2 channel in complex with FITC-cAMP (Fig. 5, C–E). Similarly, the photochemical transformation of the mHCN2-SOG channel was sensitive to oxygen.

$^{1}$O$_2$ modification of the mHCN2 channel

Next, we investigated the molecular basis of the phototransformation process. To further exclude nonspecific effects on the HCN channel by blue excitation light or green fluorescent emission, we used the HCN-EGFP fusion channel because EGFP and FITC share similar excitation and emission spectra (Fig. S8). Laser treatment had little effect on the channel. To test any potential effects by the green fluorescent light, we replaced the 473-nm laser with a green laser (532 nm) and directly illuminated the membrane patch. None of these manipulations produced any noticeable change in channel function. Collectively, it appears that the transformation of the HCN channel is through a photochemical process that involves the excitation of FITC.

Why does exciting FITC, but not EGFP, produce such dramatic effects on channel function? Compared

Figure 6. $^{1}$O$_2$ modification of the mHCN2 channel is state dependent. (A) Schematic drawings of closed and open channels. (B) Laser pulses were delivered preceding the hyperpolarization step. (C) Current traces before (black; no. 3 in D and E) and after (blue; no. 7 in D and E) laser treatments. (D and E) Normalized $\tau_{\text{deactivation}}$ or percentage of $I_{\text{inst}}$ versus episode number. 0.5 µM FITC-cAMP was applied to the bath. *, P < 0.05.
State dependency in $^{1}$O$_{2}$ transformation of the mHCN2 channel and a critical histidine residue in the channel pore

The short duration of laser pulses (ms) used in our study enabled us to probe whether the timing of the $^{1}$O$_{2}$ modification, corresponding to different functional states of the channel, was a critical factor. We applied a light pulse preceding the hyperpolarizing voltage step, when most of the channels remained closed (Fig. 6, A and B). To our surprise, laser treatments of the closed channel reduced the $I_h$ current amplitude but did not affect $\tau_{\text{deactivation}}$ or increase $I_{\text{inst}}$ (Fig. 6, C–E). This result suggested that some effects of the transformation process, including increases in $\tau_{\text{deactivation}}$ and $I_{\text{inst}}$, are state dependent and require the channel to be in the open state when $^{1}$O$_{2}$ is released.

The above observation suggests that certain residue(s) might become more accessible to $^{1}$O$_{2}$ when the channel is in the open state. Following this insight, we tried to locate the residue(s) that underlies the $^{1}$O$_{2}$ modification effects. We focused on the regions that go through significant conformational changes during channel opening, such as the intracellular end of S6 where the activation gate was presumably located (del Camino et al., 2000; Shin et al., 2004; Prole and Yellen, 2006; Kwan et al., 2012; Wu et al., 2012). We discovered H434 to be important (Fig. 7 A). In the presence of FITC-cAMP, applying laser pulses negatively shifted the I-V curve of the mHCN2/H434A mutant channel and decreased the $I_h$ amplitude (Figs. 7 B, S10, and S11). The negative shift in $V_{1/2}$ was about the same as the control (without laser pulses between two I-Vs), indicating a contribution by current rundown (Fig. 7 C). The decrease in the $I_h$ amplitude of mHCN2/H434A is more pronounced than that of the WT channel (Fig. S12).

Importantly, alanine replacement of H434 effectively abolished the increases in $\tau_{\text{deactivation}}$ and $I_{\text{inst}}$ upon light

![Figure 7.](image)
stimulation (Fig. 7, D and E). These results support the working model that for channels in the open state, H434 becomes more accessible to $^{1}O_{2}$; subsequent modification of H434 leads to a delay in channel deactivation and the expression of the instantaneous HCN current (Fig. S1). In contrast, in the H434A mutant channel, $^{1}O_{2}$ becomes more abundant and modifications of other parts of the channel by $^{1}O_{2}$ might underlie the significant reduction in $I_{h}$ current amplitude.

**DISCUSSION**

Here we report that HCN channels are very sensitive to photodynamic modification by $^{1}O_{2}$. FITC-cAMP or in-frame inserted SOG greatly increases the spatial specificity of $^{1}O_{2}$ production. In contrast with earlier studies that used second-to-minute long light illuminations, our study relied on millisecond light pulses, which exhibited significant changes in HCN channel function. Taking advantage of the short lifetime of $^{1}O_{2}$ and the slow gating kinetics of the HCN channel, we discovered that $^{1}O_{2}$ modification of HCN channels is state dependent and has distinct effects on channels in the open state compared with channels in the closed state. Following this lead, we identified a critical histidine residue at a critical region in S6. Impressively, replacing H434 abolished the effects of photodynamic transformation. Our study provides new insights into the instantaneous current conducted by the HCN channel and paves the way for further exploration of $^{1}O_{2}$ as an effective photonics tool.

HCN channels are known to conduct $I_{\text{inst}}$, but the physiological significance and the molecular basis have been unclear. The $I_{\text{inst}}$ carried by HCN channels has been recorded from native cells, including neurons and cardiomyocytes, and heterologous expression systems (McCormick and Pape, 1990; Hagiwara et al., 1992; Irisawa et al., 1993; Maccarelli and McBain, 1996; Graf et al., 2001; Anderson et al., 2011). The $I_{\text{inst}}$ conducted by HCN channels might have significant physiological consequences. On the one hand, it is known that nonphysiological negative potentials are required to activate the canonical $I_{h}$ current, especially the currents carried by HCN2 and HCN4 channels. On the other hand, any compromise to HCN channel function, through either genetic or pharmacological approaches, consistently leads to a hyperpolarization shift of the resting membrane potential and an increase in the input resistance. $I_{\text{inst}}$ might provide a hint for the resolution of this dilemma and some answers for exactly how HCN channels contribute to various physiological functions.

A molecular understanding of $I_{\text{inst}}$ has been lacking. The most recent study reported that $I_{\text{inst}}$ is conducted by a group of HCN channels that are distinct from the $I_{h}$-conducting channels (Proenza and Yellen, 2006). That observation is consistent with our current study in that the photodynamic transformation is an irreversible process, and the generated $I_{\text{inst}}$ stayed at the same level during the recording period. Moreover, we observed similar results showing that $I_{\text{inst}}$ can be up-regulated by cAMP and responds much faster to open channel blockers than $I_{h}$ does. What is the molecular basis of $I_{\text{inst}}$? Our study suggests that modifications made to residues near the activation gate, such as H434, could slow down channel deactivation and produce $I_{\text{inst}}$. It is possible that under physiological conditions, certain residues including H434 are modified so that the channel’s gate is decoupled from the gating machinery and remains open to produce $I_{\text{inst}}$. This is consistent with previous reports that the coupling between voltage sensor and gate in HCN channels is intrinsically weak compared with that in Kv channels (Bruening-Wright et al., 2007; Ryu and Yellen, 2012).

Our study revealed two major changes after photodynamic transformation: slowdown in channel deactivation and enhancement in $I_{\text{inst}}$. The two phenomena occurred concurrently and might even share the same molecular basis, but the connection between them requires further investigation. Delayed or incomplete deactivation should be able to directly contribute to the expression of $I_{\text{inst}}$ by HCN channels, which had been seen in previous studies of a mutation in the S4–S5 linker that disrupts channel closing (Macri and Accili, 2004) and on the regulation of $I_{\text{inst}}$ by intracellular chloride ions (Mistrík et al., 2006). As shown in Figs. 2 B and S5, it appears that the deactivation was slowed down after the first laser pulse (delivered in episode 4), but only in the next episode (5) could significant $I_{\text{inst}}$ be detected. We kept the start-to-start interval between two episodes at 15 s, which is much longer than the cycle of membrane potential changes under physiological conditions when delayed deactivation will enhance the expression of $I_{\text{inst}}$ upon repeated stimulations. Furthermore, the intrinsic connection between delayed deactivation and $I_{\text{inst}}$ is supported by the observation that both were abolished when laser pulses were applied to the channels in the closed state or to the H434 mutant channel. However, we recognize the possibility that delayed deactivation and the generation of $I_{\text{inst}}$ are not related. After photodynamic transformation, $I_{\text{inst}}$ still exists even after a minute-long waiting period before the next hyperpolarizing stimulation. It is possible that modifications to H434 of different chemical natures are separately responsible for delayed or incomplete deactivation and the generation of $I_{\text{inst}}$. In the literature on $I_{\text{inst}}$, many studies do not report any changes in channel deactivation, although this could be caused by the fact that the $I_{h}$ with delayed deactivation (and $I_{\text{inst}}$) only occupies a small fraction of the total current, so that the kinetics will not be affected macroscopically.

Our study only provided a peek into $^{1}O_{2}$ modification of proteins, which understandably is complicated. State-dependent photodynamic modification, most likely
through H434, suggests that the movement of \(^{1}\text{O}_2\) and the modification of protein residues are not random processes. H434 is probably more accessible to \(^{1}\text{O}_2\) when the channel is in the open state. This actually fits with a previous cysteine accessibility study reporting that the equivalent histidine in the sPHCN channel (H462) is located approximately one to two \(\alpha\)-helical turns above the critical region where four S6 \(\alpha\) helices cross to form the channel gate (Rothberg et al., 2003). Because \(^{1}\text{O}_2\) does not carry any extra electrostatic charges, the van der Waals force or steric clashes might be the dominant factor influencing the diffusion of \(^{1}\text{O}_2\) through proteins. Moreover, we found that photochemical modification of the HCN channel reduced the \(I_{h}\) current amplitude and slightly shifted the channel activation curve toward negative potentials. The fact that \(I_{h}\) was reduced more in the mHCN2/H434A mutant channel suggests that in the WT channel, H434 is dominant in the competition for photochemically generated \(^{1}\text{O}_2\), but residues other than H434 might also be targeted by \(^{1}\text{O}_2\), and the modification of those residues could underlie the decrease in \(I_{h}\). Potential candidates include residues located in regions such as the S4–S5 linker or the intracellular ends of S5 and S6, which are known to be critical for channel function. In contrast to the decrease in \(I_{h}\), the negative shift in \(V_{1/2}\) upon photodynamic transformation was less significant for either WT or mHCN2/H434A mutant channels. Notably, because of the slow activation (seconds), the measurement of \(V_{1/2}\) for HCN channels can be complicated by subtle changes in gating kinetics and the duration of voltage step applied. The effects on channel activation and the related shift in \(V_{1/2}\) by photodynamic transformation require further investigation. FITC-cAMP also binds to other cyclic nucleotide–binding proteins including PKA and exchange proteins activated by cAMP, which should not be a major concern, as our experiments only involve isolated membrane patches in the inside-out configuration (Fig. 1A). Nonspecific modifications could be largely excluded, as supported by the clear state dependency of \(^{1}\text{O}_2\) modification of HCN channels and the results with the mHCN2/H434A mutant channel and the mHCN2-SOG channel.

The significance of the LOV domain in many different types of protein and the biological meaning of the sensitivity to \(^{1}\text{O}_2\) remain to be clarified. The SOG protein used in this study was derived from the LOV domain of phototropin 2, a blue light photoreceptor from Arabidopsis thaliana (Shu et al., 2011). This domain was also found in the N terminus of the eag family (KCNH) of Kv channels (Morais Cabral et al., 1998; Haitin et al., 2013). Interestingly, both the LOV and the CNBD domains in KCNH channels lose the ability to interact with their corresponding cofactors, flavin mononucleotide and cyclic nucleotides, respectively, but they interact with each other to regulate channel function. The LOV domain has also been discovered in transcription factors that regulate circadian rhythms (Sassone-Corsi, 1998), some of which play a role in regulating \(^{1}\text{O}_2\) signaling pathways (Metz et al., 2012). HCN channels share a similar topology with KCNH channels and do not contain the N-terminal LOV domain, but interestingly, they are very sensitive to regulation by \(^{1}\text{O}_2\) generated by a mutated LOV domain. We anticipate that with a more powerful laser source and an ample supply of oxygen in the local microenvironment, it will be possible to push the time limit further to submilliseconds, a resolution that is essential for probing protein dynamics (Fig. S13). Further investigation of \(^{1}\text{O}_2\) modification at the molecular level will provide insights into the role of \(^{1}\text{O}_2\) as a signaling molecule and help establish \(^{1}\text{O}_2\) as an effective photonics tool for biomedical research.

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Figure S1. $^{1}$O$_2$ production through photosensitization process and the working model for $^{1}$O$_2$ modification of HCN channels. (A) ISC refers to intersystem crossing between singlet (S) and triplet (T) spin multiplicity states (Ogilby. 2010. Chem. Soc. Rev. 39:3181–3209). The longer lifetime of Tn states is essential for the production of $^{1}$O$_2$. (B) Working model for the modification of HCN channel by photochemically generated $^{1}$O$_2$.

Figure S2. Construction of the mHCN2-EGFP fusion channel.
Figure S3. Construction of the mHCN2-SOG fusion channel.

Figure S4. Decrease of Ih amplitude under different conditions. (A) Amplitude of Ih current was normalized to the maximal current (Ih + Iinst). The concentration of cAMP or FITC-cAMP was 0.5 µM. *, P < 0.05 (one-way ANOVA followed by Tukey's post-hoc test). (B) Normalized time constant for channel deactivation. *, P < 0.05.
Figure S5. Current traces at the moment when the laser pulse was delivered. (A) Voltage protocol for channel activation. (B) Timing of the 100-ms laser pulse. (C) Overlay of the current traces before (black) and with laser pulse applied (red). A close-up view of the moment when the laser pulse was applied is shown in the bottom-right corner.

Figure S6. cAMP enhances photochemically generated $I_{\text{inst}}$. (A) Current traces in response to a hyperpolarizing voltage step before (black) and after (blue) laser pulses. The components of $I_{\text{inst}}$ and $I_h$ have been marked for the current trace after laser pulses (blue). (B) The $I_{\text{inst}}$ recorded from the patch shown in A. Three traces were recorded before (black), during (red), and after cAMP application (green). To prevent the activation of $I_h$, a voltage step to $-60$ mV was used to record $I_{\text{inst}}$. (C) Time course of $I_{\text{inst}}$ amplitude before, during, and after cAMP application. Timing of the three current traces shown in B is indicated. This experiment was repeated five times. The corresponding negative control membrane patches from uninjected oocytes exposed to cAMP are shown in Fig. S7.
Figure S7. Negative control of cAMP-enhancing I_{inst}: membrane patches from un.injected oocytes. Membrane patches were pulled from the surface of un.injected oocytes. Ionic current was driven by a hyperpolarizing voltage step to \(-80\) mV. After six episodes were collected as the control, 10 µM cAMP, 20 times higher than the typical concentration used in this study (0.5 µM), was applied to the bath solution. No obvious increase in the baseline (leak) current was observed. This experiment was repeated four times.

Figure S8. Laser treatments of membrane patches expressing HCN-EGFP did not generate I_{inst}. (A) The mHCN2-EGFP fusion channel. (B) Bright field and fluorescence images of the membrane patch expressing mHCN2-EGFP channels. Arrow indicates the position of the membrane patch. (C) Timing of the laser pulse and the voltage protocol used for channel activation. Laser pulses were given during the channel activation, the same as in Fig. 2 in the main text. (D) Current traces before (black; no. 3 in E) and after (blue; no. 7 in E) laser treatment. (E) Average \(\tau_{\text{deactivation}}\) (left) or percentage of \(I_{\text{max}}\) (right) versus episode number. *, \(P < 0.05\).
Figure S9. Rose bengal was used as the photosensitizer in the photodynamic transformation of the mHCN2 channel. (A) 100 nM rose bengal was applied to the intracellular side of the membrane patch. (B) 100-ms laser pulses were delivered during the 3-s hyperpolarizing voltage step. Black, control; blue, current trace after laser treatment. (C) Averaged $\tau_{\text{deactivation}}$ (left) or percentage of $I_{\text{in}}$ (right) versus episode number. Laser pulses were delivered from the third episode ($n = 3$).

Figure S10. cAMP enhances the gating of the mHCN2/H434A mutant channel. (A) Current traces of mHCN2/H434A in response to a series of voltage steps in $-15$-mV intervals (shown in C). No cAMP was added. (B) Current traces of mHCN2/H434A in the presence of 1 $\mu$M cAMP. (C) Voltage protocol used for collecting the I-V curve. (D) I-V curves of the current traces shown in A and B. Tail currents were measured at a holding potential of $-40$ mV. (E) Summarized $V_{1/2}$ results.

$V_{1/2}$ for mHCN2/H434A:
- control: $-143.2 \pm 1.4$ mV
- 1 $\mu$M cAMP: $-113.8 \pm 1.4$ mV
- $\Delta V_{1/2}$: $+28.2 \pm 0.8$ mV ($n=6$)
Dose–response curves showing FITC-cAMP or cAMP to enhance the I_h current. HCN channels were activated by a hyperpolarizing voltage step to −130 mV for the WT mHCN2 channel or to −140 mV for the mHCN2/H434A mutant channel. Different concentrations of FITC-cAMP or cAMP were sequentially added to the bath solution. The increases in I_h amplitude for each patch were normalized to the maximal value obtained with 10 µM cAMP. For FITC-cAMP, the EC50 value is 0.017 ± 0.002 µM (WT mHCN2 channel). For cAMP, the EC50 values are 0.041 ± 0.008 µM (WT mHCN2 channel) and 0.054 ± 0.004 µM (mHCN2/H434A mutant channel).

Decreases of the I_h current amplitude in WT mHCN2 and mHCN2/H434A mutant channels. (A) Bright field (left) and fluorescence image (right) of a membrane patch expressing mHCN2/H434A mutant channel. 0.5 µM FITC-cAMP was added to the bath solution. (B) Current traces before (black; no. 3 in C) and after (blue; no. 8 in C) laser pulses. Membrane patch was held at −40 mV, and a hyperpolarizing voltage step to −140 mV was used to activate the channel. (C) Normalized I_h current amplitude versus episode number. Laser pulses were applied from number 4. *, P < 0.05 (one-way ANOVA followed by Tukey’s post-hoc test).
Figure S13. Photodynamic transformation of the HCN channel by short laser pulses (2 ms). $^{1}$O₂ is known to have a short lifetime ($10^{-6}$ sec), but most previous studies used long light irradiation—from seconds to minutes—to produce observable effects. Here we show that brief laser pulses (2 ms) were able to transform the HCN channel, still in a state-dependent manner. The laser intensity ($\approx 14$ W/cm²) was $\approx 40$ times higher than typically used in this study. The same concentration of FITC-cAMP (0.5 µM) was used. Solutions were degassed and then purged with pure oxygen. (A) Timing of the 2-ms laser pulse and the hyperpolarizing voltage step. Laser pulses were delivered before the voltage step when most channels stayed in the closed state. (B) Laser pulses were delivered during the voltage step when most channels were in the open state. (C and D) Current traces before (black) and after laser treatment (blue). (E) Average time constant of deactivation versus episode number. (F) Percentage of $I_{\text{max}}$ versus episode number.