Enhanced Ca\textsuperscript{2+}-Sensing Receptor Function in Idiopathic Pulmonary Arterial Hypertension

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Rationale: A rise in cytosolic Ca\textsuperscript{2+} concentration ([Ca\textsuperscript{2+}]\textsubscript{cyt}) in pulmonary arterial smooth muscle cells (PASMC) is an important stimulus for pulmonary vasoconstriction and vascular remodeling. Increased resting [Ca\textsuperscript{2+}]\textsubscript{cyt} and enhanced Ca\textsuperscript{2+} influx have been implicated in PASMC from patients with idiopathic pulmonary arterial hypertension (IPAH).

Objective: We examined whether the extracellular Ca\textsuperscript{2+} influx and proliferation in IPAH-PASMC and whether blockade of CaSR inhibits experimental pulmonary hypertension.

Methods and Results: In normal PASMC superfused with Ca\textsuperscript{2+}-free solution, addition of 2.2 mmol/L Ca\textsuperscript{2+} to the perfusate had little effect on [Ca\textsuperscript{2+}]\textsubscript{cyt}. In IPAH-PASMC, however, restoration of extracellular Ca\textsuperscript{2+} induced a significant increase in [Ca\textsuperscript{2+}]\textsubscript{cyt}. Extracellular application of spermine also markedly raised [Ca\textsuperscript{2+}]\textsubscript{cyt} in IPAH-PASMC but not in normal PASMC. The calcimimetic R568 enhanced, whereas the calcilytic NPS 2143 attenuated, the extracellular Ca\textsuperscript{2+}-induced [Ca\textsuperscript{2+}]\textsubscript{cyt} rise in IPAH-PASMC. Furthermore, the protein expression level of CaSR in IPAH-PASMC was greater than in normal PASMC; knockdown of CaSR in IPAH-PASMC with siRNA attenuated the extracellular Ca\textsuperscript{2+}-mediated [Ca\textsuperscript{2+}]\textsubscript{cyt} increase and inhibited IPAH-PASMC proliferation. Using animal models of pulmonary hypertension, our data showed that CaSR expression and function were both enhanced in PASMC, whereas intraperitoneal injection of the calcilytic NPS 2143 prevented the development of pulmonary hypertension and right ventricular hypertrophy in rats injected with monocrotaline and mice exposed to hypoxia.

Conclusions: The extracellular Ca\textsuperscript{2+}-induced increase in [Ca\textsuperscript{2+}]\textsubscript{cyt} due to upregulated CaSR is a novel pathogenic mechanism contributing to the augmented Ca\textsuperscript{2+} influx and excessive PASMC proliferation in patients and animals with pulmonary arterial hypertension. (Circ Res. 2012;111:469-481.)

Key Words: pulmonary artery ■ smooth muscle cell ■ proliferation ■ G-protein–coupled receptor ■ pulmonary hypertension ■ receptors

Idiopathic pulmonary arterial hypertension (IPAH) is a fatal and progressive disease with unidentified etiologic causes. Pulmonary vascular remodeling and sustained pulmonary vasoconstriction are 2 major causes for the elevated pulmonary vascular resistance and pulmonary arterial pressure in patients with IPAH. A central aspect of pulmonary vascular remodeling is intimal and medial hypertrophy caused by enhanced proliferation and inhibited apoptosis of pulmonary arterial smooth muscle cells (PASMC).\textsuperscript{1} An increase in cytosolic free Ca\textsuperscript{2+} concentration ([Ca\textsuperscript{2+}]\textsubscript{cyt}) in PASMC is a major trigger for pulmonary vasoconstriction and an important stimulus for PASMC proliferation leading to pulmonary vascular remodeling.\textsuperscript{2,3} In PASMC, [Ca\textsuperscript{2+}]\textsubscript{cyt} can be increased by Ca\textsuperscript{2+} release from the intracellular stores and Ca\textsuperscript{2+} influx through plasma-membrane Ca\textsuperscript{2+} channels.\textsuperscript{4,5} PASMC express various Ca\textsuperscript{2+}-permeable channels including voltage-dependent Ca\textsuperscript{2+} channels (VDCC), receptor-operated Ca\textsuperscript{2+} channels (ROC), and store-operated Ca\textsuperscript{2+} channels (SOC). VDCC are activated by membrane depolarization. ROC channels are mainly opened by vasoconstrictors (eg, endothelin-1 and serotonin) via an intracellular second messenger, diacylglycerol (DAG), and by growth factors (eg, epidermal growth factor and platelet-derived growth factor). Activation of ROC by interaction with ligands greatly contributes to the increase in [Ca\textsuperscript{2+}]\textsubscript{cyt}.
due to receptor-operated Ca\(^{2+}\) entry (ROCE) in PASMC. On activation of membrane receptor and subsequent increase in inositol 1,4,5-trisphosphate (IP\(_3\)) synthesis, SOC are opened by the depletion of Ca\(^{2+}\) from the sarcoplasmic reticulum (SR), an important intracellular store in PASMC, to elicit store-operated \(\text{Ca}^{2+}\) entry (SOCE) or capacitative \(\text{Ca}^{2+}\) entry. SOCE is an important mechanism involved in maintaining a sustained elevation of [Ca\(^{2+}\)]\(_{\text{cyt}}\) and refilling Ca\(^{2+}\) into the SR.

We have previously demonstrated that the resting [Ca\(^{2+}\)]\(_{\text{cyt}}\) is increased, whereas SOCE and ROCE are both enhanced in PASMC isolated from IPAH patients in comparison to PASMC isolated from normal subjects and patients without pulmonary hypertension.\(^6\)\(^7\) We have also shown that increased Ca\(^{2+}\) influx during PASMC proliferation is due largely to the enhancement of SOCE; downregulation and blockade of SOC significantly inhibits PASMC proliferation. These results indicate that SOCE plays an important role in regulating cell proliferation in vascular smooth muscle cells.\(^2\)\(^-\)\(^8\) Furthermore, expression and activity of ROC and SOC are both upregulated in PASMC isolated from patients with IPAH and animals with hypoxia-induced pulmonary hypertension.\(^2\)\(^9\)\(^-\)\(^1\)\(^1\)

Opening of ROC and SOC is caused initially by activation of various membrane receptors including G protein–coupled receptors (GPCR) and receptor tyrosine kinases. The extracellular Ca\(^{2+}\)-sensing receptor (CaSR) is a member of GPCR subfamily C (also known as GPRC2A),\(^1\)\(^2\)\(^-\)\(^1\)\(^4\) which was originally identified in the parathyroid glands and is activated by its ligands including Ca\(^{2+}\), Gd\(^{3+}\), Mg\(^{2+}\), polyamines, antibiotics, and amino acids.\(^1\)\(^2\)\(^,\)\(^1\)\(^5\) The CaSR is involved in multiple cellular processes of the parathyroid glands in response to changes in serum Ca\(^{2+}\) concentrations such as proliferation, differentiation, and apoptosis.\(^1\)\(^2\)\(^,\)\(^1\)\(^3\)\(^,\)\(^1\)\(^5\) In addition to parathyroid glands, the CaSR is also expressed in kidney, bone, smooth muscle, endothelium, gastrointestinal tract, and brain.\(^1\)\(^3\)\(^,\)\(^1\)\(^6\)\(^-\)\(^1\)\(^9\) The physiological and pathological significance of CaSR in the development and progression of pulmonary arterial hypertension, however, remains unknown.

In this study, we examined whether CaSR was involved in the enhanced Ca\(^{2+}\) signaling and augmented proliferation in PASMC from patients with IPAH and whether inhibition of CaSR attenuates IPAH-PASMC proliferation and prevents the development of experimental pulmonary hypertension in animal models.

Methods

Preparation of Human and Animal PASMC

Human PASMC were isolated from normal control subjects and patients with IPAH and chronic thromboembolic pulmonary hypertension (CTEPH).\(^8\)\(^,\)\(^2\)\(^0\)\(^,\)\(^2\)\(^1\) Approval to use the human lung tissues and cells was granted by the UIC Institutional Review Board. Human PASMC were cultured in Medium 199 supplemented with 10% fetal bovine serum at 37°C. The cells at passages 5 to 8 were used for the experiments. In some experiments, we also used freshly-dissociated PASMC from rats and PASMC from mice.\(^2\)\(^5\)

\([\text{Ca}^{2+}]_{\text{cyt}}\) Measurement

\([\text{Ca}^{2+}]_{\text{cyt}}\) was measured in PASMC using fura-2 and a Nikon digital fluorescent imaging system.\(^2\)\(^4\) Cells were loaded with 4 \(\mu\)mol/L fura-2 acetoxyethyl ester (fura-2/AM) for 60 minutes at 25°C and [Ca\(^{2+}\)]\(_{\text{cyt}}\) was measured using a ratiometric method at 32°C.

Western Blot

Solubilized protein isolated from PASMC, pulmonary arteries, and lung tissues was loaded on an 8% acrylamide gel, transferred to an Immobilon-P transfer membrane (Millipore, Bedford, MA), and immunoblotted with anti-CaSR monoclonal antibody (MA1–934, 1:200; Thermo Scientific, Rockford, IL). To isolate the fraction of cellular membrane, the cell lysate was centrifuged at 100 000 × g and then the pellet was resuspended to use for Western blot analysis. Signals were detected using a Super Signal West Pico Chemiluminescent Substrate (Thermo Scientific). The protein levels were normalized to β-tubulin (sc-9104, 1:200; Santa Cruz Biotechnology) and expressed in arbitrary units.

Transfection of cDNA and Small Interfering RNA

PASMC were transiently transfected with vector cDNA (2 μg, pcDNA3.1[+]), human CaSR cDNA (2 μg), control small interfering RNA (siRNA) (50 nmol/L, sc-7007; Santa Cruz Biotechnology), or CaSR siRNA (50 nmol/L, s2440; Applied Biosystems, Austin, TX) using an Amza Basic Nucleofector kit for primary smooth muscle cells (Lonza). [Ca\(^{2+}\)]\(_{\text{cyt}}\) measurements and Western blot using cDNA- and siRNA-transfected cells were performed 48 to 72 hours after electroporation.

Proliferation Assay

Proliferation of PASMC was determined using an automated cell counter (TC10; Bio-Rad Laboratories, Hercules, CA). At 48 hours after subculture, PASMC were counted and replated (0 hours) into 8-well multishes (Nunclon Δ, 10.5 cm² of culture area per well; Thermo Scientific) with 1 × 10⁵ cells/well (0.95 × 10⁶ cells/cm²).

Preparation of MCT-PH Rats and Hypoxia-Induced PH Mice

All experiments were approved by the Ethics/Animal Care Committee of University of Illinois at Chicago. For MCT-PH rat experiments, male Sprague-Dawley rats (190–200 g) were treated with single subcutaneous (sc) injection of vehicle (dimethyl sulfoxide, DMSO) or 60 mg/kg MCT. For NPS 2143-treated group, rats were intraperitoneally injected (ip) with NPS 2143 at a dose of 4.5 mg/kg per day (from day 1–10). Fourteen days after injection, rats were anesthetized with ketamine/xylazine and then RVSP was measured using an MPVS Ultra system (Millar Instruments). For hypoxia-
induced pulmonary hypertension (HPH) mouse experiments, male mice (8-week-old C57BL/6) were exposed to hypoxia (10% O2) in a ventilated chamber to develop pulmonary hypertension. For NPS 2143-treated group, mice were injected (ip) with NPS 2143 (1.0 mg/kg per day; from day 1–22). Four weeks after exposure to normobaric hypoxia, mice were anesthetized with ketamine/xylazine, and then RVSP was measured by right heart catheterization.

**Reverse Transcription-PCR**

The extraction of total RNA from rat PASMC and the reverse transcription were performed using TRizol Reagent (Invitrogen) and High-Capacity cDNA Reverse Transcription Kit (Applied Biosystems, Foster City, CA), respectively. For semiquantitative analysis of mRNA, Platinum PCR SuperMix (Invitrogen) and specific primers for rat CaSR and GAPDH were used. Quantitative real-time PCR analysis was performed based on the SYBR assay (SYBR Green Master Mix; Roche Applied Science, Indianapolis, IN) using gene-specific primers for rat CaSR and GAPDH on a Bio-Rad CFX384 Real-Time System C1000 Thermal Cycler system (Bio-Rad Laboratories, Hercules, CA).

**Immunohistochemical and Hematoxylin and Eosin Staining**

Immunohistochemistry and hematoxylin and eosin staining were performed using formalin-fixed and paraffin-embedded sections (3 μm) from left lung lobes of rats. The tissue sections were treated with PBS containing 5% normal goat serum and either CaSR (1:100 dilution) or SM (3 μg/mL) antibody for 1 hour at 4°C. After washing repeatedly in PBS, the sections were covered with PBS containing Alexa Fluor 488-labeled (1:500 dilution) or Cy3-labeled (1:500) secondary antibody for 1 hour at room temperature and then rinsed with PBS. Then sections were mounted in VECTASHIELD hard-set mounting medium with DAPI (1.5 μg/mL). To measure the external diameter of pulmonary arteries stained with hematoxylin and eosin, the microscopic images were analyzed using ImageScope software (Ver.11).

**Drugs**

Pharmacological reagents were obtained from Sigma-Aldrich except for KB-R7943, NPS 2143, and R568 (Tocris, Ellisville, MO). All hydrophobic compounds were dissolved in DMSO at the concentration of 10 or 100 mmol/L as a stock solution.

**Statistical Analysis**

Composite data are shown as the mean±SE. The statistical significance between two groups was determined by Student t test. The statistical significance among groups was determined by Scheffe test after 1-way analysis of variance. Significant difference is expressed as P<0.05 or P<0.01.

**Results**

**Extracellular Ca2+ Induces a Significant Increase in [Ca2+]c in IPAH-PASM But Not in Normal PASMC**

We first examined and compared the effects of extracellular Ca2+ restoration on changes in [Ca2+]c in PASMC from normal subjects, IPAH patients and CTEPH patients. In normal PASMC superfused with Ca2+-free solution (plus 1 mmol/L EGTA; for 10 minutes), restoration of extracellular Ca2+ (2.2 mmol/L) into the bath solution had no effect on [Ca2+]c (Figure 1A through 1C). Even after long exposure (30 and 60 minutes) of normal PASMC to Ca2+-free solution, there was no change in [Ca2+]c after restoration of extracellular Ca2+. In IPAH-PASM superfused with Ca2+-free solution (for 10 minutes); however, restoration of extracellular Ca2+ resulted in a significant increase in [Ca2+]c in 96% of the cells tested. The extracellular Ca2+-induced increase in [Ca2+]c in IPAH-PASM was independent of the exposure time (5–30 minutes) to Ca2+-free solution. Interestingly, as shown in Figure 1A through 1C (IPAH1 versus IPAH2), the kinetics of the extracellular Ca2+-induced increases in [Ca2+]c were different in IPAH-PASM. Approximately 48% of IPAH-PASM tested (IPAH1) exhibited a rapid transient increase in [Ca2+]c, whereas more than 50% of the cells (IPAH2) had a sustained plateau phase of [Ca2+]c increase after the initial transient (Figure 1A, middle panels, and Figure 1C). In PASMC isolated from CTEPH patients superfused with Ca2+-free solution (for 10 minutes), restoration of extracellular Ca2+ had no effect on [Ca2+]c (Figure 1A through 1C).

The extracellular Ca2+-induced [Ca2+]c increase in IPAH-PASM was dependent on Ca2+ concentration (Figure 1D); the EC50 was approximately 1.22 mmol/L (n=57–183 cells), which resulted an increase of [Ca2+]c by 1,250 mmol/L (Figure 1D, right panel). In contrast, we were unable to detect a significant increase in [Ca2+]c in normal PASMC with restoration of 10 mmol/L extracellular Ca2+ (Figure 1D).

**Protein Expression of CaSR in IPAH-PASM Is Greater Than in Normal PASMC**

To investigate the potential mechanism of extracellular Ca2+-mediated increase in [Ca2+]c, we compared the protein expression level of CaSR in normal and IPAH PASMC. As shown in Figure 2, the protein expression of CaSR in IPAH-PASM (Figure 2A and 2B) and lung tissues from IPAH patients (Figure 2C and Online Figure I) was significantly higher than in normal PASMC and lung tissues in both total protein lysates and in the membrane bound fraction (n=5, P<0.01). These data indicate that upregulation of CaSR may be involved in the enhanced Ca2+-induced [Ca2+]c increase in IPAH-PASM.

**The Extracellular Ca2+-Induced [Ca2+]c Rise in IPAH-PASM Is Not Due Simply to Ca2+ Leakage**

To rule out the possibility that the extracellular Ca2+-induced [Ca2+]c increase in IPAH-PASM was caused by membrane leakage to Ca2+, we first compared the resting [Ca2+]c in normal and IPAH-PASM. In cells superfused with 2.2 mmol/L Ca2+-containing solution, the resting [Ca2+]c in IPAH-PASM (n=370 cells) was significantly higher than in normal PASMC (n=96 cells). Removal of extracellular Ca2+ negligibly affected the resting [Ca2+]c in normal PASMC but significantly decreased the resting [Ca2+]c in IPAH-PASM (Online Figure IIA). To examine whether IPAH-PASM had leaky membranes, we incubated normal and IPAH PASMC with trypan blue (TB). No blue (TB-stained) cells were detected in normal and IPAH PASMC incubated in TB-containing solution, whereas after treatment of the cells with 10 μmol/L ionomycin (for 10 minutes), a Ca2+ ionophore, all normal and IPAH PASMC were TB-stained; there was no difference between normal and IPAH PASMC (Online Figure IIB). Furthermore, we were unable to detect any fluorescent signals in normal and IPAH PASMC incubated with membrane-impermeable fura-2 (Online Figure IIC). All these experiments indicate that the extracellular Ca2+-induced...
[Ca\(^{2+}\)]\(_{\text{cyt}}\) increase in IPAH-PASMC was not due to Ca\(^{2+}\) leakage through the plasma membrane.

Effects of Specific CaSR Modulators on the Extracellular Ca\(^{2+}\)-Induced [Ca\(^{2+}\)]\(_{\text{cyt}}\) Increase in Normal and IPAH-PASMC

To further confirm that the upregulated CaSR in IPAH-PASMC is involved in the enhanced extracellular Ca\(^{2+}\)-induced [Ca\(^{2+}\)]\(_{\text{cyt}}\) rise, we examined whether the polyamine spermine and the calcimimetic R568 induced the same effect on [Ca\(^{2+}\)]\(_{\text{cyt}}\) as did restoration of extracellular Ca\(^{2+}\), and whether the calcilytic NPS 2143 inhibited extracellular Ca\(^{2+}\)-mediated increase in [Ca\(^{2+}\)]\(_{\text{cyt}}\) (Figure 3A). As shown in Figure 3B, extracellular application of 3 mmol/L spermine, a CaSR agonist, induced a slight increase in [Ca\(^{2+}\)]\(_{\text{cyt}}\) (52 ± 24 nmol/L, n = 13) in normal PASMC in the presence of 2.2 mmol/L extracellular Ca\(^{2+}\). In IPAH-PASMC, however, extracellular application of spermine caused a huge [Ca\(^{2+}\)]\(_{\text{cyt}}\) increase (1308 ± 123 nmol/L, n = 49; P < 0.01 versus normal PASMC) in the presence of 2.2 mmol/L extracellular Ca\(^{2+}\). In IPAH-PASMC, short-time treatment with the positive allosteric modulator of CaSR, R568 (1 μmol/L) significantly enhanced the extracellular Ca\(^{2+}\)-mediated increase in [Ca\(^{2+}\)]\(_{\text{cyt}}\) (Figure 3B), whereas the negative allosteric modulator of CaSR, NPS 2143 (10 μmol/L), significantly inhibited extracellular Ca\(^{2+}\)-mediated increase in [Ca\(^{2+}\)]\(_{\text{cyt}}\) (Figure 3C). Collectively, these results demonstrate that the upregulated CaSR (Figure 2) is involved in the enhancement of the extracellular Ca\(^{2+}\)-induced [Ca\(^{2+}\)]\(_{\text{cyt}}\) increase in PASMC from IPAH patients.

Extracellular Ca\(^{2+}\)-Induced [Ca\(^{2+}\)]\(_{\text{cyt}}\) Increase in IPAH-PASMC Is Dependent of Phospholipase C and the Inositol-2,4,5-Trisphosphate Receptor

To examine the potential signaling pathway involved in the CaSR-mediated increase in [Ca\(^{2+}\)]\(_{\text{cyt}}\) in IPAH-PASMC, we performed pharmacological experiments on the extracellular Ca\(^{2+}\)-mediated increase in [Ca\(^{2+}\)]\(_{\text{cyt}}\). As shown in Figure 4, short-time pretreatment of IPAH-PASMC with the inhibitor of phospholipase C (PLC), U73122 (1 μmol/L), or the specific blocker of Inositol-2,4,5-Trisphosphate receptor (IP\(_3\)R), xestospongin C (3 μmol/L), significantly inhibited extracellular Ca\(^{2+}\)-induced increase in [Ca\(^{2+}\)]\(_{\text{cyt}}\) (Online Figure IIIA and C). The inactive form of U73122, U73343 (1 μmol/L), however, had no effect on the extracellular Ca\(^{2+}\)-induced increase in [Ca\(^{2+}\)]\(_{\text{cyt}}\].
Ca\(^{2+}\)-induced increase in [Ca\(^{2+}\)\(_{\text{cyt}}\) (Online Figure IIIIB). Pretreatment of IPAH-PASMC with the blocker of VDCC, diltiazem (10 \(\mu\)mol/L) or the inhibitor of Na\(^+\)/Ca\(^{2+}\) exchanger KB-R7943 (10 \(\mu\)mol/L), however, had no effect on the extracellular Ca\(^{2+}\)-induced increase in [Ca\(^{2+}\)\(_{\text{cyt}}\) (Online Figure IIID and E). These results indicate that activation of PLC and IP\(_3\)R is involved in the CaSR-mediated [Ca\(^{2+}\)\(_{\text{cyt}}\) increase in normal PASMC, whereas VDCC and the reverse mode of Na\(^+\)/Ca\(^{2+}\) exchanger are not involved in the Ca2R-mediated Ca\(^{2+}\) influx or inward transportation.

**CaSR Is Functionally Upregulated in PASMC from Animal Models of Experimental Pulmonary Hypertension, and Blockade of CaSR Prevents the Development of PH**

The presented in vitro experimental data show that the upregulated CaSR and augmented extracellular Ca\(^{2+}\)-mediated [Ca\(^{2+}\)\(_{\text{cyt}}\) increase in PASMC are involved in the enhanced PASMC proliferation in patients with IPAH. To investigate whether CaSR can be a target for treatment of pulmonary arterial hypertension, we used the rat model of monocrotaline (MCT)-induced pulmonary hypertension (MCT-PH) and the mouse model of HPH to test the potential therapeutic effect of the calcilytic NPS 2143. We first examined and compared the mRNA and protein expression level of CaSR in PASMC from control and MCT-treated rats. As shown in Figure 6A and 6B, the mRNA level of CaSR in PASMC isolated from rats (rPASMC) with MCT-PH was much greater than in PASMC isolated from normotensive control rats injected with vehicle. The immunohistochemistry and immunoblotting experimental data indicate that the protein expression level of CaSR in the small pulmonary artery (Figure 6C) and PASMC (Figure 6D) of MCT-rats was significantly higher than in small pulmonary artery and PASMC from control rats. Furthermore, the basal or resting [Ca\(^{2+}\)\(_{\text{cyt}}\) and the extracellular Ca\(^{2+}\)-induced increase in [Ca\(^{2+}\)\(_{\text{cyt}}\) were both enhanced in freshly-dissociated PASMC from MCT-PH rats compared with freshly-dissociated PASMC from normotensive control rats (Figure 6E). Treatment with NPS 2143 not only decreased the basal [Ca\(^{2+}\)\(_{\text{cyt}}\) but also inhibited the extracellular Ca\(^{2+}\)-induced increase in [Ca\(^{2+}\)\(_{\text{cyt}}\) in PASMC isolated from MCT-PH rats (Figure 6E). These results imply that upregulation of CaSR and subsequent enhancement of extracellular Ca\(^{2+}\)-induced [Ca\(^{2+}\)\(_{\text{cyt}}\) increase and enhanced cell proliferation in IPAH-PASMC.
increase in PASMC contribute to the development of pulmonary hypertension in rats injected with MCT.

To test the in vivo therapeutic effect of the CaSR antagonist, we examined and compared the right ventricular systolic pressure (RVSP), the Fulton index (i.e., the ratio of right ventricle/left ventricle septum, RV/(LV+S)), and muscularization of distal pulmonary arteries in normotensive control (Norm) rats and MCT-injected rats with and without treatment with NPS 2143, a CaSR antagonist. Injection of MCT (60 mg/kg) in rats significantly increased RVSP and caused right ventricular (RV) hypertrophy compared with the normotensive control (Norm) rats injected with vehicle (DMSO) (Figure 7A through 7C). Intraperitoneal injection of NPS 2143 (4.5 mg/kg per day) had little effect on RVSP and RV/(LV+S) ratio in Norm rats but significantly attenuated the increase in RVSP and the Fulton index in MCT-PH rats (Figure 7A through 7C). There were no significant changes in heart rate in Norm rats with (412±17 bpm, n=6) or without (411±21 bpm, n=6) NPS treatment and MCT-injected rats with (414±23 bpm, n=6) or without (413±21 bpm, n=6) NPS treatment. The MCT-induced increases in RVSP and RV hypertrophy were associated with significant pulmonary vascular remodeling; the vascular medial wall thickness of small pulmonary arteries with the outer diameter less than 100 μm was significantly greater in MCT-injected rats than in Norm rats (Figure 7D and 7E). Treatment with the CaSR antagonist (NPS 2143) significantly inhibited the muscularization of small pulmonary arteries (Figure 7D and 7E). The in vivo animal experiments are consistent with the in vitro experiments using normal and IPAH PASMC.

To further validate the pathogenic role of upregulated CaSR in the development of pulmonary hypertension and the therapeutic effect of CaSR antagonists on experimental pulmonary hypertension, we repeated the experiments mentioned above in
the HPH mouse model. As shown in Figure 8, the mRNA and protein expression of CaSR was significantly higher in pulmonary arteries and lung tissues in HPH mice than in normoxic control mice (Figure 8A and 8B), whereas the extracellular Ca\(^{2+}\)-induced increase in \([\text{Ca}^{2+}]_{\text{cyt}}\) in freshly isolated PASMC from HPH mice was significantly enhanced in comparison to cells from normoxic mice (Figure 8C). These data indicate that CaSR is functionally upregulated in PASMC from HPH mice.

Intraperitoneal injection of NPS 2143 (1 mg/kg per day from day 1–10) had little effect on RVSP and RV/(LV+S) ration in normoxic control mice (Nor) but significantly inhibited the hypoxia-mediated pulmonary arterial wall thickening (Figure 8G) and reversed the hypoxia-induced decrease in branch and junction numbers (and total length) of small pulmonary arterial trees (Figure 8H and 8I). There were no significant changes in heart rate in normoxic mice with (411±17 bpm, n = 6) or without (410±20 bpm, n = 6) NPS treatment and hypoxic mice with (412±18 bpm, n = 6) or without (413±18 bpm, n = 6) NPS treatment.

These data imply that intraperitoneal injection of the CaSR antagonist is an efficient therapeutic approach to inhibit the development and progression of pulmonary vascular remodeling and right ventricular hypertrophy in animal models with experimental pulmonary hypertension induced by injection of monocrotaline and exposure to hypoxia. The observations from this study strongly indicate that increased expression and function of CaSR may play a pathogenic role in the development of pulmonary vascular remodeling and antagonists of CaSR, or calcilytics, may have great therapeutic potential for patients with pulmonary arterial hypertension.

**Discussion**

In this study, we found that (1) extracellular application of Ca\(^{2+}\) (0.5–10 mmol/L) and spermine (3 mmol/L) induced a large increase in \([\text{Ca}^{2+}]_{\text{cyt}}\) in IPAH-PASMC but not in normal PASMC; (2) the protein expression level of CaSR in IPAH-PASMC was greater than in normal PASMC; (3) downregulation of CaSR in IPAH-PASMC (with siRNA) inhibited the extracellular Ca\(^{2+}\)-induced increase in \([\text{Ca}^{2+}]_{\text{cyt}}\) and attenuated cell proliferation, whereas overexpression of CaSR in normal PASMC augmented the extracellular Ca\(^{2+}\)-induced rise in \([\text{Ca}^{2+}]_{\text{cyt}}\); (4) the expression and function of CaSR were also increased in PASMC from rats with MCT-PH and mice with HPH, and intraperitoneal injection of a CaSR antagonist (NPS 2143) significantly inhibited pulmonary vascular remodeling and attenuated the development and progression of the experimental pulmonary hypertension. Collectively, the observations from this study indicate that (1) functionally upregulated CaSR and subsequently augmented extracellular Ca\(^{2+}\)-induced rise in \([\text{Ca}^{2+}]_{\text{cyt}}\) in PASMC contribute to the enhanced Ca\(^{2+}\) signaling and excessive cell proliferation in IPAH patients; and (2) blockade of the upregulated CaSR with calcilytics may be a novel therapeutic approach for pulmonary arterial hypertension.

\([\text{Ca}^{2+}]_{\text{cyt}}\) plays an important role in the regulation of contraction, proliferation, and migration of PASMC. An increase in \([\text{Ca}^{2+}]_{\text{cyt}}\) in PASMC is a major trigger for pulmonary vasoconstriction and an important stimulus for PASMC proliferation and pulmonary vascular remodeling under pathological conditions. Elevation of \([\text{Ca}^{2+}]_{\text{cyt}}\) in PASMC results from Ca\(^{2+}\) release from intracellular stores and Ca\(^{2+}\) influx through plasmalemmal Ca\(^{2+}\) channels. We
previously showed that the resting $[\text{Ca}^{2+}_{\text{cyt}}]$ was increased, whereas ROCE and SOCE were enhanced in PASMC from IPAH patients compared with PASMC from normal subjects and patients without pulmonary hypertension.6,7

CaSR is a GPCR (belongs to the Family C GPCR) with 1085 amino acids, which is present constitutively in a homodimeric configuration formed by covalent and noncovalent linkages25–27 and is able to form heterodimers with the metabotropic glutamate receptors (mGLuR1 and mGluR5).27 One of the hallmarks of CaSR is the cysteine-rich large N-terminal extracellular domain (ECD, approximately 600 amino acids). The region between alanine 116 and proline 136 in the ECD is important for maintaining CaSR in an inactive conformation28 and is associated with the activating mutations or single nucleotide polymorphism (SNPs) identified in the human CaSR gene. The ligands or activators of CaSR include polyvalent cations (eg, $\text{Ca}^{2+}$, $\text{Mg}^{2+}$, $\text{Gd}^{3+}$), polypeptides (eg, amyloid-β peptide), polyamines (eg, spermine, spermidine, putrescine), aminoglycoside antibiotics (eg, neomycin, kanamycin), and amino acids (eg, phenylalanine, tyrosine, tryptophan, glutamate). In addition, there are synthetic CaSR activators, or calcimimetics (eg, NPS-R-568, NPS-R-467), and CaSR antagonists, or calcilytics (eg, NPS 2143), that affect CaSR function.12–14,29–31 The cysteine-rich domain in the ECD also sensitizes the receptor to redox changes and hypoxia/hyperoxia. In Sprague-Dawley rats, treatment with the CaSR activator or the calcimimetic R-568 attenuates aortic wall thickening induced by uremia.32 Our data from this study, however, indicate that the extracellular $\text{Ca}^{2+}$-mediated $[\text{Ca}^{2+}_{\text{cyt}}]$ increase in IPAH-PASMC was potentiated by NPS-R-568, an allosteric agonist of CaSR, and inhibited by NPS 2143, an allosteric antagonist of CaSR. Extracellular application of spermine significantly increased $[\text{Ca}^{2+}_{\text{cyt}}]$ in IPAH-PASMC superfused in $\text{Ca}^{2+}$-containing solution. These data imply that multiple ligands can activate the upregulated CaSR in IPAH-PASMC leading to cell proliferation, contraction and migration via $\text{Ca}^{2+}$ signaling and other signal transduction cascades.

Extracellular $\text{Ca}^{2+}$ binding to CaSR is a highly cooperative process. The $E_{\text{50}}$ for extracellular $\text{Ca}^{2+}$-induced $[\text{Ca}^{2+}_{\text{cyt}}]$ increase in IPAH-PASMC is approximately 1.2 mmol/L (Figure 1D), whereas the $E_{\text{50}}$ has been reported to be 1.7 mmol/L in parathyroid cells,33 1.5 mmol/L in cardiomyocytes,34 and 5.6 mmol/L in bronchial epithelial cells.35 However, in reconstructed systems with CaSR clones isolated from parathyroid glands, the $E_{\text{50}}$ for CaSR activation (or the $\text{Ca}^{2+}$ sensitivity of CaSR) is 3.0 to 3.5 mmol/L.12,13,15,36–38 The lower $E_{\text{50}}$ for $\text{Ca}^{2+}$-induced $[\text{Ca}^{2+}_{\text{cyt}}]$ rise in IPAH-PASMC and native vascular smooth muscle cells (compared with the $E_{\text{50}}$ for the recombinant CaSR) is presumably due to the high degree of cooperativity in the interaction between the upregulated CaSR (eg, in IPAH-PASMC) and ligands. CaSR is always exposed to various coagonists physiologically (eg, $\text{Mg}^{2+}$, polyamines, and...

Figure 5. Overexpression of CaSR in normal PASMC enhances extracellular $\text{Ca}^{2+}$-induced $[\text{Ca}^{2+}_{\text{cyt}}]$ increase and promotes cell proliferation. A and B, Representative records of $[\text{Ca}^{2+}_{\text{cyt}}]$ changes (left) and summarized data (mean±SE) (right) extracellular $\text{Ca}^{2+}$-induced $[\text{Ca}^{2+}_{\text{cyt}}]$ increases in human (A) and rat (B) PASMC transfected with an empty vector (vector, n=12) and the human CaSR cDNA (CaSR, n=8). C, Summarized data (mean±SE) showing the total numbers of normal human PASMC transfected with the vector (solid circles) and CaSR gene (gray circles) after incubation in growth media for 24, 48, 72, 96, and 120 hours. The growth curves for vector control PASMC and IPAH PASMC are significantly different ($P<0.01$, n=3 experiments). **$P<0.01$ versus vector. D, Western blot analysis on CaSR in human PASMC transfected with an empty vector (Vector) or CaSR.
CaSR is widely distributed in the parathyroid glands,\textsuperscript{15} kidney,\textsuperscript{46} bone,\textsuperscript{47} gastrointestinal tract,\textsuperscript{48} skin,\textsuperscript{49} brain,\textsuperscript{50} immune cells,\textsuperscript{51} and heart.\textsuperscript{52} In addition, CaSR is expressed in vascular smooth muscle cells from rat subcutaneous artery,\textsuperscript{52} aorta,\textsuperscript{53} pulmonary artery,\textsuperscript{16,17} gerbil spiral modiolar artery,\textsuperscript{54} human renal artery,\textsuperscript{55} aorta,\textsuperscript{55,56} and internal mammary artery,\textsuperscript{57} as well as in endothelial cells from rat mesenteric artery,\textsuperscript{16,17} human coronary artery,\textsuperscript{58} and human aorta.\textsuperscript{19} Activation of CaSR in vascular smooth muscle cells increases \([Ca^{2+}]_{cyt}\) and induces vasoconstriction\textsuperscript{17,54,56}; therefore, CaSR is involved in regulating myogenic tone, peripheral vascular resistance,\textsuperscript{57} and arterial blood pressure.\textsuperscript{59,60} Recent observations demonstrate that the CaSR in vascular smooth muscle cells contributes to regu-
lating cell proliferation and apoptosis through the MEK1/ERK1/2 and PLC signaling pathways and expression of CaSR is involved in the regulation of mouse lung development. Our study indicated that in normal human PASMC, CaSR protein was expressed at a low level and extracellular application of Ca²⁺/H⁺ (from 0.5–10 mmol/L) failed to cause a significant increase in [Ca²⁺/]cyt (Figure 1D), whereas extracellular application of spermine caused a small increase in [Ca²⁺/]cyt (Figure 3A). These observations imply that CaSR is expressed at very low level in normal human PASMC and is not a major contributor to the regulation of pulmonary vascular tone under physiological conditions.

In patients with IPAH and animals with experimental pulmonary hypertension, CaSR is functionally upregulated in PASMC and thus becomes an important GPCR involved in the initiation and progression of pulmonary vascular remodeling and pulmonary hypertension. Knockdown of CaSR with siRNA in PASMC from IPAH patients not only diminished extracellular Ca²⁺/H⁺-induced increase in [Ca²⁺/]cyt but also inhibited cell proliferation (Figure 4). Overexpression of CaSR in PASMC from normal subjects conferred an extracellular Ca²⁺/H⁺-induced increase in [Ca²⁺/]cyt and enhanced cell proliferation (Figure 5).

These experimental data provide compelling evidence that CaSR is necessary and sufficient for the augmented Ca²⁺/H⁺ signaling and excessive PASMC proliferation in IPAH patients. In this scenario, Ca²⁺ is an extracellular ligand and an intracellular signaling element involved in the development and progression of sustained pulmonary vasoconstriction and vascular remodeling in patients with IPAH. The pathogenic role of upregulated CaSR in pulmonary hypertension is further confirmed by the therapeutic effect of CaSR antagonists on experimental pulmonary hypertension in rats injected with MCT and in mice exposed to chronic hypoxia.

The gain-of-function (or activating) mutations or SNP in the human CaSR gene causes autosomal dominant hypocalcemia and Bartter syndrome type V. CaSR antagonists (calcilytics), that is, negative allosteric modulators that indirectly stimulate parathyroid hormone secretion through a decrease in CaSR activity, are potential drug candidates for the treatment of osteoporosis and other bone metabolism diseases. Using 2 well-established animal models of pulmonary hypertension (MCT-injected rats and chronic hypoxic mice), we found that increased RVSP and pulmonary vascular medial hypertrophy, as well as right ventricular...
hypertrophy [determined by the Fulton index, RV/(LV+S)] were associated with upregulated CaSR expression and enhanced extracellular \( \text{Ca}^{2+} \)-induced \( \text{Ca}^{2+} \) rise (and basal \( \text{Ca}^{2+} \)) in PASMC (Figures 6 through 8). Intrapерitoneal injection of the CaSR antagonist NPS 2143 (4.5 mg/kg once a day) had little effect on the pulmonary hemodynamics and the Fulton index in control rats or normoxic mice, but significantly decreased RVSP, RV/(LV+S) ratio and small pulmonary vascular wall thickening in rats with MCT-PH (Figure 7) and mice with HPH (Figure 8). These results strongly suggest that CaSR is involved in the development of experimental pulmonary hypertension and a potential target for developing therapeutic approaches for pulmonary arterial hypertension.

In conclusion, upregulated expression of CaSR in PASMC and augmented function of CaSR through intracellular \( \text{Ca}^{2+} \) signaling (and other signal transduction cascades) are new pathogenic mechanisms involved in the initiation and progression of pulmonary vascular remodeling in patients with pulmonary arterial hypertension. Pharmacological blockade of CaSR in the pulmonary vasculature by synthetic calcilytics and downregulation of CaSR by siRNA (and/or specific microRNA) may be a novel therapeutic approach for IPAH patients who do not respond to the conventional drug therapy.

Figure 8. Upregulation of CaSR in PASMC from HPH mice and blockade of CaSR by NPS 2143 inhibits the development of HPH in mice. **A** and **B**, Real-time RT-PCR (**A**) and Western blot (**B**) analyses on CaSR in PA and lung tissues isolated from normoxic (Nor) and hypoxic (Hyp) mice. **C**, Representative record (left) and summarized data (mean±SE, right) showing the extracellular \( \text{Ca}^{2+} \)-induced increase in \( [\text{Ca}^{2+}]_{\text{cyt}} \) in PASMC isolated from normoxic and hypoxic mice. \( *P<0.01, **P<0.001 \) versus Nor. **D** and **E**, Representative record of right ventricular pressure (RVP, **D**) and summarized data (mean±SE) showing the peak value of right ventricular systolic pressure (RVSP, **E**) in normoxic (Nor, \( n=6 \)) and hypoxic (Hyp, \( n=6 \)) mice that are treated with vehicle or NPS 2143 (+NPS, 1 mg/kg once a day). **F**, Averaged Fulton index \( [\text{RV}/(\text{LV}+\text{S})] \), mean±SE in normoxic and hypoxic mice treated with or without NPS 2143. \( P<0.05 \) versus Hyp along. **G**, Representative hematoxylin and eosin images of small pulmonary arteries showing that the medial thickness is significantly increased in Hyp mice and the hypoxia-induced medial hypertrophy is inhibited by NPS 2143. **H**, Representative angiography of the whole lung (**top**) and enlarged area of the whole lung (**bottom**, indicated by the box in the **top**) in normoxic and hypoxic mice treated with vehicle or NPS (+NPS). The vertical bars denote 2 mm (**top**) and 0.5 mm (**bottom**). **I**, Summarized data (mean±SE) showing the number of branches, the number of junctions, and the total length of vascular segments per square millimeter. \( **P<0.01 \) versus other bars.

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Disclosures

None.
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Novelty and Significance

What Is Known?

- Pulmonary vascular remodeling and sustained pulmonary vasconstriction contribute to the development of idiopathic pulmonary arterial hypertension (IPAH).
- Increased cytosolic free Ca\(^{2+}\) concentration ([Ca\(^{2+}\)]\(_{cyt}\)) stimulates pulmonary arterial smooth muscle (PASM) proliferation leading to pulmonary vascular remodeling.
- Ca\(^{2+}\)-sensing receptor (CaSR) is a G-protein-coupled receptor important for multiple cellular processes of the parathyroid glands such as proliferation, differentiation, and apoptosis.

What New Information Does This Article Contribute?

- CaSR is functionally upregulated in IPAH-PASM contributing to enhanced Ca\(^{2+}\) signaling and excessive cell proliferation in IPAH patients.
- Blockade of the CaSR with an antagonist inhibits the development of pulmonary hypertension in animal models.
- Targeting the CaSR may be a novel therapeutic approach for IPAH patients.

Idiopathic pulmonary arterial hypertension is a rare, progressive and fatal disease that predominantly affects women. The pathogenic mechanisms involved in the pulmonary vascular abnormalities (eg, arterial remodeling and sustained vasocostriction) in IPAH patients remain unclear. An increase in cytosolic Ca\(^{2+}\) concentration ([Ca\(^{2+}\)]\(_{cyt}\)) in PASMC is a major trigger for pulmonary vasocostriction and an important stimulus for PASMC migration and proliferation (which subsequently cause pulmonary vascular wall thickening leading to the increase in pulmonary vascular resistance). In this study, we report that a unique G-protein-coupled receptor (GPCR), CaSR, is significantly upregulated in PASMC isolated from patients with IPAH and animals with experimental pulmonary hypertension. The upregulated CaSR is necessary for the enhanced extracellular Ca\(^{2+}\)-induced increase in [Ca\(^{2+}\)]\(_{cyt}\) and the augmented cell proliferation in IPAH-PASM. Pharmacological blockade of CaSR with a calcilytic, NPS 2143, markedly inhibits the extracellular Ca\(^{2+}\) entry via TRPC-encoded receptor-operated channels in human aortic smooth muscle cells. Am J Physiol Cardiol. 2001;288:F946–F955.


Enhanced Ca$^{2+}$-Sensing Receptor Function in Idiopathic Pulmonary Arterial Hypertension

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Online Supplementary METHODS

Preparation of human and animal PASMC. Human PASMC were isolated from explanted lung tissues of normal control subjects (2 unsuitable organ donors and 2 COPD patients without pulmonary hypertension) and patients with IPAH (3 patients diagnosed on the basis of NIH IPAH Registry with an averaged mean PAP of 56±5 mmHg).1, 2 In addition, PASMC were isolated and prepared from endarterectomized pulmonary arterial tissues of patients with chronic thromboembolic pulmonary hypertension (CTEPH, 4 patients with an averaged mean PAP of 39±5 mmHg).3 Approval to use the human lung tissues and cells was granted by the UIC Institutional Review Board. Human PASMC were cultured in Medium 199 supplemented with 10% fetal bovine serum (Invitrogen, Grand Island, NY), 100 U/ml penicillin plus 100 µg/ml streptomycin, 50 µg/ml D-valine (Sigma-Aldrich, St. Louis, MO), and 20 µg/ml endothelial cell growth supplement (BD Biosciences, Franklin Lakes, NJ) at 37ºC. The cells at passages 5 to 8 were used for the experiments. In some experiments, we also used freshly-dissociated PASMC from rats (by a modified protocol based on the methods published previously).4 In the modified protocol, cell suspensions were plated onto cover slips for a short time (2-3 hrs) before experiments. We also used PASMC from mice by a modified method previously published by Marshall et al.5

[Ca²⁺]cyt measurement. The [Ca²⁺]cyt measurement was performed as described previously6. In brief, cultured PASMC on cover slips were placed in a recording chamber on the stage of an invert fluorescent microscope (Eclipse Ti-E; Nikon, Tokyo, Japan) equipped with an objective lens (S Plan Fluor 20×0.45 ELWD; Nikon), an EM-CCD camera (Evolve; Photometrics, Tucson, AZ), and NIS Elements 3.2 software (Nikon). The cells were loaded with 4 µM fura-2 acetyoxymethyl ester (fura-2/AM; Invitrogen/Molecular Probes, Eugene, OR) for 60 min at room temperature (25°C). The HEPES-buffered external solution contained an ionic composition of 137 mM NaCl, 5.9 mM KCl, 2.2 mM CaCl₂, 1.2 mM MgCl₂, 14 mM glucose, and 10 mM HEPES (pH 7.4 with NaOH). In the Ca²⁺-free solution, 2.2 mM CaCl₂ was replaced by equimolar MgCl₂ and 1 mM EGTA was added to chelate the residual Ca²⁺. The fura-2-loaded cells in the recording chamber were continuously perfused with HEPES-buffered solution at 32°C for 30 min to wash out extracellular fura-2/AM and allow sufficient time for the intracellular esterase to cleave acetyoxymethyl ester from fura-2 so it can stay in the cytosol. The cells were then excited with 340-nm and 380-nm wavelength (D340×v2 and D380×v2 filters, respectively; Chroma Technology, Bellows Falls, VT) by a xenon arc lamp (Lambda LS; Sutter Instrument, Novato, CA) and an optical filter changer (Lambda 10-B; Sutter Instrument). Fura-2 fluorescence (or emission of fura-2) from a region of interest (5×5 µm) of PASMC, as well as background fluorescence, was collected through a dichroic mirror (400DCLP; Chroma Technology) and a wide band emission filter (D510/80m; Chroma Technology). The fluorescence signals emitted from the region of interest in cells were monitored and recorded continuously on a Nikon digital imaging fluorescence microscope system and recorded in a PC. The ratio (R) of 340-nm and 380-nm fluorescence intensities (F₃⁴⁰/F₃₈⁰), recorded every 2 seconds, was then used to calculate [Ca²⁺]cyt using the following equation: [Ca²⁺]cyt = K_d × (S_f₂/S_b₂) × (R-R_min) / (R_max-R), where S_f₂ and S_b₂ are the emission fluorescence values at 380-nm excitation in the presence of EGTA and triton X-100, respectively; K_d (225 nM) is the dissociation constant of the Ca²⁺-fura-2 complex; and R_max and R_min were calculated according to the standard protocol.7, 8
Pharmacological Experiments in Rats with MCT-PH. Adult male Sprague-Dawley rats (190-200 g in body weight; Charles River Laboratories, Wilmington, MA) were randomly divided into two groups: 1) normal control group which was injected subcutaneously of vehicle (DMSO); 2) MCT-PH group which was given a subcutaneous injection of MCT (60 mg/kg, Sigma-Aldrich) to induce pulmonary hypertension. The normal control group was further divided into two subgroups (n=6 for each): one subgroup received the intraperitoneal injection of NPS2143 (Tocris, solubilized into DMSO) at a dose of 4.5 mg/kg per day (from day 1 to day 10) and the other subgroup was injected intraperitoneally with the vehicle (DMSO) (from day 1 to day 10). The MCT-PH group was also further divided into two subgroups (n=6 for each): one subgroup received the intraperitoneal injection of NPS2143 at a dose of 4.5 mg/kg per day (from day 1 to day 10) and the other subgroup was injected intraperitoneally with the vehicle (DMSO) (from day 1 to day 10). Two weeks (14 days) later, the rats were anesthetized with ketamine (100 mg/kg, i.p.) and xylazine (26 mg/kg, i.p.) and then right ventricular pressure (RVP) was measured by a pressure-transducer catheter (Millar Instruments: SPF869 and SPF1030) inserted into the right ventricle through the right jugular vein. The hemodynamic data were recorded using an MPVS Ultra® data acquisition system and analyzed with an AD Instruments Lab Chart Pro7.0 software. The protocol used for the rat experiments was approved by the Animal Care Committee of the University of Illinois at Chicago.

Pharmacological Experiments in Mice with HPH. Male C57BL/6N mice (18-22 g in body weight and 6 weeks of age, Charles River Laboratories, Wilmington, MA) were randomly divided into two groups: normoxic control group and hypoxic group which were placed into a normobaric hypoxic chamber (10% O2) for 4 weeks to establish pulmonary hypertension. The normoxic group was further divided into two subgroups (n=6 for each): one subgroup received the intraperitoneal injection of NPS2143 at a dose of 1 mg/kg per day (from day 1 to day 22) and the other subgroup was injected intraperitoneally with the vehicle (DMSO) (from day 1 to day 22). The hypoxic group was also further divided into two subgroups (n=6 for each): one subgroup received the intraperitoneal injection of NPS2143 at a dose of 1 mg/kg per day (from day 1 to day 22) and the other subgroup was injected intraperitoneally with the vehicle (DMSO) (from day 1 to day 22). Four weeks (28 days) later, the mice were anesthetized with ketamine/xylazine (i.p.) and then right ventricular pressure (RVP) was measured by the right heart catheterization similar to that protocol for rats. The hemodynamic data were recorded using the MPVS Ultra® data acquisition system and analyzed with the AD Instruments Lab Chart Pro7.0 software. The protocol used for the mouse experiments was approved by the Animal Care Committee of the University of Illinois at Chicago.

Assessment of Pulmonary Artery Thickness. The left lung lobes (from rats or mice) were fixed in a 3% paraformaldehyde solution and the lobes were dissected in the middle for paraffin embedding. Sectioning at 3 µm was performed for all paraffin-embedded tissue blocks. H&E staining was performed according to common histopathological procedures. Histological analysis was performed in a blinded way: the person who dissected the lobes coded the tissue blocks with numbers and gave to another person to analyze the pulmonary vascular wall thickness. Microscopic images were analyzed using a computerized morphometric system (Aperio Imagescope v11.1.2.752 software) to assess the pulmonary arterial wall thickness. Pulmonary arteries were categorized according to their external diameter: category 1 are the arteries with an
external diameter between 25 and 50 µm; category II are the arteries with an external diameter between 51 and 100 µm; and category III are the arteries with an external diameter greater than 100 µm. Thickness of an artery was determined by the average values obtained in multiple areas of the artery.

**Angiography in Rats and Mice.** Rats and mice were anesthetized to dissect out the whole lungs. A PE10 (BD) tube was inserted into the main pulmonary artery and superfused with warm PBS solution (36-38°C) via a syringe pump (SyringePump.com NE-300) at a rate of 0.25 ml/min for 4 min. Then MICROFIL® Silicone Rubber Injection Compounds (Flow-Tech, Inc., Carver, MA), a liquid silicon polymer, was infused into the main pulmonary artery at 0.25 ml/min for 4 min using the syringe infusion pump. The MICROFIL-infused lung tissues were stored at 4°C for 12 hrs before the lungs were sequentially bathed in ethanol at gradually increased concentrations. The tissues were then placed in methyl-salicylate and photographed with a digital camera (MD600E, Amscope, USA) through a dissecting microscope (WILD M651, Leica, Switzerland). The ImageJ software was used to evaluate the number of arterial branches, the number of arterial junctions and the total length of arterial segments in a given area (usually a square mm area, i.e., 1 mm²). We selected the areas (in 1 mm² unit) of the lung vascular images with Photoshop CS software, and made binary images using ImageJ software. The pictures were then skeletonized for analyzing the vessel branches, junctions and total length. These data were normalized by the area selected in each lung.

**Immunofluorescence Staining of Human and Rat Lung Sections.** Immunohistochemistry for CaSR and SM-α-actin was performed on formalin-fixed, paraffin-embedded (human, rat and mouse) lung tissue sections. Briefly, sections were first deparaffinized in xylene, rehydrated in graded ethanol solutions, and rinsed in deionized water. Then, sections were incubated (for 30 min) in a Tris-EDTA Buffer (10 mM Tris Base, 1 mM EDTA solution, with 0.05% Tween20; pH 9.0) for heat-induced epitope retrieval. After washing in PBS, the sections were blocked by incubating with 5% bovine serum albumin (Sigma) for 1 hr. The slides were rinsed in PBS and incubated first with a CaSR polyclonal antibody (rabbit anti-mouse IgG, Abcam) at a dilution of 1:50 for 1 day at 4°C. Then the slides were incubated with a monkey anti-rabbit IgG antibody conjugated with Alexa488 (Invitrogen) as the secondary antibody for 1 hr and a monoclonal antibody against the SM-α-actin clone 1A4 (Cy3 conjugate) (Purified Mouse Immunoglobulin) at a dilution of 1:200. After washing in PBS, sections were mounted in Vectashield hard-set mounting medium with DAPI (Vector Laboratories) and viewed under an Axiovert 200M fluorescence microscope. The expression of CaSR was quantified by grey value using the of Image J software.
Online Figure I. Upregulated CaSR in pulmonary arteries from IPAH patients.
A. Immunohistochemistry data showing CaSR expression level (green fluorescence intensity) in pulmonary arteries of normal subjects and IPAH patients. The lung tissue sections were stained with antibodies against CaSR (green) and smooth muscle α-actin (SM-α-Actin, red) and with DAPI (blue). The overlay images are shown in the bottom. B. Summarized data (means±SE, n=3 for each group) showing CaSR expression level (green fluorescence intensity) in pulmonary arteries of normal subjects (Norm) and IPAH patients. **P<0.01 vs. Normal.
Online Figure II. Extracellular Ca\(^{2+}\)-induced increase \([\text{Ca}^{2+}]_{\text{cyt}}\) in IPAH-PASMCs is not due to Ca\(^{2+}\) leakage.

A. Representative traces showing change in resting \([\text{Ca}^{2+}]_{\text{cyt}}\) before and during application of Ca\(^{2+}\)-free solution in normal and IPAH PASMC. Summarized data (right panel, n=96-370 cells) showing the resting \([\text{Ca}^{2+}]_{\text{cyt}}\) in normal and IPAH PASMC superfused with 2.2 mM Ca\(^{2+}\)-containing solution (black bars) or Ca\(^{2+}\)-free solution (grey bars). **P<0.001 vs. normal PASMC.  

B. Representative images (left panels) of trypan (TB) blue staining (0.4%, 1 min) before (-) and during (+) treatment with 10 \(\mu\)M ionomycin for 10 min in normal (upper panels) and IPAH (lower panels) PASMC. Summarized data (right panel) showing no correlation between the extracellular Ca\(^{2+}\)-induced increase in \([\text{Ca}^{2+}]_{\text{cyt}}\) and the Ca\(^{2+}\) leakage through the plasma membrane. 

C. Representative images showing \([\text{Ca}^{2+}]_{\text{cyt}}\) (or Fura-2 fluorescence intensity) in normal (left panels) and IPAH (right panels) PASMC in the absence and presence of 10 \(\mu\)M CPA, an inhibitor of Ca\(^{2+}\)-ATPase in the SR. The cells were loaded with the membrane-permeable fura-2/AM (4 \(\mu\)M, upper panels) or the membrane-impermeable fura-2 (4 and 40 \(\mu\)M, middle and lower panels). Data were obtained from 21 to 64 cells.
Online Figure III. Inhibition of PLC and IP3R attenuates extracellular Ca\(^{2+}\)-induced [Ca\(^{2+}\)]\(_{\text{cyt}}\) increases in IPAH-PASMC

Representative records of [Ca\(^{2+}\)]\(_{\text{cyt}}\) changes (left panels), pseudo images (middle panels) and summarized data (means±SE, right panels) showing extracellular Ca\(^{2+}\)-induced increase in [Ca\(^{2+}\)]\(_{\text{cyt}}\) before and during treatment with 1 μM U73122 (a PLC inhibitor; n=57, A), 1 μM U73343 (an inactive form of U73122; n=45, B), 3 μM xestospongin C (an IP3R blocker; n=34, C), 10 μM diltiazem (a VDCC blocker; n=46, D), and KB-R7943 (an Na\(^+\)/Ca\(^{2+}\) exchanger inhibitor; n=22, E) in IPAH-PASMC. **P<0.01 vs. control.
Online Supplementary REFERENCES


