Acta Pharmacol Sin 2009 Jan; 30 (1): 78–89

Original Article

Hydrogen peroxide mobilizes Ca^{2+} through two distinct mechanisms in rat hepatocytes

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Aim: Hydrogen peroxide (H_2O_2) is produced during liver transplantation. Ischemia/reperfusion induces oxidation and causes intracellular Ca^{2+} overload, which harms liver cells. Our goal was to determine the precise mechanisms of these processes.

Methods: Hepatocytes were extracted from rats. Intracellular Ca^{2+} concentrations ($[Ca^{2+}]_i$), inner mitochondrial membrane potentials and NAD(P)H levels were measured using fluorescence imaging. Phospholipase C (PLC) activity was detected using exogenous PIP_2. ATP concentrations were measured using the luciferin-luciferase method. Patch-clamp recordings were performed to evaluate membrane currents.

Results: H_2O_2 increased intracellular Ca^{2+} concentrations ($[Ca^{2+}]_i$) across two kinetic phases. A low concentration (400 μmol/L) of H_2O_2 induced a sustained elevation of $[Ca^{2+}]_i$ that was reversed by removing extracellular Ca^{2+}. H_2O_2 increased membrane currents consistent with intracellular ATP concentrations. The non-selective ATP-sensitive cation channel blocker amiloride inhibited H_2O_2-induced membrane current increases and $[Ca^{2+}]_i$ elevation. A high concentration (1 mmol/L) of H_2O_2 induced an additional transient elevation of $[Ca^{2+}]_i$, which was abolished by the specific PLC blocker U73122 but was not eliminated by removal of extracellular Ca^{2+}. PLC activity was increased by 1 mmol/L H_2O_2 but not by 400 μmol/L H_2O_2.

Conclusions: H_2O_2 mobilizes Ca^{2+} through two distinct mechanisms. In one, 400 μmol/L H_2O_2-induced sustained $[Ca^{2+}]_i$ elevation is mediated via a Ca^{2+} influx mechanism, under which H_2O_2 impairs mitochondrial function via oxidative stress, reduces intracellular ATP production, and in turn opens ATP-sensitive, non-specific cation channels, leading to Ca^{2+} influx. In contrast, 1 mmol/L H_2O_2-induced transient elevation of $[Ca^{2+}]_i$ is mediated via activation of the PLC signaling pathway and subsequently, by mobilization of Ca^{2+} from intracellular Ca^{2+} stores.

Keywords: hydrogen peroxide; Ca^{2+} dynamics; non-selective cation channel; intracellular ATP; phospholipase C; hepatocyte; patch-clamp
Acta Pharmacologica Sinica (2009) 30: 78–89; doi: 10.1038/aps.2008.4; published online 15th December 2008

Introduction

The development of ischemia-reperfusion injury is a major risk factor associated with liver transplantation[1–4] and coronary bypass surgery[5]. In the liver, one of the mechanisms causing ischemia-reperfusion injury seems to be oxidative stress to liver cells (hepatocytes), which occurs when pro-oxidants overwhelm cellular anti-oxidant defense mechanisms[3, 6]. Oxygen that is rapidly supplied to cells immediately following reperfusion of the liver is converted to oxygen radicals, including superoxide anions, hydroxyl radicals and hydrogen peroxide (H_2O_2). Subsequent oxidation by these radicals of critical proteins, DNA and lipids, and oxidation-related mitochondrial dysfunction, causes lethal damage to cells[2, 7]. Reactive oxygen and nitrogen species also are generated in the mitochondria, which then exert a toxic effect on mitochondrial function.

In oxidation-related cellular damage, an increase in intracellular Ca^{2+} concentration ($[Ca^{2+}]_i$), which is likely produced by oxygen radicals, is known to accelerate cellular

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Received 2008-07-24 Accepted 2008-09-18

damage[8, 9]. In fact, excess Ca^{2+} in the cell causes cellular damage by activating Ca^{2+}-dependent proteases[10], although cellular Ca^{2+} overload is unlikely to be the sole mechanism mediating cell death[11].

Various mechanisms by which oxygen radicals cause an elevation of $[Ca^{2+}]_i$ have been described in different types of cells. For instance, oxygen radicals induce Ca^{2+} release from intracellular Ca^{2+} stores in pancreatic acinar cells[12] and neutrophils[13]. In mesangial cells[14], oxygen radicals induce Ca^{2+} influx from the extracellular space. In cardiac myocytes[15], an inhibition of cellular Ca^{2+} extrusion or uptake seems to be responsible for the elevation of $[Ca^{2+}]_i$ induced by oxygen radicals. In addition, oxygen radicals have also been shown to be responsible for Ca^{2+}-dependent mitochondrial dysfunction[16] and Ca^{2+} entry[17]. The Ca^{2+} influx resulting from H_2O_2 seems to involve the Fas protein[17]. However, the precise mechanisms of H_2O_2-induced $[Ca^{2+}]_i$ elevation have remained elusive, and more information about the mechanisms by which H_2O_2 affects the Ca^{2+} dynamics of hepatocytes is needed in order to develop strategies for preventing reperfusion-related hepatic injury.

In the present study, we first examined the effect of H_2O_2 on $[Ca^{2+}]_i$ in freshly dissociated rat hepatocytes. After confirming that H_2O_2 elevates $[Ca^{2+}]_i$ according to two dynamic pathways, we investigated the underlying mechanisms using multiple experimental approaches. Our techniques included patch-clamp recordings to monitor membrane currents, fluorescence imaging to examine $[Ca^{2+}]_i$ and mitochondrial function, and biochemical measurements to determine levels of PLC activity and intracellular ATP concentrations.

Materials and methods

This study was carried out in accordance with the Guidelines for Animal Experimentation, Hirosaki University, and Guiding Principles for the Care and Use of Animals in the Field of Physiological Sciences, as approved by the Council of the Physiological Society of Japan.

Hepatocyte dissociation Isolated hepatocytes were prepared using a method used in a previous study[18]. Briefly, adult male rats (Wistar) were anesthetized with diethyl ether, and a perfusion catheter was inserted into the portal vein after the hepatic vein had been cut open. The perfusion solution (pH 7.4) contained (all units are mmol/L): 137 NaCl, 5.4 KCl, 0.5 NaH_2PO_4, 0.4 Na_2HPO_4, 2.0 $CaCl_2$, 4.2 $NaHCO_3$, 5 glucose and 10 HEPES. Perfusion was carried out at a rate of 20 mL/min for the first 2 min using the perfusion solution and then for another 8 min using the perfusion solution with collagenase (Type I, Wako Pure Chemical, Japan). The liver was then excised and diced into small pieces (approximately 1 mm^3). The specimens were subsequently incubated in the collagenase-containing solution at 37 °C for 15 min and aerated with 100% O_2. Afterwards, the specimens were filtered through gauze and centrifuged. In certain cases, a piece of liver tissue was removed without perfusion, diced and incubated in the collagenase-containing solution for 17 min.

Measurement of $[Ca^{2+}]_i$ The $[Ca^{2+}]_i$ of hepatocytes was estimated using fluorescence imaging. Cells were plated onto glass coverslips coated with poly-*D*-lysine, and incubated in Williams E medium containing 10% fetal calf serum, 0.02 U/mL insulin, 10 U/mL penicillin, 10 mg/mL streptomycin, 0.05 mg/mL gentamycin, 4 mg/mL dexamethasone and 2 mmol/L glutamine. Following incubation for 2 h, the coverslips and cells were transferred into a chamber that contained a HEPES buffer extracellular solution plus 1 mmol/L Fura-2/AM (Dojin Chem, Japan) and were loaded for 30 min. Images were captured using an inverted microscope (Axiovert 135, Zeiss, Germany) with 40X Plan-Neofluar objectives and a silicon intensifier target camera. Images were recorded on a fluorescence-imaging system (Argus 50/CA, Hamamatsu Photonics, Japan). To record Fura-2 fluorescence, excitation wavelengths selected from a xenon light source were 340 and 380 nm, and the emission wavelength was 510 nm. $[Ca^{2+}]_i$ was calculated using the following formula[16]: $[Ca^{2+}]_i=K_d \beta (R-R_{min})/(R_{max}-R)$, where R is the ratio of the fluorescence intensities at the two wavelengths (F_{340}/F_{380}), K_d is the dissociation constant of Fura-2 binding to Ca^{2+}, and β is the maximum fluorescence at 380 nm ($F_{380\ max}$) divided by the minimal fluorescence at 380 nm ($F_{380\ min}$). The values R_{max}, R_{min}, $F_{380\ max}$, and $F_{380\ min}$ were obtained by calibration using ionomycin (Calbiochem, La Jolla, CA) and EGTA. In our system, numerical values of the coefficients were as follows: K_d=224 nmol/L, R_{min}=0.33, R_{max}=8.56, and β=12.52. All microfluorimetric experiments were carried out at room temperature (22±2 °C).

Measurement of PLC activity The PLC activity of islets was examined using a protocol utilized in previous reports[19, 20]. Liver tissues were homogenized in an ice-cold Tris-sucrose buffer (270 mmol/L sucrose buffered with 50 mmol/L Tris-HCl; pH 7.4) using a Teflon-glass homogenizer. The homogenate was centrifuged at 500×*g* for 10 min, and the pellet was discarded. The supernatant was centrifuged at 40 000×*g* for 15 min, and the pellet was washed two more times at 40 000×*g*, once in 50 mmol/L Tris-HCl buffer (pH 7.7) containing 5 mmol/L EDTA and once in EDTA-free Tris-HCl. The resulting pellets were stored at –80 °C. The protein content of the membrane fractions was

measured spectrophotometrically. The pellet containing the membrane fractions was divided into four groups, and PLC activity was measured using exogenous PIP_2. The following components were added to the PLC assay: 50 mmol/L HEPES (pH 7.0), 0.1 mmol/L $CaCl_2$, 9 mmol/L sodium cholate, [^{3}H]-PIP_2 (40,000 cpm) and membrane protein (10–40 μg/assay) in a final volume of 200 μL. To the four different groups, the following materials were further added 10 min before initiation of incubation: vehicle only, 10 μmol/L H_2O_2, 100 μmol/L H_2O_2 or 1 mmol/L H_2O_2. The reaction mixture was incubated for 2 min at 37 ºC. The reaction was stopped with 1 mL chloroform/methanol/concentrated HCl (100:100:0.6) followed by 0.3 mL of 1 mol/L HCl containing 5 mmol/L EGTA. After extraction, a 400-μL portion of the aqueous phase was removed for liquid scintillation counting. For determination of inositol trisphosphate (IP_3) in the aqueous phase, 400 μL of aqueous phase was neutralized with 133 mL of 1 mol/L NaOH, and after 15 min on ice, the precipitated perchloric acid extract was pelleted by centrifugation. One-milliliter aliquots of the neutralized supernatants were diluted with 9 mL of 5 mmol/L sodium tetraborate and applied onto pre-washed 0.8-mL columns packed with AG1X8 (200–400 mesh) formate anion exchange resin. The columns were rinsed twice with 12 mL of a 60 mmol/L sodium formate-5 mmol/L tetraborate solution, and the inositol phosphates were eluted sequentially with 1 mol/L NH_4 formate in 0.1 mol/L formic acid and counted using liquid scintillation.

Measurement of inner mitochondrial membrane potential and NAD(P)H To measure changes in inner mitochondrial membrane potentials, dissociated hepatocytes were loaded with 10 mg/mL rhodamine 123 (Rh123, Sigma) for 10 min. The Rh123 fluorescence was excited at a wavelength of 490 nm and filtered at 510 nm[21]. To further examine mitochondrial function, cellular NAD(P)H intensity (emission: 510 nm) was also measured[22].

Measurement of ATP concentrations in hepatocytes The levels of ATP in hepatocytes were measured using the luciferin-luciferase method[23]. Assay kits (FL-ASC) were purchased from Sigma. For the ATP assay, dissociated cells were suspended at a density of 1×10^5 cells/mL in the Na-HEPES buffer. Following application of H_2O_2, the cell samples were transferred to a reaction tube and the emission was immediately measured using a luminescence reader (BLR-301, Aloka, Japan). The bioluminescence, produced by the luciferin-luciferase reaction, was amplified and output in terms of count rate (cpm) after conversion to pulse signals.

Patch-clamp recordings Dissociated rat hepatocytes were kept in a 35-mm Petri dish, and the dish was placed on the stage of an inverted microscope (IMT-2, Olympus, Tokyo, Japan). The membrane currents in response to clamped voltage stimulations were measured using a patch-clamp amplifier (EPC-7, List Electronic, Darmstadt, Germany). The whole-cell configuration was established by two methods: the amphotericin B-perforation method and the conventional standard method. The inside-out patch was also used to measure the conductance of the patch membrane. The resistance of the electrodes, when filled with the pipette solution, ranged from 2 to 4 MΩ. Voltage stimulations were applied in two ways: 10 mV increasing and decreasing step pulses from the holding potential of -20 mV and ramp pulses from -90 to 80 mV using a voltage stimulator (SET-2100, Nihon Kohden, Tokyo, Japan). All electrophysiological experiments were carried out at room temperature.

Solutions and drugs The standard extracellular solution (pH 7.3) for measurement of $[Ca^{2+}]_i$ and electrophysiological studies contained (in mmol/L): 135 NaCl, 5.6 KCl, 1.2 $MgCl_2$, 1 $CaCl_2$, 5.5 glucose and 10 HEPES. The pipette solution (pH 7.2) used for recording whole-cell membrane currents using perforated patches contained (in mmol/L): 100 K-gluconate, 35 KCl, 0.5 EGTA, 10 HEPES, 5.5 glucose, and 240 μg/mL amphotericin B (Sigma). To obtain whole-cell recordings using the conventional method, amphotericin B was removed from the pipette solution described above and 5 mmol/L ATP was added. For inside-out patch recordings, the pipette solution contained (in mmol/L): 135 NaCl, 5.6 KCl, 1.2 $MgCl_2$, 1 $CaCl_2$, 5.5 glucose, 0.5 EGTA and 10 HEPES. The bath solution contained (in mmol/L): 100 K-gluconate, 35 KCl, 1.2 $MgCl_2$, 0.5 EGTA, 10 HEPES, 5.5 glucose and 1 ATP. H_2O_2 was purchased from Wako Chem, Japan, and was dissolved daily in the extracellular solution. ATP, amiloride, ouabain, melatonin and U73122 were purchased from Sigma.

Statistics Data are expressed as means±SD. The statistical significance of the average values was evaluated using the paired or non-paired Student's *t*-test. ANOVA was also used. A value of $P<0.05$ was considered to be significant.

Results

H_2O_2 increased $[Ca^{2+}]_i$ consistent with two kinetic patterns in rat hepatocytes In the presence of extracellular Ca^{2+} (1 mmol/L), H_2O_2 at concentrations below 50 μmol/L showed little effect on $[Ca^{2+}]_i$ in acutely dissociated rat hepatocytes (Figure 1A). At 100 μmol/L, H_2O_2 initiated a transient small drop and then gradually increased $[Ca^{2+}]_i$ (Figure 1B). At 400 μmol/L, H_2O_2 induced a marked elevation of $[Ca^{2+}]_i$ following a transient drop (Figure 1C).

Interestingly, a further increase in H_2O_2 concentration to 1 mmol/L induced a biphasic elevation of $[Ca^{2+}]_i$, including an initial transient elevation followed by a sustained elevation (Figure 1D). These results indicate that H_2O_2 elevates $[Ca^{2+}]_i$ in a concentration-dependent manner and suggest that these two dynamic phases of $[Ca^{2+}]_i$ elevation elicited by different concentrations of H_2O_2 may be mediated through different mechanisms.

Effects of extracellular Ca^{2+} on H_2O_2-induced biphasic elevation of $[Ca^{2+}]_i$ Initial experiments were designed to identify the possible sources of the elevation of $[Ca^{2+}]_i$ induced by H_2O_2. Extracellular Ca^{2+} was artificially removed from the external solution by perfusion of the cell with a Ca^{2+}-free (plus 1 mmol/L EGTA) external solution. Under external Ca^{2+}-free conditions, 400 μmol/L H_2O_2 failed to elevate $[Ca^{2+}]_i$, but after replacing extracellular Ca^{2+} (1 mmol/L), H_2O_2 elevated $[Ca^{2+}]_i$ (Figure 2A). Under the same Ca^{2+}-free conditions, 1 mmol/L H_2O_2 induced only a transient elevation of $[Ca^{2+}]_i$ (Figure 2B). These results suggest that 400 μmol/L H_2O_2 induces a sustained $[Ca^{2+}]_i$ elevation that is dependent on extracellular Ca^{2+}, but that 1 mmol/L H_2O_2-induced transient elevation of $[Ca^{2+}]_i$ is independent of extracellular Ca^{2+}.

Effects of H_2O_2 on membrane currents of hepatocytes Figure 2 clearly demonstrates that low concentrations (400 μmol/L) of H_2O_2 induce a sustained increase of $[Ca^{2+}]_i$ that is dependent on an influx of extracellular Ca^{2+} into the cell. A key question concerns which Ca^{2+}-permeable channels and/or pathways mediate H_2O_2-induced Ca^{2+} influx? To address this question, we measured membrane currents using patch-clamp recordings and tested the effects of H_2O_2 on membrane currents of rat hepatocytes. Under perforated (amphotericin B) patch-clamp recording conditions in current-clamp mode, the resting membrane potential of rat hepatocytes was between -4 and -15 mV (n=30), and the single-cell capacitance of hepatocytes was 9–11 pF (n=30). In voltage-clamp mode, whole-cell membrane currents induced by voltage-step pulses were nearly instantaneous in their onset, and current-voltage (I-V) relationships showed a slight inward rectification (Figure 3Aa, c). Bath-applied 400 μmol/L H_2O_2 increased voltage-step pulse-induced membrane currents (Figure 3Ab, c). The two curves obtained from I-V relationships in the presence or absence of H_2O_2 crossed each other near the original membrane potential (Figure 3Ac). When conventional whole-cell patch-clamp recordings were performed (with 5 mmol/L ATP in the pipette solution), 400 μmol/L H_2O_2 failed to increase voltage-step pulse-induced membrane currents (Figure 3Bb, c), suggesting that H_2O_2 (400 μmol/L) increased voltage-step pulse-induced membrane currents likely via a reduction of intracellular ATP.

ATP-sensitive non-specific cation channels in rat hepatocytes The results shown in Figure 3 suggest that H_2O_2-induced enhancement of membrane current is dependent on intracellular substances, likely ATP. To test this hypothesis,

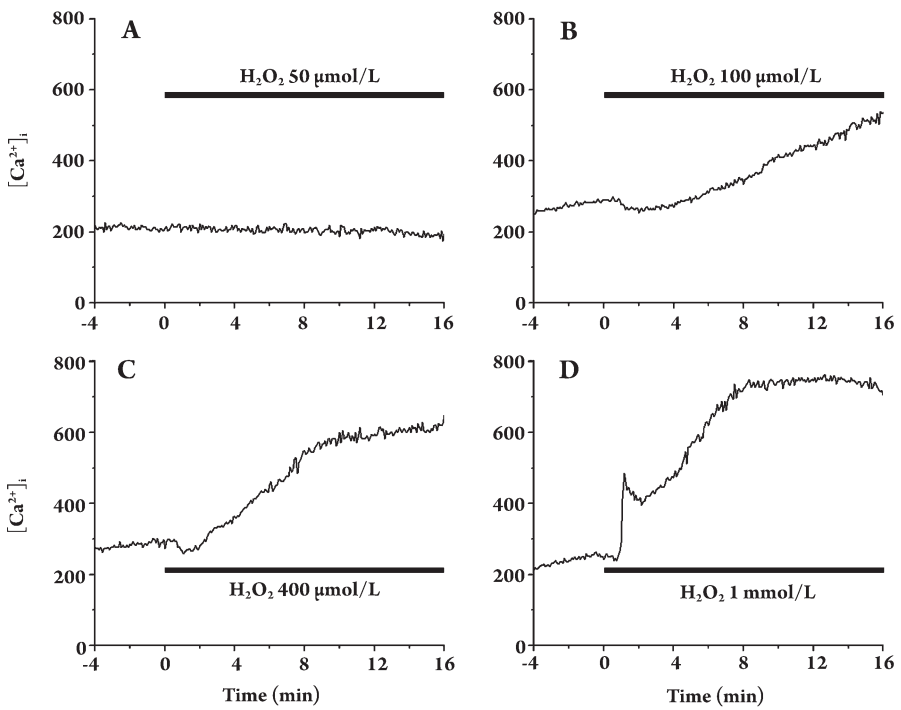

Figure 1. H_2O_2 elevates $[Ca^{2+}]_i$ across two kinetic patterns in a concentration-dependent manner. In the presence of 1 mmol/L Ca^{2+} in the extracellular solution, H_2O_2 was applied to recorded hepatocytes at the concentrations of 50 μmol/L (A), 100 μmol/L (B), 400 μmol/L (C) and 1 mmol/L (D), and the effects on $[Ca^{2+}]_i$ were evaluated. The horizontal bar in each trace indicates the exposure period to H_2O_2. Representative traces are typical case from 5–12 experiments tested.

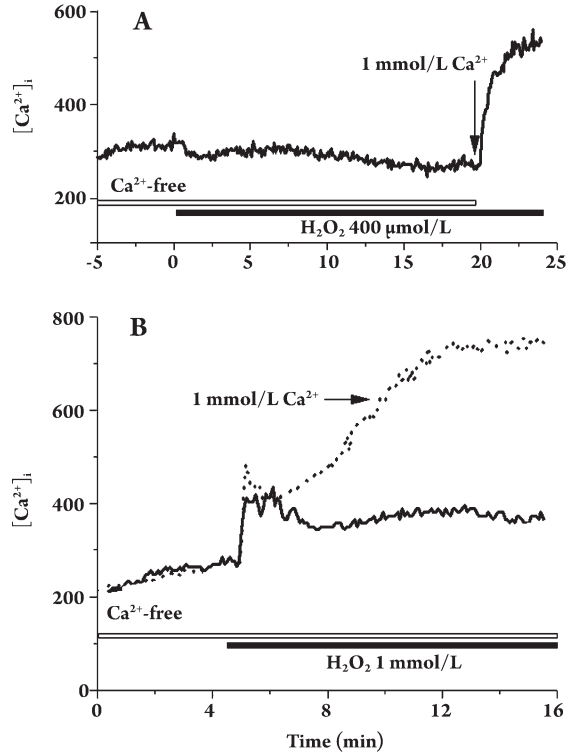

Figure 2. Effects of removal of extracellular Ca^{2+} on H_2O_2-induced elevation of $[Ca^{2+}]_i$. (A) Under extracellular Ca^{2+}-free conditions (open horizontal bar), 400 μmol/L H_2O_2 failed to induce a detectable elevation of $[Ca^{2+}]_i$, and the reperfusion of 1 mmol/L extracellular Ca^{2+} (indicated by arrow) induced an elevation of $[Ca^{2+}]_i$. (B) Under the same extracellular Ca^{2+}-free conditions, 1 mmol/L H_2O_2 still induced a transient, initial elevation of $[Ca^{2+}]_i$, but the sustained phase of elevation of $[Ca^{2+}]_i$ was abolished. The dashed trace represents 1 mmol/L H_2O_2-induced elevation of $[Ca^{2+}]_i$ in the presence of 1 mmol/L extracellular Ca^{2+}. Representative traces in (A) and (B) are typical cases from 6–9 experiments.

we performed a series of experiments. First, we tested for the existence of ATP-sensitive channels in rat hepatocytes. Under perforated whole-cell patch-clamp recording conditions (pipette solution contained no ATP), voltage-step pulse-induced membrane currents were substantially increased by switching the recording mode from perforated to conventional whole-cell recording, suggesting that reducing intracellular ATP enhances voltage-step pulse-induced membrane currents (Figure 4A). To avoid enhancing membrane currents via a decrease in access resistance (Ra) by converting to conventional whole-cell recording, we compared voltage-step pulse-induced membrane currents using conventional whole-cell recordings at different time points. Under this experimental condition, Ra values were the same at different time points during whole-cell recordings. Voltage-step pulse-induced membrane currents were significantly enhanced 5 min after whole-cell formation compared to 1 min (Figure 4B), thereby supporting the notion that reducing intracellular ATP enhances voltage-step pulse-induced membrane currents. To provide direct evidence that rat hepatocytes contain ATP-sensitive non-selective cation channels, we artificially removed ATP from the space inside the cell during inside-out patch recording, and we investigated whether this manipulation increased membrane current. The removal of ATP increased voltage-ramp pulse-induced membrane currents (Figure 4C). The non-specific cation channel blocker amiloride (1 mmol/L), but not the ATP-sensitive K^+ channel blocker tolbutamide (data not shown), mitigated ATP-free induced membrane current increases (Figure 4C). These results further support the existence of ATP-sensitive non-specific cation channels in rat hepatocytes.

Oxidation is involved in H_2O_2-induced membrane current enhancement and $[Ca^{2+}]_i$ elevation Considering that H_2O_2 may impair intracellular ATP production through an oxidation mechanism, we tested the effects of the antioxidant melatonin on H_2O_2-induced membrane current increases. As shown in Figure 5A, 10 μmol/L melatonin alone did not influence membrane currents, while pre-treatment of hepatocytes with 10 μmol/L melatonin for 3 min followed by co-application of 400 μmol/L H_2O_2 plus melatonin failed to induce membrane current increases (Figure 5B). These results suggest that 400 μmol/L H_2O_2 may reduce intracellular ATP production through oxidative stress, in turn leading to the opening of ATP-sensitive cation channels, resulting in Ca^{2+} influx through these channels and thereby elevating intracellular Ca^{2+} levels.

The effect of amiloride on H_2O_2-induced changes in membrane conductance and $[Ca^{2+}]_i$ Figure 6A shows whole-cell currents established by the amphotericin B-perforation method. In the presence of 100 μmol/L amiloride, H_2O_2 resulted in only a small increase in $[Ca^{2+}]_i$ (Figure 6Ba), while 1 mmol/L amiloride abolished the effects of H_2O_2 (Figure 6Ab,c; Bb). In these experiments, we found that the amiloride itself reduced intracellular Ca^{2+} level, but the mechanism of this direct effect of amiloride is unclear. Figure 6Bc summarizes the effects of amiloride on H_2O_2 (400 μmol/L)-induced increases in $[Ca^{2+}]_i$ and suggests that H_2O_2 (400 μmol/L)-induced increases in both current magnitudes and $[Ca^{2+}]_i$ are mediated via the opening of ATP-sensitive non-specific cation channels.

H_2O_2 reduces intracellular ATP by impairing the mitochondrial function of rat hepatocytes We then addressed the question of how H_2O_2 (400 μmol/L) reduced the intracellular ATP concentration via oxidative mechanisms. One possible hypothesis is that H_2O_2 induces oxidation-

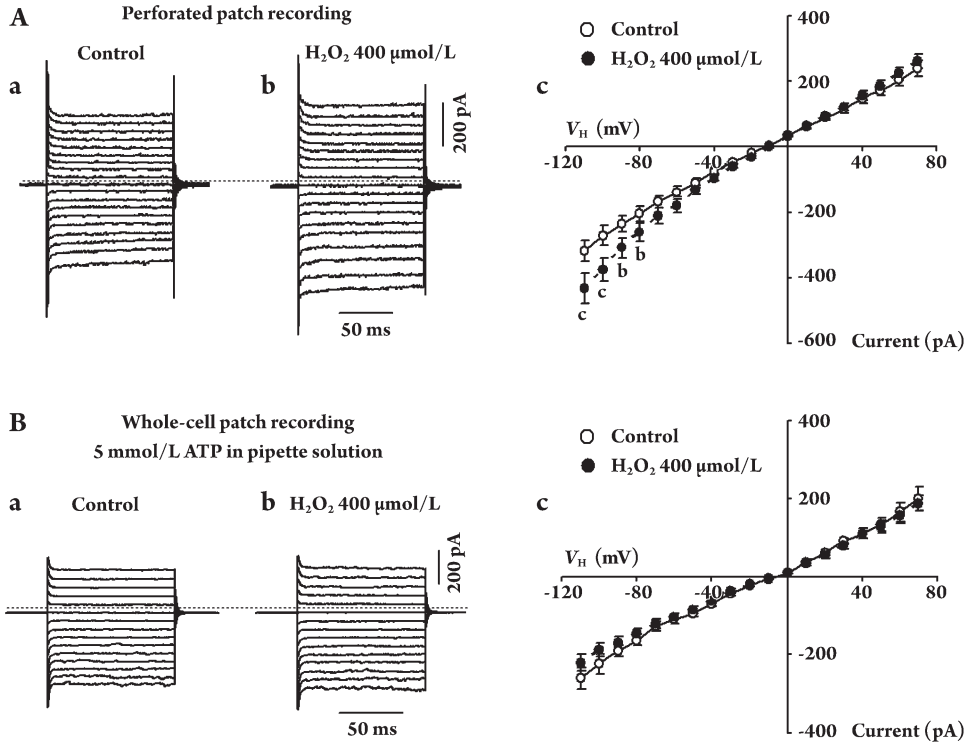

Figure 3. Effects of H_2O_2 on membrane currents of hepatocytes. (A) Amphotericin B-perforated whole-cell membrane currents induced by 10 mV-increasing and decreasing voltage-step pulses before (a) and during (b) application of 400 μmol/L H_2O_2. The holding potential was -20 mV (horizontal dashed line). Ac: Current-voltage relationships obtained from the data presented in (Aa,b) before (○) and during (●) application of H_2O_2. (B) Whole-cell membrane currents recorded using the conventional whole-cell method. The pipette solution contained 5 mmol/L ATP. Bc: Current-voltage relationships obtained from the data presented in (Ba,b) before (○) and during (●) application of H_2O_2. Representative traces from 5 experiments are shown in (A) and (B). $^bP<0.05$, $^cP<0.01$ before application of H_2O_2, respectively.

related mitochondrial dysfunction, which leads to a decrease in ATP production. To test this hypothesis, we monitored inner mitochondrial membrane potential using Rh123 fluorescence imaging and determined the cellular content of NAD(P)H in the mitochondrial pool using NAD(P)H fluorescence imaging. First, we examined the effect of the classic mitochondrial toxin NaCN on mitochondrial membrane potential and NAD(P)H content. NaCN (1 mmol/L) increased Rh123 intensity (Figure 7A) but decreased NAD(P)H autofluorescence intensity (Figure 7B), indicating that it decreased the inner mitochondrial membrane potential (ie, depolarization) and decreased NAD(P)H in the mitochondrial pool[22]. Then, we compared the effect of H_2O_2 (400 μmol/L) to 1 mmol/L NaCN. Similar to NaCN, H_2O_2 (400 μmol/L) also increased Rh123 intensity (Figure 7A, C) and decreased NAD(P)H autofluorescence intensity (Figure 7B, C). Direct measurements of intracellular concentrations of ATP in hepatocytes demonstrated that after exposure for 6 min to 400 μmol/L H_2O_2, intracellular ATP concentrations decreased from 25.6±5.2 cpm (before exposure) to 18.4±4.7 (exposure for 3 min, $P<0.05$, $n=5$) and 16.4±3.7 (exposure for 6 min, $P<0.05$, $n=5$) (data not shown). These results suggest that H_2O_2 (400 μmol/L) impairs mitochondrial function and consequently reduces intracellular ATP concentrations.

Role of the PLC pathway in H_2O_2-induced transient elevation of $[Ca^{2+}]_i$ Finally, we conducted experiments to determine whether PLC pathway activation was involved in the transient elevation of $[Ca^{2+}]_i$[20] induced by a high concentration (1 mmol/L) of H_2O_2 (which was not sensitive to the removal of extracellular Ca^{2+}, Figure 2B). As shown in Figure 8A, in the presence of the PLC inhibitor U73122 (1 μmol/L, 5-min pre-treatment), the 1 mmol/L H_2O_2-induced transient (but not sustained) elevation of $[Ca^{2+}]_i$ was eliminated, suggesting that PLC pathway activation does contribute to H_2O_2-induced transient elevation of $[Ca^{2+}]_i$. To further confirm the role of PLC activation in 1 mmol/L H_2O_2-induced transient elevation of $[Ca^{2+}]_i$, we also directly measured the effect of 1 mmol/L H_2O_2 on PLC activity. Figure 8B demonstrates that 1 mmol/L, but not 400 μmol/L

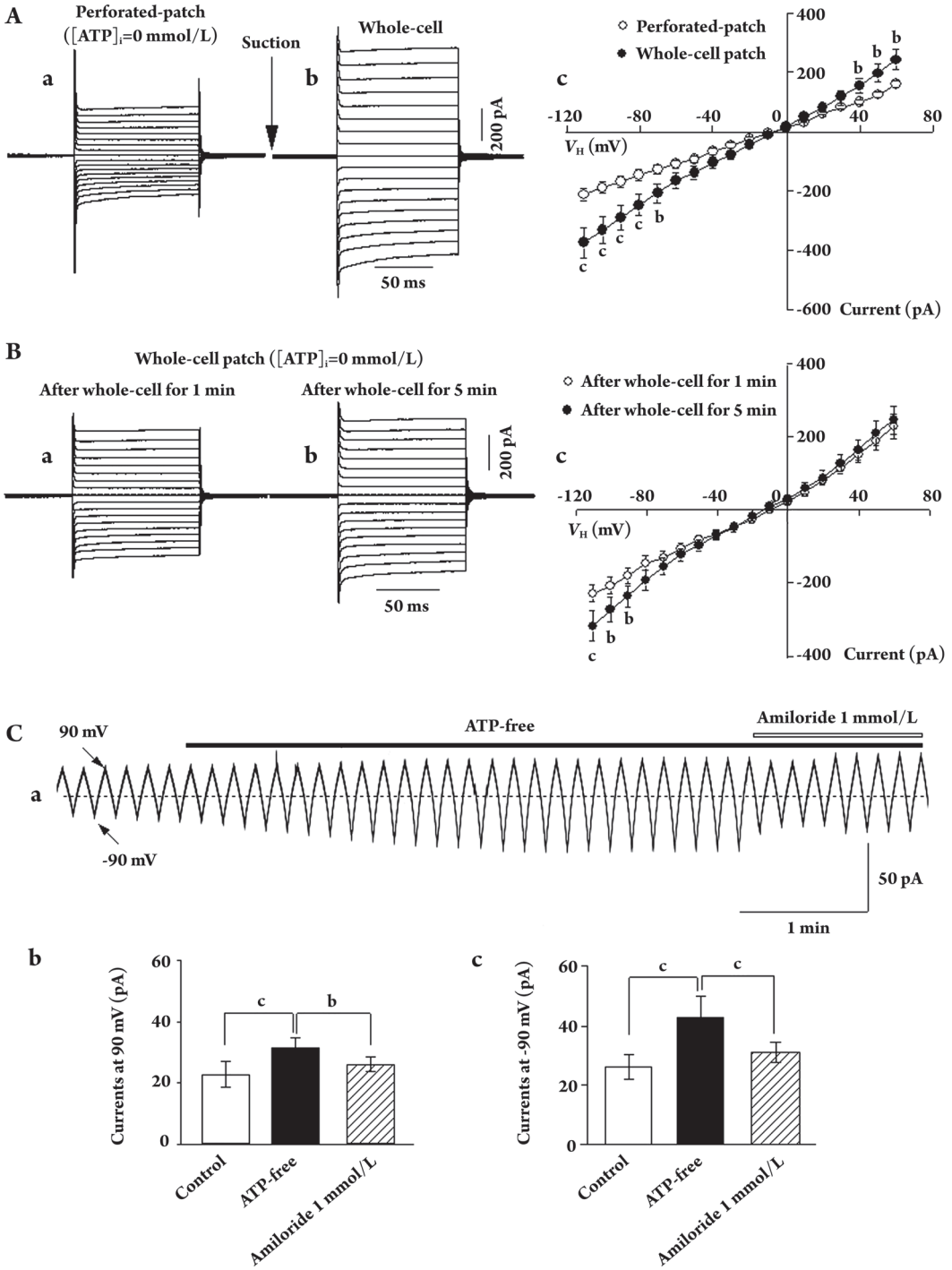

Figure 4. ATP-sensitive conductance in hepatocytes. (A) Under perforated-patch conditions with ATP-free pipette solution, step-pulse-induced currents (a) were enhanced by conversion (suction) to conventional whole-cell configuration (b,c). (B) Under whole-cell patch conditions with ATP-free pipette solution, step-pulse-induced currents were tested at 1 (a) and 5 (b) min after conversion to whole-cell conditions and showed an enhancement of membrane currents (c). (C) Inside-out patch recordings. Currents through the membrane in response to repeatedly applied voltage-ramp pulses from -90 to 90 mV are shown (a). Initially, the concentration of ATP in the bath solution was 1 mmol/L, and then ATP was removed and an ATP-free bath solution was used. Amiloride (1 mmol/L) was applied under ATP-free conditions. Representative traces from 5 experiments are shown. The magnitudes of currents were measured at 90 mV (b) and -90 mV (c) of the transmembrane potential. Each column represents the mean from 5 series of experiments. $^{b}P<0.05$, $^{c}P<0.01$.

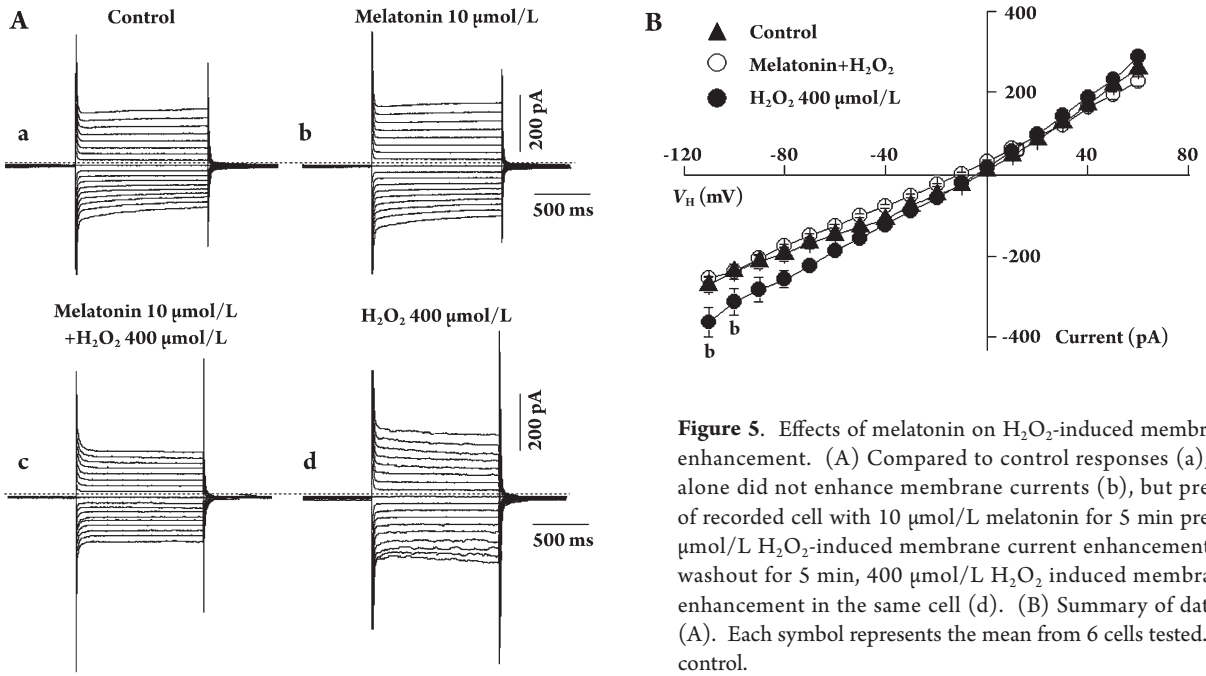

Figure 5. Effects of melatonin on H_2O_2-induced membrane current enhancement. (A) Compared to control responses (a), melatonin alone did not enhance membrane currents (b), but pre-treatment of recorded cell with 10 μmol/L melatonin for 5 min prevented 400 μmol/L H_2O_2-induced membrane current enhancement (c). After washout for 5 min, 400 μmol/L H_2O_2 induced membrane current enhancement in the same cell (d). (B) Summary of data shown in (A). Each symbol represents the mean from 6 cells tested. $^bP<0.05$ *vs* control.

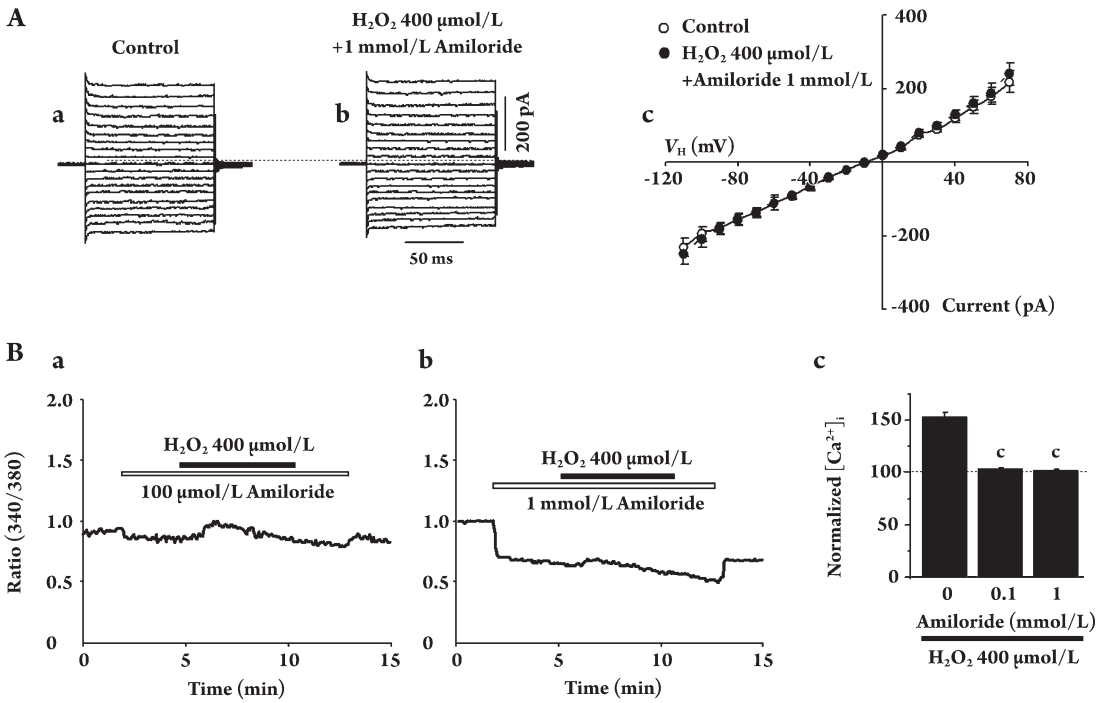

Figure 6. Effects of amiloride on H_2O_2-induced changes in membrane conductance and $[Ca^{2+}]_i$. (A) Amphotericin B-perforated whole-cell currents recorded in the presence of 1 mmol/L amiloride before (a) and during (b) application of 400 μmol/L H_2O_2. Ac: Current-voltage relationships from the data (n=6) shown in (Aa,b) before (○) and during (●) application of H_2O_2. Ba: $[Ca^{2+}]_i$ was measured in the presence of amiloride (100 μmol/L), and then 400 μmol/L H_2O_2 was applied. Bb: The concentration of amiloride was 1 mmol/L. Bc: Normalized $[Ca^{2+}]_i$ from the data of 4–8 experiments shown in (Ba) and (Bb). Application of amiloride by itself caused a decrease in the Fura-2 intensity ratio. The change in the baseline level (Fura-2 intensity ratio) by amiloride seems to be due to some non-specific, direct reversible effect of amiloride on Fura-2 activity because both the appearance and disappearance of the effect are very quick. $^cP<0.01$ *vs* Amiloride 0 mmol/L.

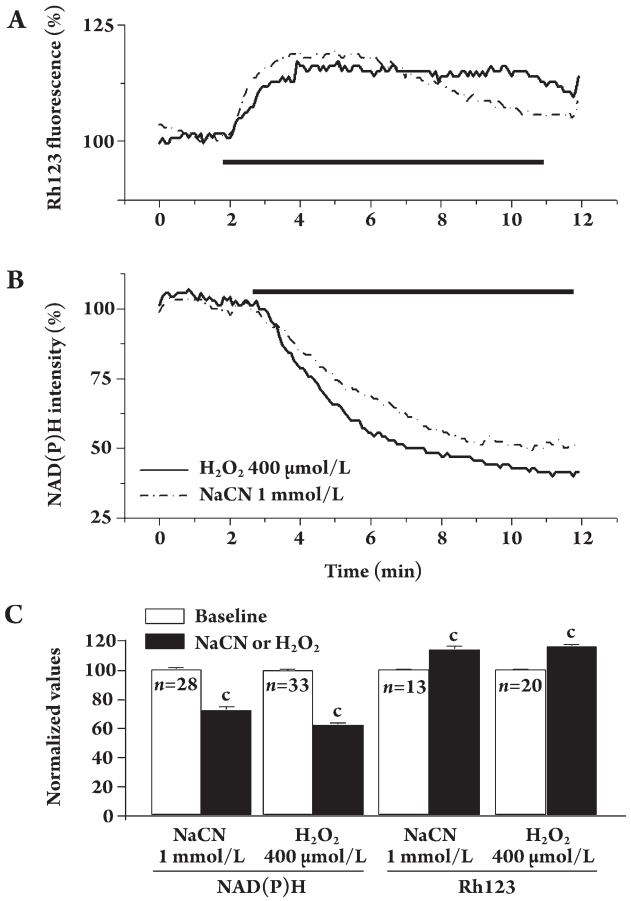

Figure 7. H_2O_2 impaired mitochondrial function. (A) Rh123 intensity changes induced by 1 mmol/L NaCN (dashed line) and 400 μmol/L H_2O_2 (bold line). (B) NAD(P)H intensity changes induced by 1 mmol/L NaCN (dashed line) and 400 μmol/L H_2O_2 (bold line). (C) Summary of the effects of 1 mmol/L NaCN and 400 μmol/L H_2O_2 on NAD(P)H and Rh123. Baseline values were measured at the 2-min time point and the NaCN-induced and H_2O_2-induced responses were measured at the 4-min time point for Rh123 intensity and at the 8-min time point for NAD(P)H intensity. Representative columns from 13–33 cells tested. $^cP<0.01$ *vs* baseline.

H_2O_2, increased PLC activity, supporting the hypothesis that PLC activation-induced mobilization of Ca^{2+} from intracellular Ca^{2+} stores underlies 1 mmol/L H_2O_2-induced transient elevation of $[Ca^{2+}]_i$. Theoretically, PLC pathway activation produces IP_3, which mobilizes Ca^{2+} from IP_3-induced Ca^{2+} release (IICR), while released Ca^{2+} from IICR also can trigger the Ca^{2+}-induced Ca^{2+} release (CICR) mechanism. To test whether ryanodine-sensitive Ca^{2+} stores play a role in generating 1 mmol/L H_2O_2-induced transient elevation of $[Ca^{2+}]_i$, we examined the effects of 100 μmol/L ryanodine on the 1 mmol/L H_2O_2-induced transient elevation of $[Ca^{2+}]_i$. Our results demonstrated that pretreatment with 100 μmol/L ryanodine for 2 min failed to abolish 1 mmol/L H_2O_2-induced transient elevation of $[Ca^{2+}]_i$ (supplemental Figure 1). This suggests that ryanodine-sensitive Ca^{2+} stores may not play an important role in generating the 1 mmol/L H_2O_2-induced transient elevation of $[Ca^{2+}]_i$.

Discussion

Our study's major contribution is the identification of two distinct mechanisms of $[Ca^{2+}]_i$ elevation induced by H_2O_2. Low-concentration (400 μmol/L) H_2O_2-induced sustained $[Ca^{2+}]_i$ elevation is mediated through a Ca^{2+} influx mechanism, in which H_2O_2 impairs mitochondrial function, reduces intracellular ATP production, opens ATP-sensitive, non-specific cation channels, and leads to Ca^{2+} influx. An increase in the H_2O_2 concentration to 1 mmol/L induced an additional, transient elevation of $[Ca^{2+}]_i$, which is mediated through activation of the PLC signaling pathway followed by mobilization of Ca^{2+} from intracellular Ca^{2+} stores.

H_2O_2 elevates $[Ca^{2+}]_i$ consistent with two dynamic patterns, which are mediated through distinct mechanisms Our research suggests that acute exposure to H_2O_2

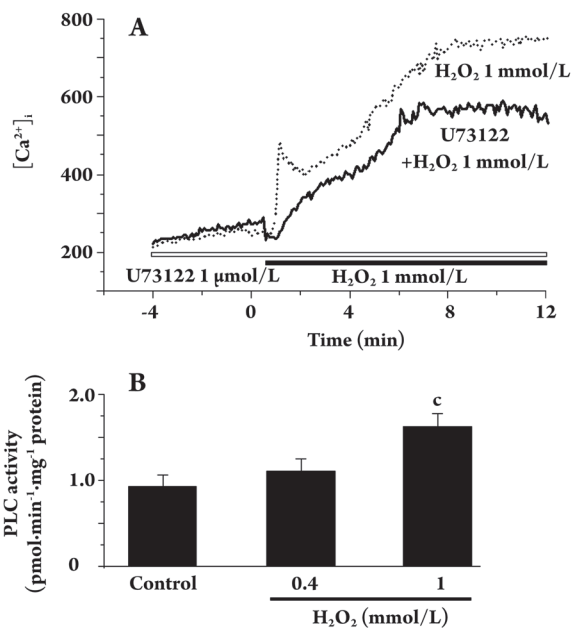

Figure 8. Role of the PLC pathway in H_2O_2-induced elevation of $[Ca^{2+}]_i$. (A) Hepatocytes were pre-treated with 1 μmol/L U73122 for 30 min and then stimulated with 1 mmol/L H_2O_2 in the presence of 1 mmol/L Ca^{2+}. (B) Direct measurements of PLC activity during exposure to different concentrations of H_2O_2 showed that only 1 mmol/L H_2O_2 significantly increased PLC activity. Each column represents the average from 5 experiments and the vertical bars represent SD. $^cP<0.01$ *vs* control.

mobilizes Ca^{2+} from rat hepatocytes via two distinct mechanisms: Ca^{2+} entry from the extracellular space and Ca^{2+} release from intracellular stores. In many other cell types, these two mechanisms are often linked. For instance, in exocrine cells, agonists induce Ca^{2+} release first from intracellular Ca^{2+} stores triggered by IP_3 produced via a membrane receptor-PLC-linked signal transduction cascade[24], and then the emptied Ca^{2+} stores mediate the opening of Ca^{2+}-permeable channels in the cell membrane[25, 26]. In this case, lower concentrations of the agonist cause only Ca^{2+} release from stores, and at higher concentrations or with long-time exposure to low concentrations of the agonist, the phase reflective of the Ca^{2+} influx appears[26]. On the other hand, in cardiac myocytes and smooth muscle cells, Ca^{2+} entry first occurs through voltage-gated Ca^{2+} channels that are opened by depolarizing stimuli. The incoming Ca^{2+} triggers Ca^{2+} release from the sarcoplasmic reticulum, thereby activating ryanodine-sensitive Ca^{2+} channels in the sarcoplasmic reticulum membrane[27]. In the present study, the concentrations of H_2O_2 were relatively high (0.4 and 1 mmol/L). We chose these concentrations on the basis of published literature and our previous results. It has been reported that high concentrations of H_2O_2 (>1 mmol/L) are necessary to induce apoptosis of liver cells[28]. In addition, Lu and Tian reported[17] that exposure of liver cells to 10 mmol/L H_2O_2 for 2 h induced cell apoptosis through intracellular Ca^{2+} overloading. In the present study, the results (Figure 1) clearly showed that H_2O_2 induced a strong and sustained Ca^{2+} elevation at the concentration of 400 μmol/L. In particular, 1 mmol/L of H_2O_2 was required to induce the transient Ca^{2+} component (Figure 1D), and also to increase PLC activity (Figure 8B). Accordingly, for the purpose of studying the mechanisms of acute H_2O_2-induced sustained and transient Ca^{2+} signals in liver cells, the H_2O_2 concentrations used in the present study were appropriate.

Ca^{2+} entry induced by H_2O_2 occurs through the opening of ATP-sensitive non-specific cation channels Although hepatocytes have no voltage-gated Ca^{2+} channels, various pathways for Ca^{2+} entry have been proposed in rat and guinea-pig hepatocytes. For instance, hepatocytes possess non-specific cation channels that are permeable to Na^+, K^+, and Ca^{2+} [29], and these types of channels are activated by membrane stretch[29] and externally applied ATP[30]. Various hormones, including hepatocyte growth factor[31], vasopressin[32], insulin[33], and norepinephrine[10], have been reported to activate Ca^{2+}-permeable channels. In addition, hepatocytes possess Ca^{2+} release-activated Ca^{2+} channels[4, 34, 35]. Membrane currents through Ca^{2+} release-activated Ca^{2+} channels (I_{CRAC}) can be recorded in intact hepatocytes[35], and both ATP and vasopressin can activate I_{CRAC}[36], suggesting that this type of channel is capable of being opened without altering the volume of Ca^{2+} stores. In addition, the transient receptor potential canonical 1 protein has been shown to form a Ca^{2+}-permeable non-specific cation channel responsible for both store depletion-induced Ca^{2+} entry and cell volume regulation in liver cells[37]. In L02 cells (a human hepatic cell clone), I_{CRAC}-linked Fas protein was expressed by Fas mRNA transduction, and H_2O_2 promoted Ca^{2+} influx, which was responsible for cell apoptosis[17]. Further studies are required to elucidate the characteristic similarities of the non-specific cation channels and Fas protein.

In our study, H_2O_2-induced Ca^{2+} influx through non-specific cation channels may be related to a possible decrease in the concentration of intracellular ATP. The action of ATP on non-specific cation channels differs at sites where ATP is utilized and across cell types. As mentioned previously, extracellular ATP activates non-specific cation channels in hepatocytes[30, 36]. A similar effect induced by extracellular ATP has been shown in basophilic leukemia cells[38]. Non-specific cation channels that are inhibited by intracellular ATP (or activated by a decrease in intracellular ATP concentration) have been identified in a number of cell types[39–41]. Thus, it is possible that ATP-sensitive non-specific cation channels are expressed in hepatocytes, and our data showing that the removal of intracellular ATP increases membrane currents (Figure 4) supports this hypothesis. However, to date no selective antagonists are available to further characterize these ATP-sensitive non-specific cation channels.

H_2O_2 impairs mitochondrial function and decreases intracellular ATP concentrations The results shown in Figure 7 indicate that H_2O_2 impairs hepatocyte mitochondrial function, which in turn results in a decreased intracellular ATP concentration. Oxidative stress induced by oxygen and nitrogen species is known to cause cell injury and/or death, particularly by impairing mitochondrial function. Oxygen radicals are produced by mitochondria, and those produced in other cells can easily enter a target cell via the cell membrane and thereby reach the interior of mitochondria. The mechanisms by which oxygen radicals impair mitochondrial function involve mitochondrial membrane permeability transitions[16] and mitochondrial DNA damage[42], leading to cell death. In such processes, mitochondrial and cytosolic Ca^{2+} likely play important roles. In fact, reactive oxygen and nitrogen species regulate mitochondrial Ca^{2+} homeostasis[23], and impairment of mitochondrial function is also dependent on Ca^{2+} [43]. In neurons, Ca^{2+}-dependent mitochondrial dysfunction is known to result in the release of apoptogenic

proteins from mitochondria, thereby leading to cell death[44]. Furthermore, impaired mitochondrial function leads to a loss of ATP synthesis[45].

Acknowledgments

This work was supported by a Grant-in-Aid for scientific research from the Japan Ministry of Education, Science, Sports, and Culture to Dr Makoto WAKUI (1247005).

The authors thank Kevin ELLSWORTH for his assistance in preparing this article.

Author contribution

Hirohiko SATO, Qiang LIU: perform patch-clamp experiments and data analysis. Teruko TAKEO, Sechiko SUGA: perform Ca^{2+} image experiments and data analysis. Kyoko NAKANO, Tomohiro OSANAI: perform biochemical experiments and data analysis. Makoto WAKUI, Jie WU: design experiments, analyze data and write the manuscript.

Abbreviations

H_2O_2, hydrogen peroxide; OH·, hydroxyl radical; O^{2-}, superoxide anion; PLC, phospholipase C; IP_3, inositol trisphosphate; rhodamine 123, (Rh123); SR, sarcoplasmic reticulum

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