Abnormalities of gallbladder muscle associated with acute inflammation in guinea pigs

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Xiao, Zuo-Liang, Qian Chen, Piero Biancani, and Jose Behar. Abnormalities of gallbladder muscle associated with acute inflammation in guinea pigs. Am J Physiol Gastrointest Liver Physiol 281: G490–G497, 2001.—Muscle strips from experimental acute cholecystitis (AC) exhibit a defective contraction. The mechanisms responsible for this impaired contraction are not known. The present studies investigated the nature of these abnormalities. AC was induced by ligating the common bile duct of guinea pigs for 3 days. Contraction was studied in enzymatic dissociated muscle cells. Cholecystokinin (CCK) and prostaglandin E2 (PGE2) receptor binding studies were performed by radioreceptor assay. The levels of lipid peroxidation, cholesterol, phospholipid, and H2O2 as well as the catalase and superoxide dismutase (SOD) activities were determined. PGE2 content was measured by radioimmunoassay. Muscle contraction induced by CCK, ACh, or KCl was significantly reduced in AC, but PGE2-induced contraction remained normal. GTPγS, diacylglycerol (DAG), and 1,4,5-trisphosphate (IP3), which bypass the plasma membrane, caused a normal contraction in AC. The number of functional receptors for CCK was significantly decreased, whereas those for PGE2 remained unchanged in AC. There was a reduction in the phospholipid content and increase in the level of lipid peroxidation as well as H2O2 content in the plasma membrane in AC. The PGE2 content and the activities of catalase and SOD were also elevated. These data suggest that AC cause damage to the constituents of the plasma membrane of muscle cells. The preservation of the PGE2 receptors may be the result of muscle cytoprotection.

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CALCULUS AND ACALCULUS acute cholecystitis (AC) is responsible for considerable morbidity and mortality (31). Acute acalculous cholecystitis is less common than acute calculous cholecystitis but has a rapid course and frequently results in complications and death. Between 6 and 17% of cases of AC occur in the absence of gallstones (45). The incidence as well as the surgical risk of this acute inflammatory condition increases with age, particularly in patients over 65, where the incidence is three times higher than in younger patients (10). The pathogenesis of human AC, however, has not been fully elucidated (17, 24). It has been suggested that the initial event is a transient obstruction of the cystic duct. The evidence supporting this hypothesis is circumstantial. Cystic duct ligation does not result in AC in animal models (45) unless the bile is supersaturated with cholesterol (38) or unless concentrated bile is introduced in the ligated gallbladder (44, 47). Furthermore, the contribution of the gallbladder mucosa and muscle in the pathogenesis of AC is not fully understood. Bile stasis frequently precedes the development of AC and could facilitate the diffusion of noxious agents (2). The mechanisms whereby these factors lead to AC are unclear.

The pathological changes seen in human AC with or without gallstones are similar (44, 45). These abnormalities can be reproduced in animals by ligating the common bile duct for 1 to 3 days (4, 31, 35). This model produces a picture of acute inflammation, which is pathologically indistinguishable from that seen clinically in acutely inflamed human gallbladders (31) (J. Behar, unpublished observations). Both specimens showed variable neutrophil and mononuclear infiltrates. Further, the guinea pig gallbladder muscle shares similar signal transduction pathways with human gallbladder (6, 7, 50–52). It is therefore a useful model for the study of the mechanisms of gallbladder muscle dysfunction induced by this acute inflammatory process.

The present studies therefore were aimed at determining the functional changes in gallbladder muscle cells induced by experimental acute inflammatory reaction in guinea pigs.

MATERIALS AND METHODS

AC model: common bile duct ligation. Ligation of the common bile duct for 3 days induced AC in guinea pigs (4, 35). The Animal Welfare Committee of Rhode Island Hospital approved their use. Adult male guinea pigs were purchased from Elm Hill Breeding Laboratory (Chelmsford, MA). They were housed in thermoregulated rooms with free access to food and water. After an overnight fast, guinea pigs were initially anesthetized with ketamine hydrochloride (30 mg/kg im) followed by an intraperitoneal injection of Nembutal (50 mg/kg). Additional Nembutal is given as needed to keep the animal deeply sedated. The animals were then placed on a warming pad of the surgical table. The entire procedure was

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performed under sterile conditions. The upper abdomen was shaved, scrubbed with betadine solution, and covered with sterile drapes. After a midline incision (2 cm), the gallbladder and pericholecystic region was carefully exposed. Then, the distal end of the common bile duct was identified and ligated at its junction with the duodenum using a 4–0 silk ligature using minimal manipulation and avoiding damage to the cystic artery or any other major blood vessels. Following the ligation of the bile duct, the abdomen was closed in a two-layer closure and the surgical incision was cleaned and covered with sterile gauze and taped. Control animals were sham operated, which included all the surgical steps except layer closure and the surgical incision was cleaned and covered with petroleum jelly for tissue harvest.

**Isolation and permeabilization of muscle cells.** Gallbladder muscle cells were obtained by a method that has been previously reported (52, 55–57). Briefly, after the gallbladder was removed, its mucosa was rinsed with ice-cold, oxygenated Kreb’s solution. The mucosa and serosa were carefully peeled off under a dissecting microscope. The muscle layer was cut into 2-mm wide strips and digested in HEPES buffer containing 0.5 mg/ml type A collagenase and 2 mg/ml papain (activity of ∼13.9 U/mg protein) for 20 min at 35°C in a shaking water bath. The buffer was gently gassed with 100% O2 during digestion. At the end of the digestion, the tissue was filtered through a Nitex mesh 200 (Tetko, Elmsford, NY) and rinsed with 0.2 ml HEPES. The tissue remaining on the filter was collected and incubated in HEPES buffer at 35°C for 15 min to allow the free dispersion of cells, which were then provided with food (laboratory chow) and water ad libitum for next 3 days. All guinea pigs received routinely analgesia with buprenorphine 0.05 mg/kg b.i.d. for the duration of the postoperative period. Three days later all animals were reanesthetized with ketamine followed by Nembutal (50 mg/kg ip) and killed for tissue harvest.

**Measurements of cholesterol and phospholipids.** Lipids were extracted from purified plasma membranes with chloroform-methanol (54). After centrifugation at 2,000 × g for 5 min, the lower organic phase was collected and equally dispensed to six glass test tubes for triplicate measurements of cholesterol and phospholipids. Samples were dried under a stream of nitrogen. The cholesterol content was measured with the cholesterol-oxidase method using a Sigma kit. One milliliter of cholesterol reagent was added to each dried sample and incubated at 25°C for 10 min. They were measured at an optical density of 500 nm in a Beckman DU-7 spectrophotometer. The cholesterol content was calculated according to the standards, calibrated by the protein content, and expressed as micromoles per milligrams of protein.

**Assessment of lipid peroxidation.** Purified plasma membranes were resuspended with 1.15% KCl (34) and mixed with 0.2 ml of 8.1% SDS, 1.5 ml of 20% acetic acid solution (pH 3.5), and 1.5 ml of 0.8% aqueous solution of TBA. This mixture was added to a volume of 4 ml with distilled water. The sample was heated at 95°C for 60 min. After cooling, 1 ml was further homogenized using a Dounce grinder (Whenton, Millville, NJ). The homogenates were centrifuged at 600 × g for 5 min; the supernatant was collected in a clean centrifuge tube (Beckman Instruments, Fullerton, CA) and centrifuged at 150,000 × g for 45 min to make a crude particulate pellet. The pellet was resuspended in sucrose-HEPES. This homogenate was then layered over a linear 9–60% sucrose gradient and centrifuged at 90,000 × g for 3 h. The plasma membranes were collected at ∼24% sucrose. They were then diluted and pelleted by centrifugation at 150,000 × g for 30 min. The pellet of plasma membranes was stored at −70°C.
of distilled water and 5 ml of the mixture of n-butanol and pyridine (15:1, vol/vol) were added and shaken vigorously. Spun at 2,000 g for 10 min, the organic layer was taken and its absorbency (red pigment) was measured at 532 nm. Tri-methoprim (TMP) was used as an external standard. The level of lipid peroxides was expressed as nanomoles of malonaldehyde (MDA, a secondary product of lipid peroxidation). Measurements were standardized to 100 mg of protein.

Determination of H2O2 content. It is based on the oxidation of ferrous ions to ferric ions by H2O2 (16). Under acidic conditions, ferrous ions bind with the indicator dye xylene orange to form a stable colored complex that can be measured at 560 nm. H2O2 was measured in homogenized single gallbladder muscle cells from control animals and animals with AC. The production of H2O2 was determined by the H2O2-560 quantitative assay kit (OXIS International, Portland, OR). Briefly, H2O2 standard was prepared at a range of 0.1–100 μM. One volume of sample or standard was added to 10 vol of working reagent. This solution was mixed well and incubated at room temperature for 25–30 min, and the absorbency was measured at 560 nm. The content of H2O2 was calculated from the standard curve. The results were expressed as micromoles per milligrams of protein.

Measurements of PGE2 content. The content of PGE2 was measured by using a radioimmunoassay kit from NEN (NEN Life Science Products, Boston, MA; Ref. 13). Muscle cells were homogenized in HEPES buffer containing EDTA/indomethacin to inhibit the metabolism of arachidonic acid to prostaglandins. The suspension was centrifuged at 10,000 g for 15 min. PGE2 was extracted from the supernatant by the methods of Kelly et al. (19). Extracted PGE2 was measured by converting this prostaglandin into its methyl oximate derivative using the methyl oximation reagent. The determination of PGE2 content was achieved by following the kit’s protocol. The content of PGE2 was expressed as picomoles per milligrams of protein.

Measurement of catalase activity. The catalase activity was determined by using the method reported by others (8, 33). Muscle cells were homogenized in HEPES buffer, and the suspension was centrifuged at 10,000 g for 15 min. Duplicate 25-μl aliquots of each sample of the supernatant and 75 μl of 10 mM phosphate buffer, pH 7.4, were placed into 3-ml cuvettes. Duplicate blanks (B) of solutions containing 90 μl of phosphate buffer, 10 μl of 1% sodium azide, 200 μl of 6 N sulfuric acid, and 1 ml of 6 mM H2O2 were also prepared. The enzymatic reactions were initiated sequentially at fixed intervals by adding 1 ml of 6 mM H2O2 to the samples. After 3 min, the reactions were stopped sequentially at the same fixed intervals by rapidly adding and mixing 200 μl of 6 N H2SO4. Finally, 1.4 ml of 0.01 N KMnO4 was added to each cuvette and mixed thoroughly. A spectrophotometric standard (S0) was prepared by adding 7.0 ml of 0.01 N KMnO4 to a mixture of 5.5 ml phosphate buffer and 1.0 ml of 6 N H2SO4. The absorbency of the solution was read at 480 nm within 30–60 s. One unit of catalase activity (k) was defined as the amount of enzyme that consumed 1 μmol H2O2·mg protein−1·min−1. Calculation of the catalase activity was achieved according to the equation: k = log(S0/SF)/t × 2.3/t. (S0 was obtained by subtracting the absorbency of B from the S0, SF was obtained by subtracting the absorbency of the samples from SF, t = 3 min in this experiment). Data were expressed as units per milligrams of protein.

Measurement of SOD activity. The total SOD activity was measured by using a spectrophotometric assay kit (R&D systems, Minneapolis, MN; Ref. 32). Muscle cells were homogenized in HEPES buffer. The supernatant was obtained after the suspension was centrifuged at 8,500 g for 10 min at 4°C; 400 μl of ice-cold extraction reagent [ethanol/chloroform, 62.5/37.5 (vol/vol)] was added to 250 μl of the supernatant, vortexed for at least 30 s, and centrifuged at 3,000 g for 10 min at 4°C. Then, the aqueous upper layer was collected for assay of the SOD activity. The determination of SOD activity was achieved by following the kit’s protocol. Data were expressed as units per milligrams of protein.

Protein determination. The protein content of the muscle membranes was measured using the Bio-Rad protein assay kit (Bio-Rad Laboratories, Melny, NY). Values for each sample were means of triplicate measurements.

Drugs and chemicals. 125I-CCK-8, 3H-PGE2, and PGE2 radioimmunoassay kits were obtained from NEN Life Science Products. H2O2 quantitative assay kit was from OXIS International (Portland, OR). Type F collagenase, papain, cholester, TMP, thiobarbituric acid, pyridine, IP3, GTPγS, DAG, and other reagents were purchased from Sigma.

Data analysis. One and two factorial repeated analysis of variance (ANOVA) and student’s t-test were used for statistical analysis. P < 0.05 was considered to be statistically significant.

RESULTS

The average resting lengths of intact and permeabilized smooth muscle cells isolated from sham-operated guinea pig gallbladders were 59.2 ± 1.1 and 58.7 ± 0.9 μm (n = 3), respectively. In animals with AC, it was 55.8 ± 1.2 and 57.4 ± 1.9 μm (n = 3), respectively. No significant differences in resting cell length were observed between these two groups (one-factor ANOVA).

Membrane receptor-dependent agonists CCK-8, ACh, PGE2, and the receptor-independent agonist KCl induced a dose-dependent contraction of muscle cells from sham-operated and from AC animals. The CCK-8 dose-response relationship in the sham-operated group was significantly higher than that in the AC group (Fig. 1, P < 0.05, by ANOVA); 10 nM CCK-8 caused a maximal shortening of 20.3 ± 1.0% in sham-operated guinea pigs compared with only 13.0 ± 0.2% in AC animals. Similar results were observed with ACh (Fig. 2, P < 0.01, by ANOVA) and KCl (Fig. 3, P < 0.01, by ANOVA) induced muscle cell contraction in these two

![Fig. 1. Role of CCK-8 on the contraction of gallbladder muscle cells from sham-operated guinea pigs (control; ○) and guinea pigs with acute cholecystitis (AC; ●). In guinea pig with AC, response of muscle cells to CCK-8 was significantly reduced at all doses, with respect to the control group. Values are means ± SE of 3 experiments. *P < 0.05, by ANOVA.](http://ajpgi.physiology.org/)
groups. However, the PGE₂-mediated contraction in AC was unaffected (Fig. 4).

To examine the functional integrity of the signal transduction pathway, muscle cells were stimulated with the G protein activator GTPγS and its messengers IP₃ and DAG. GTPγS and IP₃ were used in muscle cells permeabilized by brief exposure to saponin to allow GTPγS and IP₃ to diffuse across the plasma membrane. DAG was used in intact muscle cells. GTPγS caused a dose-dependent contraction of muscle cells from both sham-operated and AC guinea pigs with maximal contractions of 20.6 ± 0.5 and 20.1 ± 0.2%, respectively (Fig. 5). The magnitude of contraction caused by GTPγS in these two groups was not different from that induced by CCK-8 in intact cells from sham-operated gallbladders. Similar results were observed after the muscle cells from both groups were treated with IP₃ (Fig. 6). There was also no significant difference between sham-operated guinea pigs and those with AC in the DAG-induced contraction (Fig. 7). These findings suggest that with the exception of the PGE₂-mediated effects, the muscle defect associated with acute inflammation appears to be localized in the plasma membrane. However, the signal transduction distal to the membrane receptors is unaffected.

Scatchard analysis based on this data showed that the binding capacity of CCK receptors was 0.29 ± 0.02 pmol/mg protein. In animals with AC, the total binding of CCK receptors decreased to 6.2 ± 0.35% with a specific binding of 5.9 ± 0.13% and nonspecific binding of 1.1 ± 0.29%. The binding capacity of CCK receptors was 0.16 ± 0.05 pmol/mg protein, which was lower than that of control group (P < 0.01). These data suggest that the CCK receptors have been damaged by the inflammatory process.

PGE₂ receptor binding studies were also carried out (Fig. 9). In the control group, the total binding of PGE₂ receptors (in the absence of unlabeled PGE₂) was 7.0 ±
1.45% with a nonspecific binding of 1.7 ± 1.21% and specific binding of 5.8 ± 0.17%. The binding capacity was 0.25 ± 0.02 pmol/mg protein. In animals with AC, the total binding of PGE₂ was 7.2 ± 1.18% with nonspecific binding of 1.5 ± 1.33% and the specific binding of 5.3 ± 0.11%. The binding capacity was 0.21 ± 0.03 pmol/mg protein. These differences were not significant, suggesting that the functional integrity of the PGE₂ receptors be preserved in AC.

To determine the mechanism responsible for the damage of membrane receptors and ion channels during acute inflammation, the constituent of membrane phospholipids were investigated (Fig. 10). Data showed a significant reduction in the phospholipid content with normal cholesterol content in muscle cells from AC. The phospholipid content in sham-operated gallbladders was 1.26 ± 0.04 μmol/mg protein compared with 0.97 ± 0.05 μmol/mg protein in AC (P < 0.01), resulting in a higher cholesterol-to-phospholipid ratio in AC of 0.25 ± 0.02 compared with 0.18 ± 0.02 for controls (P < 0.05). These results suggest that acute inflammation affects the composition of the plasma membrane, especially the phospholipid component that may account for the impaired muscle cell contraction and reduced binding capacity of membrane receptors.

The lower phospholipid content in plasma membranes in AC could be due to over consumption by lipid peroxidation that is frequently associated with acute inflammatory processes. Therefore, lipid peroxidation was determined in gallbladder muscle membranes from sham-operated and AC. The magnitude of lipid peroxidation in sham-operated guinea pigs was 163.6 ± 45.5 nmol of MDA/100 mg membrane protein, which was significantly lower than 527.3 ± 19.8 nmol of MDA/100 mg membrane protein in gallbladder muscle membranes from AC (P < 0.001).

The H₂O₂ content was measured in the muscle layer because acute inflammatory processes induce lipid peroxidation by generating free radicals. The total H₂O₂ content was determined in whole cell homogenate because H₂O₂ can cross the membrane freely. In the control group, H₂O₂ content was 3.13 ± 0.56 μM/mg protein.
protein, which was significantly lower than 17.6 ± 0.61 μM/mg protein in AC (P < 0.001). These data suggest that free radicals may be responsible for the damage to the plasma membranes.

As previously mentioned, the PGE₂-induced muscle contraction and the functional integrity of PGE₂ receptors were unaffected in AC. One possible explanation for this unexpected finding is that increased production of the ligand could protect its receptors from agents that damage or inactivate them (14). The PGE₂ content of the ligand could protect its receptors from agents for this unexpected finding is that increased production tors were unaffected in AC. One possible explanation.

Fig. 10. Cholesterol, phospholipid content, and cholesterol-to-phospholipid (Ch/Pl) ratio in purified plasma membranes of gallbladder muscle from sham-operated guinea pigs (control; open bars; n = 4) and guinea pigs with AC (solid bars) (n = 4). A much lower phospholipid content and a higher Ch/Pl ratio were observed in guinea pigs with AC. *P < 0.01 and **P < 0.05 vs. control group, by Student’s t-test.

The activities of free radical scavengers were also examined because the increase in the PGE₂ content in AC could be responsible for the protection of muscle cells against free radicals. As shown in Fig. 11, the activity of catalase in muscle cells from sham-operated gallbladder was 9.4 ± 4.4 U/mg protein, which increased significantly to 40.0 ± 5.6 U/mg protein in muscle cells from AC (P < 0.001). Similar results were seen with SOD activity, which increased from 2.9 ± 2.2 in controls to 16.5 ± 5.2 U/mg protein in AC (P < 0.01). These data suggest that the increase in PGE₂ content and preservation of its receptors in AC are cytoprotective responses against the inflammatory process.

To further confirm this hypothesis, catalase and SOD activities were measured in normal muscle cells pretreated in vitro with exogenous PGE₂ for 30 min. As shown in Fig. 12, the activities of catalase and SOD increased significantly in cells pretreated with PGE₂ to levels similar to those observed in AC. Catalase activity increased from 9.4 ± 2.1 to 25.3 ± 4.7 U/mg protein, and SOD activity increased from 2.9 ± 3.5 to 14.0 ± 2.4 U/mg protein (P < 0.001 and P < 0.01).

Fig. 11. Catalase and superoxide dismutase (SOD) activities in cytosol of gallbladder muscle cells from sham-operated guinea pigs (control; open bars; n = 3) and guinea pigs with aAC (solid bars; n = 3). Data are Units/mg protein. Activities of both catalase and SOD were significantly increased in cytosol of muscle cells from guinea pigs with AC. *P < 0.001 and **P < 0.01 by Student’s t-test.

DISCUSSION

These studies show that acute inflammation in the guinea pig gallbladder affects the muscle contraction. It impairs the response to agonists that act on membrane constituents such as CCK-8 and ACh that stimulate transmembrane receptors and KCl that opens calcium channels. Other experimental models of acute inflammation involving the cat esophagus and dog’s ileum have also shown a defective muscle contraction, although the changes in the signal transduction were somewhat different (20–23, 37, 41, 42).

The initial muscle damage in AC appears to be confined to the plasma membrane because the contraction is normal when muscle cells are stimulated with agonists that bypass membrane receptors such as GTPγS, a direct G protein activator, and, with the second messengers IP₃ and DAG. AC also impairs the response to a receptor-independent agonist such as KCl, which contracts muscle cells by increasing calcium influx. These abnormalities are similar to those found in muscle cells from gallbladders with bile supersaturated with cholesterol (5). However, there are also significant differences, particularly in the contraction induced by PGE₂ which remains normal in AC.

Fig. 12. Effects of PGE₂ pretreatment in vitro on the activities of catalase and SOD in normal muscle cells from guinea pig gallbladders. Single muscle cells were obtained by enzymatic digestion. Muscle cells were incubated with PGE₂ (10⁻⁷ M) for 30 min and activities of catalase and SOD were measured. PGE₂ pretreatment (solid bars) significantly increased the activities of catalase and SOD compared with untreated group (open bars). *P < 0.001 and **P < 0.01 by Student’s t-test.
The finding that the initial muscle damage in experimental AC is confined to the plasma membrane is also supported by biochemical studies. Measurements of membrane lipids reveal that the phospholipid but not the cholesterol content of the plasma membrane of AC muscle cells is reduced resulting in a higher cholesterol-to-phospholipid ratio. Higher cholesterol-to-phospholipid ratios decrease the fluidity of plasma membranes (5), which could affect the functions of transmembrane proteins and calcium channels (5, 43). These abnormalities could explain the defective muscle cell contraction in response to CCK-8, ACh, and KCl. However, in contrast to the defective contraction induced by PGE\textsubscript{2} in gallbladders with cholesterol stones (48), the contraction caused by PGE\textsubscript{2} in muscle cells from gallbladders with AC is normal. These findings suggest that mechanisms other than a decrease in membrane fluidity are more likely to cause this impaired contraction because the actions of PGE\textsubscript{2} are also mediated by transmembrane receptor (9). The mechanisms whereby PGE\textsubscript{2} receptors and their functions are conserved are not fully understood (29, 30, 49). It is conceivable that this receptor preservation is due to the increased PGE\textsubscript{2} generation (53).

The reduction in the phospholipid content may be due to an increase in lipid peroxidation in the plasma membranes caused by the inflammation of the muscle cells as demonstrated by the higher production of TBA metabolites. This finding also suggests that the muscle damage may be mediated by reactive oxygen species. These reactive oxygen species could be released by polymorphonuclear cells that heavily infiltrate the gallbladder wall (11, 46) or generated within the muscle cells themselves induced by the presumed chemical factors that induce AC. The finding that reactive oxygen species are significantly increased in muscle cells from specimens affected by AC is consistent with this hypothesis.

The possibility that reactive oxygen species are involved in the pathogenesis of the muscle dysfunction in AC is further supported by the finding that these muscle cells respond to the inflammatory injury with cytoprotective mechanisms that are involved in neutralizing their deleterious effects (23). Many cells, including muscle cells, respond to reactive oxygen species with an increase in prostaglandins, particularly PGE\textsubscript{2} and scavengers of reactive oxygen species (15, 18, 26, 28, 36). The PGE\textsubscript{2} content of the gallbladder muscle was increased, and the activities of SOD and catalase were also elevated in this model of experimental AC. SOD converts monochloramine into hydrogen peroxide that is then inactivated by catalase (21, 25).

Reactive oxygen species may also damage transmembrane receptors by affecting SH radicals (12). The binding capacity of CCK-A receptors is markedly reduced in muscle cells from specimens with AC. Similar damage may occur to other receptors (cholinergic receptors) and calcium channels with the exception of receptors that can be protected by their ligands such as it seems to occur with PGE\textsubscript{2} receptors.

In summary, muscle cells from experimental AC are affected by and respond to acute inflammation. The initial injury appears to be confined to the plasma membranes affected by chemical factors that still need to be elucidated. However, reactive oxygen species may be one of the factors that may cause this muscle dysfunction either by inducing lipid peroxidation and changes in the phospholipid bilayer or by acting directly on SH radicals of transmembrane receptor (12). The relationship between the preservation of the functional integrity of PGE\textsubscript{2} receptors and pathways and the increased synthesis of reactive oxygen species scavengers needs further studies.

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