

**ROLE FOR MEMBRANE FLUIDITY IN ETHANOL-INDUCED
OXIDATIVE STRESS OF PRIMARY RAT HEPATOCYTES**

ODILE SERGENT, MANUELLA PEREIRA, CORINNE BELHOMME,
MARTINE CHEVANNE, LAURENCE HUC,
DOMINIQUE LAGADIC-GOSSMANN.

Groupe de Recherche En Thérapeutique AntiCancéreuse, UPRES 6027, Université de
Rennes1 (O.S., M.P., C.B., M.C.) and Institut National de la Santé Et de la Recherche
Médicale U620, Université de Rennes 1 (L.H., D. L.-G.), 35043 Rennes Cedex, France

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Corresponding author :

Odile Sergent

Laboratoire de Biologie Cellulaire et Végétale – Faculté de Pharmacie

2, av. Pr. Léon Bernard – 35043 Rennes Cedex– France

Tel.: +33(0)223234808 Fax : +33(0)223234794

e-mail : osergent@univ-rennes1.fr

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List of abbreviations :

ROS : reactive oxygen species; GM1 : monosialoganglioside 1, H₂FDA : dihydrofluorescein diacetate; UDCA : sodium ursodeoxycholate; 12-DSA : 12-doxyl stearic acid; DMPO : 5,5-dimethyl-1-pyrroline N-oxide; Tween 20 : polyoxyethylene sorbitan monolaurate; A₂C : 2-(2-methoxyethoxy) ethyl 8-(cis-2-n-octylcyclopropyl) octanoate; EPR : electron paramagnetic resonance; LMW iron : low-molecular-weight iron.

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Abstract

Relationship between bulk membrane fluidizing effect of ethanol and its toxicity due to oxidative stress is still unknown. In order to elucidate this issue, membrane fluidity of primary rat hepatocytes was studied by measuring order parameter after inhibition of ethanol-induced oxidative stress. We showed that pretreating cells with either 4-methyl-pyrazole (to inhibit ethanol metabolism), thiourea (a ROS scavenger) or vitamin E (a free radical chain-breaking antioxidant) prevented the ethanol-induced increase in membrane fluidity, thus suggesting that ethanol metabolism and reactive oxygen species (ROS) formation were involved in this elevation. The effects of membrane stabilizing agents [ursodeoxycholic acid (UDCA) or ganglioside GM1 (GM1)], shown to prevent fluidification, next pointed to a role for this increase in membrane fluidity in the development of ethanol-induced oxidative stress. Indeed, ROS production, lipid peroxidation and cell death were all inhibited by these agents. In contrast, the fluidizing compounds, tween 20 or A₂C, which increased the membrane fluidizing effect of ethanol, enhanced the related oxidative stress. Using EPR to determine low-molecular-weight iron, we finally demonstrated that membrane fluidity influence proceeded through an increase in low-molecular-weight iron to enhance oxidative stress. In conclusion, the present findings clearly highlight the pivotal role of membrane fluidity in ethanol-induced oxidative stress and the potential therapeutic effect of membrane stabilizing compounds.

Introduction

Oxidative damage to lipids, proteins and DNA following ethanol intoxication of the liver are very well-described (Nordmann et al, 1992; Bailey and Cunningham, 2002). Since oxidative stress generated in hepatocytes is involved in processes as varied as ethanol-induced apoptosis (Kurose et al, 1997; Minama et al, 2002), immune reactions towards the liver (Albano, 2002), activation of stellate cells and hence fibrogenesis (Nieto et al, 2002), this phenomenon seems to contribute to the pathogenesis of alcoholic liver diseases. Consequently, this emphasizes the necessity to fully characterize the molecular mechanisms of ethanol-induced oxidative stress in hepatocytes, especially during the early stages of the disease. It can result from ethanol metabolism in hepatocytes which triggers reactive oxygen species (ROS) production during both acute and chronic alcoholism (Sergent et al, 1995; Bailey and Cunningham, 1998). At the very early stage of the disease, changes in membrane fluidity could also play a role, as an increase in plasma membrane fluidity has been described after acute ethanol intoxication of WRL-68 hepatic cell lines (Gutierrez-Ruiz et al, 1995) or of primary rat hepatocytes (Benedetti et al, 1994). What is particularly interesting is that liver is the only organ to maintain this increase in membrane fluidity during chronic intoxication (Polokoff et al, 1985; Yamada and Lieber, 1984), even though chronic ethanol exposure of animals or liver cells would make membranes more resistant to the disordering effects of ethanol *in vitro* (Gutierrez-Ruiz et al, 1995; Polokoff et al, 1985). However, to our knowledge, no study has looked for a close association between ROS production and the increase in liver membrane fluidity due to ethanol intoxication. Actually, the main findings have focused on mitochondrial inner membrane and have highlighted a role for a decreased fluidity in the impairment of the mitochondrial transport of reduced glutathione, one of the most important antioxidants in cells (Lluis et al, 2003).

In the present study, we have performed a series of experiments in which bulk membrane fluidity was manipulated by incorporating membrane stabilizing agents or membrane

fluidizing compounds in membranes of rat hepatocytes. This has allowed assessment of the effect of membrane fluidity changes on ethanol-induced oxidative stress. In addition, membrane fluidity was also measured following inhibition of ethanol-induced oxidative stress in order to determine whether an early oxidative stress can influence the physical state of hepatocyte membranes.

METHODS

Chemicals

Eagle minimum essential medium and medium 199 with Hanks' salts were purchased from Biomedica (Boussens, France). Fetal calf serum was from Biowest (Nuaille, France). Liberase was from Roche Diagnostics (Meylan, France). Ethanol and thiourea were obtained from Prolabo (Paris, France). Monosialoganglioside 1 sodium salt (GM1) was from Alexis (Coger, Paris, France). Dihydrofluorescein diacetate (H₂FDA) was provided by Molecular Probes (Interchim, Montluçon, France). Ursodeoxycholate sodium salt (UDCA) was from Calbiochem (Meudon, France). 12-doxyl stearic acid (12-DSA), Hoechst 33342, α -tocopherol, desferrioxamine, 5,5-dimethyl-1-pyrroline N-oxide (DMPO), 4-methylpyrazole, xanthine, xanthine oxidase, polyoxyethylene sorbitan monolaurate (Tween 20), 2-(2-methoxyethoxy) ethyl 8-(cis-2-n-octylcyclopropyl) octanoate (A₂C) were all purchased from Sigma-Aldrich (Saint Quentin Fallavier, France).

Cell isolation and culture

Briefly, adult rat hepatocytes were isolated from 2-months-old Sprague-Dawley animals by perfusion of the liver as previously described, except that a liberase solution (17 μ g/ml) was used for dissociation of liver parenchymal cells instead of a collagenase solution (Guguen-Guillouzo et al, 1983). Routinely, more than 90 % of the freshly isolated hepatocytes excluded trypan blue and 500 million of hepatocytes could be obtained from a single rat liver perfusion. Cells obtained using this protocol were shown to synthesize albumin, a specific function of hepatocytes, and to form bile canalicular-like elements (Guguen-Guillouzo et al, 1983). Cells were seeded at densities of 30×10^3 cells/well in 96-well Falcon microplates (ROS evaluation), 3×10^6 cells in 25-cm² Falcon flasks (lipid peroxidation evaluation), 10×10^6 cells in 75-cm² Falcon flasks (membrane fluidity determination), 20×10^6 cells in 175-cm² Falcon flasks (low-molecular-weight iron measurement) and cultured in a medium

composed of 75 % Eagle minimum essential medium and 25 % medium 199 with Hanks' salts, supplemented with 10 % fetal calf serum and containing streptomycin (50 µg), penicillin (5 µg), bovine insulin (5 µg), bovine serum albumin (1 mg), and NaHCO₃ (2.2 mg) per milliliter. The cells were kept at 37°C in an atmosphere of 5% CO₂ and 95% air. The medium was changed 3 hours after seeding and substituted with the same medium as above but deprived of serum. Culture treatments were in all cases started the day after seeding.

Culture treatments

Ethanol at a final concentration of 50 mM was added to rat hepatocytes and cultures maintained at 37°C for 0.5 to 24 hours. It should be noted that over our test ethanol exposure period, no significant evaporation could be found in culture media without cells (Sergent et al, 1995). In one set of experiments, some cultures were preincubated either for 1 hour with membrane stabilizing agents (100 µM UDCA or 60 µM GM1) or for 0.5 hour with membrane fluidizers (600 µg/ml tween 20 or 5 µM A₂C) and then, the medium was discarded before adding ethanol. In the experiments seeking the mechanisms underlying the fluidizing effect of ethanol, hepatocyte cultures were pretreated either for 12 hours with α-tocopherol (250 µM), a lipid peroxidation inhibitor, for 1 hour with thiourea (100 mM), a ROS scavenger, or for 0.5 hour with 4-methylpyrazole (1 mM), an ethanol metabolism inhibitor. These latter agents were kept in medium during the incubation with ethanol.

Measurement of membrane fluidity

The fluidity of hepatocyte bulk membranes (i.e. plasma membrane and possibly endosome and lysosome membranes) was determined by a spin-labelling method using electron paramagnetic resonance (EPR), as previously described in other cell cultures (Ogura et al, 1988). At the end of each incubation period, the lipid bilayer of hepatocyte membranes were spin labelled by incubation, for 15 minutes at 37°C, of hepatocyte suspensions with 12-doxyl

stearic acid (12-DSA; 50 µg/ml), a fatty acid exhibiting a stable nitroxide radical ring at the C-12 position. Cells were then washed three times with PBS to remove the free spin label. The resultant pellet was then transferred to a disposable glass capillary. The EPR spectra of labelled samples were acquired at ambient temperature on a Bruker 106 EPR spectrometer operating at 3495 G center field, 20 mW microwave power, 9.82 GHz microwave frequency, 1.771 G modulation amplitude and 100 kHz modulation frequency. The fluidity of the labelled membrane was quantified by calculating the order parameter S according to equations previously described (Ogura et al, 1988). An increase in the value of S is interpreted as a decrease in membrane fluidity, whereas a decrease of this parameter reflects an increase in membrane fluidity.

Determination of reactive oxygen species production

Intracellular levels of ROS were measured using the non-fluorescent probe, H₂FDA, as previously described (Hempel et al, 1999). Oxidation by ROS causes a conversion of this probe into fluorescent fluorescein. Briefly, hepatocytes were loaded with 50 µM of H₂FDA in Hepes-buffered solution for 30 min at 37°C, washed with Hepes and then treated with 50 mM ethanol in usual culture medium. After a last wash, fluorescence was directly recorded by a SpectraMax Gemini Spectrofluorimeter (Molecular Devices, France) using 485 nm excitation and 530 nm emission wavelengths.

Evaluation of lipid peroxidation

Lipid peroxidation was analyzed by measurement of extracellular free malondialdehyde as described previously (Morel et al, 1990). Briefly, malondialdehyde was measured by size-exclusion chromatography after ultrafiltration of the culture media through 500-Da membrane (Amicon, France).

Measurement of low-molecular-weight iron

Measurement of intracellular low-molecular-weight iron was based upon the capacity of desferrioxamine to chelate only low-molecular-weight iron and to give a paramagnetic chelate, which had the advantage to be directly detectable by EPR in whole hepatocytes (Sergent et al, 1997a).

Cell death determination by microscopy

As neither caspase activity nor lactic dehydrogenase release could be detected under our experimental conditions (unpublished results), cell death was studied by visualisation of nuclear morphology (condensed and fragmented chromatin) and by estimation of lysosome disruption. Nuclear fragmentation was monitored by Hoechst 33342 staining (excitation 330-380 nm, emission 460 nm). After 5 hours of incubation with ethanol, cells were stained in PBS with 2 mg/ml of Hoechst dye for 15 minutes at 37°C in the dark. Cells were examined using an inverted Olympus microscope and the percentage of cells with fragmented nuclei was calculated as (cells with fragmented nuclei/total cells) x 100. Total population was always > 300 cells.

Lysosome disruption was estimated from acridine orange-stained hepatocytes knowing that an increase in green acridine orange fluorescence reflected such a disruption (Zhao et al, 2000). Briefly, cultures were incubated with acridine orange (5 µM) for 20 minutes at 37°C before being detached by incubation with trypsin/EDTA. Following resuspension of cells in culture medium, cell suspensions were immediately analyzed by flow cytometry on a FACS calibur flow cytometer (Becton Dickinson, San Jose, USA). Fluorescence emission from acridine orange was detected at FL1 (Green acridine orange fluorescence) following excitation at 488 nm. Each measurement was conducted on 20 000 events and analyzed on Cell Quest software (Becton Dickinson).

Free radical scavenging properties

Scavenging properties of membrane stabilizing agents towards hydroxyl radical ($^{\circ}\text{OH}$) and superoxide anion (O_2^-) were examined by spin trapping using 5,5-dimethyl-1-pyrroline-N-oxide (DMPO) as a spin trap. For the $^{\circ}\text{OH}$ radical generation, the so-called Fenton reaction was employed. Briefly, reaction mixture was constituted as follows : 30 μl distilled water, 50 μl H_2O_2 (40 mM), 10 μl DMPO (800 mM), 90 μl ferrous sulfate (1 mM) supplemented with either 20 μl distilled water or 20 μl UDCA (1 mM), or 20 μl GM₁ (600 μM). For the spin trapping experiments of the O_2^- , the xanthine/xanthine oxidase reaction was used to generate O_2^- by preparing the following reaction mixture : 30 μl xanthine oxidase (26 U/ml), 30 μl xanthine (5 mM), 20 μl DMPO (400 mM), 100 μl ethanol supplemented with either 20 μl distilled water or 20 μl UDCA (1 mM), or 20 μl GM₁ (600 μM). Immediately after a vigorous stirring, the reaction mixtures were injected inside a glass capillary. For $^{\circ}\text{OH}$ or O_2^- detection, EPR spectra were recorded after 1 or 2 minutes, respectively, on a Bruker 106 EPR spectrometer at room temperature with the EPR settings as follows : 3495 G field center, 9.81 GHz microwave frequency, 20 mW microwave power, 100 kHz frequency modulation, 0.804 G modulation amplitude, 81.92 ms conversion time, 1.28 ms time constant. The intensities of EPR spectra were represented by the double integration of the lines of lowest field. Free radical scavenging activities of UDCA and GM₁ were expressed as percent decrease in the EPR intensity of the control performed with distilled water.

Statistical analysis

Values were expressed as means \pm SD. Hepatocytes obtained from three different isolations were generally used for all the protocols carried out. Multiple comparisons among the groups were performed using ANOVA followed by the parametric Student-Newman-Keuls test or the non parametric Mann-Whitney test, depending on the results of the normality test. Differences were considered significant at $p < 0.05$.

RESULTS

Early increase in membrane fluidity upon ethanol exposure involved oxidative stress

In order to investigate the kinetics of ethanol-induced membrane fluidizing effect, rat hepatocytes were treated with 50 mM ethanol for different incubation times (Figure 1A). The values were expressed as percent deviation from the order parameter calculated from untreated cells. An early increase (+3.3 %) in membrane fluidity of rat hepatocytes upon ethanol exposure was detectable after 30 minutes of incubation. Longer incubation times resulted in a more extensive rise, with a deviation percentage of +8.7% at 5 hours. For the 24-hour-incubation time, no change could be observed compared to control hepatocytes (data not shown). As ethanol metabolism is well-known to induce an oxidative stress which may affect membrane fluidity, the effect of ethanol on membrane fluidity was also evaluated after pretreatment of hepatocytes either by 4-methyl-pyrazole, an inhibitor of ethanol metabolism, by thiourea, a ROS scavenger, or by vitamin E, a free radical chain-breaking antioxidant. It should be noted that 4-methyl-pyrazole, at this concentration, inhibited ethanol elimination by 95 % (unpublished results). As shown in figure 1B, all these compounds prevented the increase in membrane fluidity due to ethanol. Indeed, in 4-methyl-pyrazole-, thiourea- or vitamin E- pretreated hepatocytes, no significant differences in the order parameter were found between ethanol-treated and untreated cultures.

The membrane fluidizing effect of ethanol was responsible for an enhancement of oxidative stress

To determine whether the increase in membrane fluidity could participate in oxidative stress induced by ethanol, membrane stabilizing agents such as GM1 ganglioside or ursodeoxycholic acid (UDCA) were added prior to addition of ethanol. These agents were first confirmed as being capable of blocking the membrane fluidizing effect of ethanol since, following pretreatment of cells with GM1 or UDCA, ethanol remained without effect on the

order parameter (Figure 2). In rat hepatocytes treated with ethanol, a rise in ROS production was detectable as soon as 15 minutes (Figure 3A). Following 1 and 5 hours of incubation, the level of ROS was further increased, by nearly 2 fold, when compared to untreated cells (Figures 3B and 3C, respectively); no significant effect of ethanol was detected at 24 hours (data not shown). Interestingly, membrane stabilizing agents displayed no effect on ROS formation induced by a 15 min-exposure to ethanol (Figure 3A), whereas, following 1 or 5 hours of treatment, a significant protection against ROS production was observed (Figures 3B and 3C). Besides, we found that 4-methyl-pyrazole inhibited ROS formation as soon as 15 minutes (Figure 3A). Note that ROS production increases in all groups over time. This is due to the primary culture senescence. Indeed, it is well-known that many antioxidant enzymes, such as Cu,Zn superoxide dismutase, glutathione peroxidase or catalase, are less expressed over incubation time after isolation of rat hepatocytes (Antras-Ferry et al, 1997).

In order to fully demonstrate the involvement of the increase in membrane fluidity in ethanol induced-oxidative stress, lipid peroxidation but also cell death were next followed, since oxidative stress generated by ethanol metabolism participates in ethanol-induced cell death (Kurose et al, 1997; Minama et al, 2002). Using malondialdehyde as a marker of lipid peroxidation, an increase by about 160 % of lipid peroxidation was observed in hepatocyte cultures treated for 5 hours with ethanol (Figure 4A). This elevation of malondialdehyde content was inhibited by pretreating cells with membrane stabilizing agents, GM1 or UDCA (Figure 4A). In addition, both these agents prevented ethanol induced-cell death (Figures 4B and 4C). For lower concentrations of ethanol (10, 20, 30 mM), UDCA exhibited a similar protection on both ROS formation and lipid peroxidation (data not shown).

The involvement of the membrane fluidizing effect of ethanol in its capacity to generate oxidative stress was further confirmed by adding tween 20, a mild neutral detergent, or A₂C, a fatty acid –like compound, to hepatocytes before ethanol treatment. Indeed, tween 20 and A₂C were demonstrated to increase membrane fluidity under our experimental conditions (Figure

2), both in the presence or absence of ethanol. This elevation of membrane fluidity might be responsible for potentiation of ethanol-induced oxidative stress (Figures 5A and 5B) and cell death (Figure 5C) in cultures pretreated by tween 20 or A₂C. Note also that tween 20 or A₂C alone induced slight but significant effects on oxidative stress ($p < 0.01$). In addition, the supplementation of hepatocytes with UDCA, before exposure to tween 20 or A₂C, protected cells from the potentiation by tween 20 or A₂C of ethanol-induced ROS formation (Figure 5A). Similar effect was observed with GM1 (data not shown). It should be added that membrane stabilizing agents or fluidizing compounds did not change the rate of ethanol uptake by hepatocytes (data not shown).

The protection afforded by membrane stabilizing agents was not due to a direct antioxidant property

With the aim of seeking a possible direct antioxidant property of membrane stabilizing agents, which might have explained the above results, UDCA and GM1, at the same concentrations as those used above, were tested by EPR for their capacity to scavenge superoxide anion or hydroxyl radical. UDCA and GM1 did not display a potent scavenging capacity (data not shown). Indeed, UDCA was the only agent to scavenge superoxide anion and this superoxide anion scavenging capacity was very weak (21 %).

To fully rule out the possibility of a direct antioxidant effect of UDCA or GM1, these drugs were also tested for their capacity to protect cells from lipid peroxidation induced by iron. This was carried out using a 5 h-exposure to 20 μ M ferric nitriloacetate. Lipid peroxidation was followed by measuring malondialdehyde, a secondary end product of degradation of oxidized polyunsaturated fatty acids. UDCA and GM1 were unable to abolish the increase in malondialdehyde in hepatocytes treated by ferric nitriloacetate (Control : 95 ± 6 ng/mg protein ; UDCA : 86 ± 7 ng/mg protein; GM1 : 79 ± 4 ng/mg protein; iron : 1012 ± 51 ng/mg protein; UDCA + iron : 944 ± 130 ng/mg protein; GM1 + iron : 915 ± 87 ng/mg protein ; $n = 3$

independent experiments). Even with ferric nitriloacetate at a lower concentration (5 μM) which led to a lesser extent of lipid peroxidation, UDCA and GM1 did not succeed to reduce malondialdehyde levels to those of the controls (data not shown). Taken together, these data strongly emphasized that membrane stabilizing agents, at the concentration used in our experiments, did not exhibit any direct antioxidant property.

The involvement of membrane fluidity in ethanol-induced oxidative stress proceeded through an increase in low-molecular-weight iron content.

Low-molecular-weight-iron consists of iron species that are not contained in high-molecular-weight molecules, such as ferritin or mitochondrial ferroproteins, but are able to trigger oxidative stress by catalyzing the formation of a highly reactive free radical, the hydroxyl radical, *via* Fenton or Haber-Weiss reaction. An EPR technique was used to directly measure the level of low-molecular-weight iron in intact cells. As expected from previous studies (Sergent et al, 1995; Sergent et al, 1997a), ethanol increased the content in low-molecular-weight-iron by nearly 40 % (Figure 6A). UDCA and GM1 pretreatment totally protected cells from this elevation whereas tween 20 pretreatment enhanced it (Figure 6A). As ROS formation could be inhibited by desferrioxamine, a low-molecular-weight iron chelator, (Figure 6B) and as ethanol-induced lipid peroxidation has been previously described to be inhibited by deferiprone, another low-molecular-weight iron chelator (Sergent et al, 1997b), it can be concluded from the present results that the membrane fluidizing effect of ethanol contributed to ethanol-induced oxidative stress by promoting the elevation of low-molecular-weight iron.

DISCUSSION

The present study demonstrates, for the first time, that an increase in bulk membrane fluidity can amplify the oxidative stress induced by ethanol in the liver. In addition, we have found a new interpretation based upon an early ROS production to explain how ethanol can very rapidly increase membrane fluidity. Thus, in rat hepatocytes, in only 30 minutes of incubation, ethanol elicited an early membrane fluidizing effect. Whereas the fluidizing effect of ethanol had been ascribed until now to the disruption of the orderly packing between adjacent acyl chains due to either direct entering of ethanol in the lipid portion of the membrane (Rottenberg, 1991), an increased phosphatidylcholine/sphingomyelin ratio (Polokoff et al, 1985) or a decreased cholesterol/phospholipid ratio (Yamada and Lieber, 1984) of liver plasma membranes, we showed here that oxidative stress due to ethanol metabolism also contributed to the elevation of membrane fluidity since this rise was prevented by both antioxidants and 4-methyl-pyrazole, an inhibitor of ethanol metabolism. Moreover, the earliest detectable ROS production, which was observed as soon as 15 minutes, preceded the increase in membrane fluidity detected only at 30 minutes, and was inhibited by 4-methyl-pyrazole, but not by GM1 or UDCA, suggesting that the early ROS formation was only related to ethanol metabolism. Thus, the proposed sequence of events linking ethanol metabolism to its membrane fluidizing effect is shown on figure 7. Although not directly addressed in this study, the possible molecular mechanism, whereby oxidative stress influences membrane fluidity of rat hepatocytes, can be discussed. Lipid peroxidation by-products have been widely recognized to increase membrane fluidity either by interacting with membrane proteins (Debouzy et al, 1992; Buko et al, 1996; Subramaniam et al, 1997) or more directly by their own rearrangement (Jain et al, 1994; Gabbita et al, 1998). ROS are also able, by oxidizing tubulin, to disrupt the microtubule cytoskeleton and thereby to increase membrane fluidity (Yoon et al, 1998; Remy-Kristensen et al, 2000). This remains to be tested under our conditions.

As stated above, the major finding of this study is the demonstration that an early increase in membrane fluidity can be crucially involved in the enhancement of oxidative stress. Indeed, UDCA and GM1 totally inhibited ethanol-induced ROS production, lipid peroxidation and apoptosis in rat hepatocytes, whereas tween 20 and A₂C enhanced them. The beneficial effects of UDCA and GM1 were found by EPR to be concomitant with a stabilizing effect on hepatocyte membranes, while Tween 20 enhanced the fluidizing effect of ethanol. It should be noted that UDCA and GM1 displayed a protection towards ethanol-induced ROS production only when ROS were evaluated after 1 or 5 hours of incubation with ethanol. At 15 minutes, no protection was afforded by membrane stabilizing agents, unlike the inhibitor of ethanol metabolism, 4-methyl-pyrazole. This has led us to postulate a sequence of events whereby the early ROS formation was mainly due to ethanol metabolism and the late phase might also be attributed to the increase in membrane fluidity (Figure 7). To reinforce the determinant role for the increased membrane fluidity in the initiation of oxidative stress, we have further sought the mechanism whereby membrane fluidity can elicit oxidative stress. Using EPR determination with intact hepatocytes, we show that similarly to their effects on ethanol-induced ROS production and lipid peroxidation, UDCA and GM1 inhibited the increase in low-molecular-weight iron content induced by ethanol, whereas Tween 20 enhanced it. It should be noted that, in previous studies (Sergent et al, 1995), the increase in low-molecular-weight-iron was shown to be detectable only after 30 minutes of incubation with ethanol. Altogether, these results strongly support the idea that oxidative injury due to the elevation of membrane fluidity was mediated by an increase in low-molecular-weight iron content. Indeed, low-molecular-weight iron consists of iron species that can trigger oxidative stress by catalyzing the formation of a highly reactive free radical, the hydroxyl radical. In our study, desferrioxamine, a low-molecular-weight iron chelator, was thus found to inhibit the ROS formation induced by ethanol in rat hepatocytes. These results agree with those of

Rouach and coworkers (Rouach et al, 1994), who observed an early increase of hepatic iron uptake from transferrin related to ROS produced by ethanol, but without establishing a link with the membrane fluidizing effect of ethanol. In this regard, it should be emphasized that an increased transferrin receptor mobility can favor its internalization (Paccaud et al, 1993) and that the major pool of low-molecular-weight iron is located in lysosomes or late acidic endosomes (Yu et al, 2003). In our model, it cannot be excluded that the elevation of low-molecular-weight iron content could be due to an increase ROS formation. Indeed, superoxide anion is well-described to release iron from ferritin (Biemond et al, 1988) and oxidative stress can promote rupture of late acidic endosomes or lysosomes, thus liberating iron from these organelles (Yu et al, 2003). In this regard, our results on acridine orange-stained hepatocytes, that suggested lysosome disruption, would tend to support that point.

It should be kept in mind that the toxic effect of an increase in membrane fluidity, described in this study, concerns bulk membranes. Indeed, a decrease rather than an increase in fluidity has been demonstrated in inner membranes of mitochondria isolated from HepG2 cells treated with acetaldehyde, a product of ethanol metabolism (Lluis et al, 2003). Moreover, the addition of a membrane fluidizer such as A₂C to these mitochondria can restore levels of glutathione, an important antioxidant for cells (Lluis et al, 2003). In this context, the use of membrane fluidizers should be done with caution since, from our results, it appears that they can be injurious for hepatocytes. On the contrary, UDCA and its conjugates seem to be good candidates for a potential therapeutic use : due to their membrane stabilizing properties, they re-establish the normality in membrane fluidity for every type of membranes. Thus, in case of ethanol intoxication, they are able to prevent both the increase of bulk membrane fluidity, as we observed it, and the decrease in the mitochondria membrane of hepatocytes from ethanol-fed rats, thereby restoring mitochondrial glutathione levels (Colell et al, 2001). Moreover, our results about the cytoprotection afforded by UDCA and GM1 agree with previous studies which showed the prevention by UDCA of ethanol-induced necrosis and apoptosis,

respectively, in human Hep G2 cells (Neuman et al, 1995) and primary rat hepatocytes (Rodrigues et al, 1998), or by GM1 of ethanol-induced death in mice neural crest cells (Chen et al, 1996) and rat cerebellar granule neurons (Saito et al, 1999). UDCA was also found to prevent lipid peroxidation in the liver from chronic ethanol-fed rats (Montet et al, 2002). But none of these works were capable of giving a clear understanding of the mechanism involved in the protection against oxidative injury. In our study, UDCA and GM1 actions, at the doses used in our experiments, cannot be attributed to direct antioxidant properties of these compounds since they were unable to scavenge superoxide anion and hydroxyl radical *in vitro* and to inhibit iron-induced lipid peroxidation of rat hepatocytes. This new mechanistic demonstration of a beneficial effect of UDCA is particularly interesting because UDCA is a therapeutically relevant bile acid, already used for preventing human chronic cholestatic liver diseases (Poupon et al, 2003; Colombo et al, 1992), that might be useful in the very early stages of the alcoholic liver diseases as well.

In conclusion, the present study shows that ethanol metabolism, by triggering an early ROS production, promotes a rapid increase in membrane fluidity. The fluidizing effect of ethanol is then responsible for a secondary elevation of low-molecular-weight iron leading to an enhancement of ROS production which can then induce lipid peroxidation and apoptosis (Figure 7). Consequently, early ethanol toxicity can be strongly enhanced by an increase in membrane fluidity due to ethanol metabolism itself or membrane fluidizers. The present findings clearly highlight the pivotal role of membrane fluidity in the early stages of alcoholic liver disease, and, in this context, membrane stabilization might be a very effective strategy to protect hepatocytes from oxidative damage.

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FOOTNOTES

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Person to receive reprint requests :

Odile Sergent

Laboratoire de Biologie Cellulaire et Végétale – Faculté de Pharmacie

2, av. Pr. Léon Bernard – 35043 Rennes Cedex– France

Tel.: +33(0)223234808 Fax : +33(0)223234794

e-mail : osergent@univ-rennes1.fr

LEGENDS FOR FIGURES

Figure 1 : Ethanol increased membrane fluidity in rat hepatocytes.

A : Changes in the membrane fluidity of hepatocytes treated with ethanol (50 mM) for 0.25, 0.5, 1, 5 or 24 hours. The membrane fluidity was monitored by EPR analysis of 12-DSA embedded in membranes. This analysis resulted in the obtention of an order parameter S which is inversely related to membrane fluidity. Data were expressed as a percent deviation from those obtained in untreated control cultures. **B : Effects of 4-methyl-pyrazole, an inhibitor of ethanol metabolism, thiourea, a ROS scavenger, and vitamin E, a free radical chain-breaking antioxidant, on the increase of membrane fluidity in hepatocytes treated with ethanol (50 mM) for 1 hour.** Some rat hepatocyte cultures were pre-incubated with 1 mM 4-methyl-pyrazole (4MP) for 0.5 hour, or with 100 mM thiourea (TH) for 1 hour, or with 250 μ M vitamin E (Vit E) for 12 hours. Results were obtained as in A, except that data were directly expressed as order parameter (S). Values are the mean \pm SD of three independent experiments. Ethanol-treated *versus* untreated cultures : *, $p < 0.05$; **, $p < 0.01$.

Figure 2 : Effects of membrane stabilizing agents (UDCA or GM1) or membrane fluidizers (Tween 20 or A₂C) on the membrane fluidizing effect of ethanol. The membrane fluidity was monitored by EPR analysis of 12-DSA embedded in membranes. This analysis allowed the estimation of an order parameter S which is inversely related to membrane fluidity. Rat hepatocytes were incubated or not with ethanol (50 mM) for 1 hour. Some cultures were pretreated, for 1 hour, with membrane stabilizing agents [100 μ M UDCA or 60 μ M GM1] or, for 0.5 hour, with membrane fluidizers [600 μ g/ml Tween 20 or 5 μ g/ml A₂C]. Values are the mean \pm SD of three independent experiments. Ethanol-treated *versus* untreated cultures : **, $p < 0.01$.

Figure 3 : Effects of membrane stabilizing agents (UDCA or GM1) or of 4-methylpyrazole, an inhibitor of ethanol metabolism, on ROS production induced by ethanol.

ROS production was followed by the fluorescence of FDA. Rat hepatocytes were incubated or not with ethanol (50 mM) for 15 minutes (A), 1 hour (B) or 5 hours (C). Some cultures were pretreated for 1 hour with 100 μ M UDCA or 60 μ M GM1. Values are the mean \pm SD of three independent experiments. Ethanol-treated *versus* untreated cultures : *, $p < 0.05$; ***, $p < 0.001$.

Figure 4 : Membrane stabilizing agents (UDCA or GM1) prevented ethanol-induced

lipid peroxidation (A) and cell death (B,C). Lipid peroxidation was estimated by measurement of free malondialdehyde (MDA). Cell death was identified by staining nuclear chromatin with Hoechst 33342 (B) and or by staining lysosomes with acridine orange (C). L-leucyl-L-Leucine methylester [LLeMe] 500 μ M, 20 minutes at 37°C, was used as a positive control of lysosome disruption. Rat hepatocytes were incubated or not with ethanol (50 mM) for 5 hours. Some cultures were pretreated for 1 hour with 100 μ M sodium ursodeoxycholate (UDCA) or 60 μ M sodium monosialoganglioside (GM1). Values are the mean \pm SD of three independent experiments, except for nuclear fragmentation experiments ($n = 3$ or 5). Ethanol-treated *versus* untreated cultures : *, $p < 0.05$; **, $p < 0.01$.

Figure 5 : Effects of membrane fluidizers (tween 20 or A₂C) on ROS formation (A), lipid peroxidation (B) and cell death (C) in rat hepatocytes incubated with ethanol. The

membrane fluidity was monitored by EPR analysis of 12-DSA embedded in membranes. The estimated order parameter S is inversely related to membrane fluidity. ROS production was followed by the fluorescence of FDA. Lipid peroxidation was estimated by measurement of MDA. Cell death was identified by staining nuclear chromatin with Hoechst 33342.

Concerning studies on ROS formation, rat hepatocytes were incubated or not with ethanol (50

mM) for 1 hour. For studies on lipid peroxidation and cell death, ethanol was added for 5 hours. Some cultures were pretreated for 0.5 hour with 600 $\mu\text{g/ml}$ tween 20 or 5 mg/ml A_2C . Values are the mean \pm SD of three independent experiments, except for cell death experiments ($n = 3$ or 5). Ethanol-treated *versus* untreated cultures : *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. A_2C - or tween 20-treated *versus* untreated cultures : #, $p < 0.05$; ##, $p < 0.01$.

Figure 6 : Changes in low-molecular-weight iron content can account for the involvement of membrane fluidity in ethanol-induced oxidative stress.

A : Effects of membrane stabilizing agents (UDCA and GM1) and tween 20 on low-molecular-weight iron content in rat hepatocytes treated with ethanol for 1 hour. Low-molecular-weight iron was determined by EPR analysis after chelation by 1 mM desferrioxamine. Rat hepatocytes were preincubated either for 1 hour with 100 μM UDCA or 60 μM GM1 or for 0.5 hour with 600 $\mu\text{g/ml}$ tween 20. Values are the mean \pm SD of three independent experiments. Ethanol-treated *versus* untreated cultures : **, $p < 0.01$; ***, $p < 0.001$. **B : Effect of desferrioxamine, a low-molecular-weight iron chelator, on ROS formation induced by ethanol.** Rat hepatocytes were incubated with ethanol for 1 hour or not. Some cultures were pretreated for 1 hour with 20 μM desferrioxamine (DESF). Ethanol-treated *versus* untreated cultures ; ***, $p < 0.001$.

Figure 7 : Proposed model for the role of early ROS-induced fluidizing effect of ethanol in the amplification of oxidative stress. In hepatocytes, ethanol metabolism can very rapidly lead to ROS production which, in turn, increased membrane fluidity. This increase can promote the elevation of low-molecular-weight (LMW) iron content and therefore the enhancement of ROS production and lipid peroxidation to finally trigger cell death. Membrane fluidizers (Tween or A_2C) by potentiating the increase in membrane fluidity

enhanced oxidative stress, while membrane stabilizing agents (UDCA or GM1), by protecting from the fluidizing effect of ethanol, inhibited it.

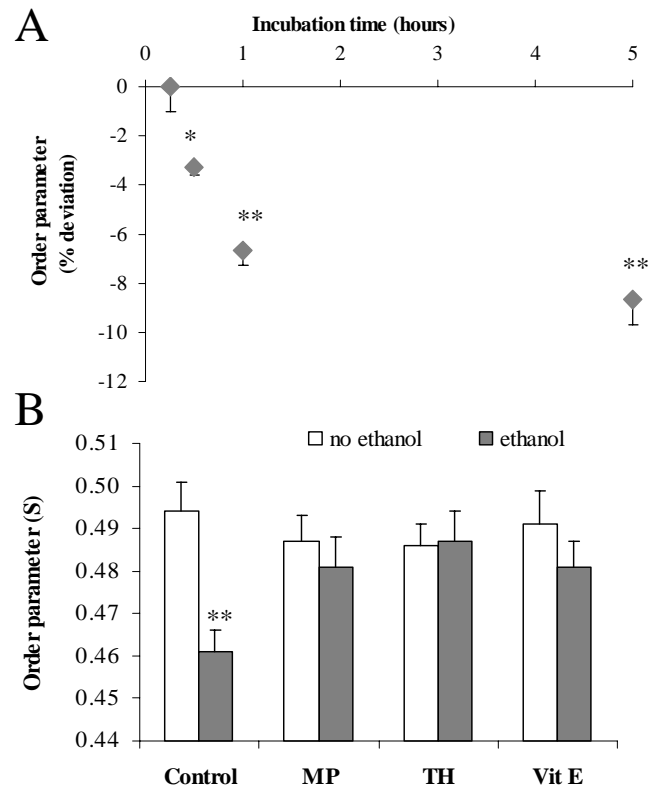


Figure 1

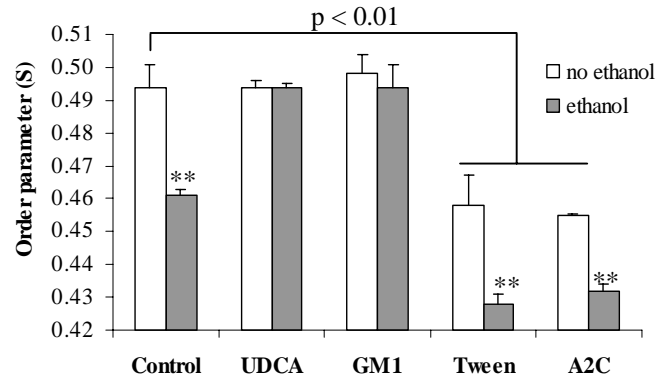


Figure 2

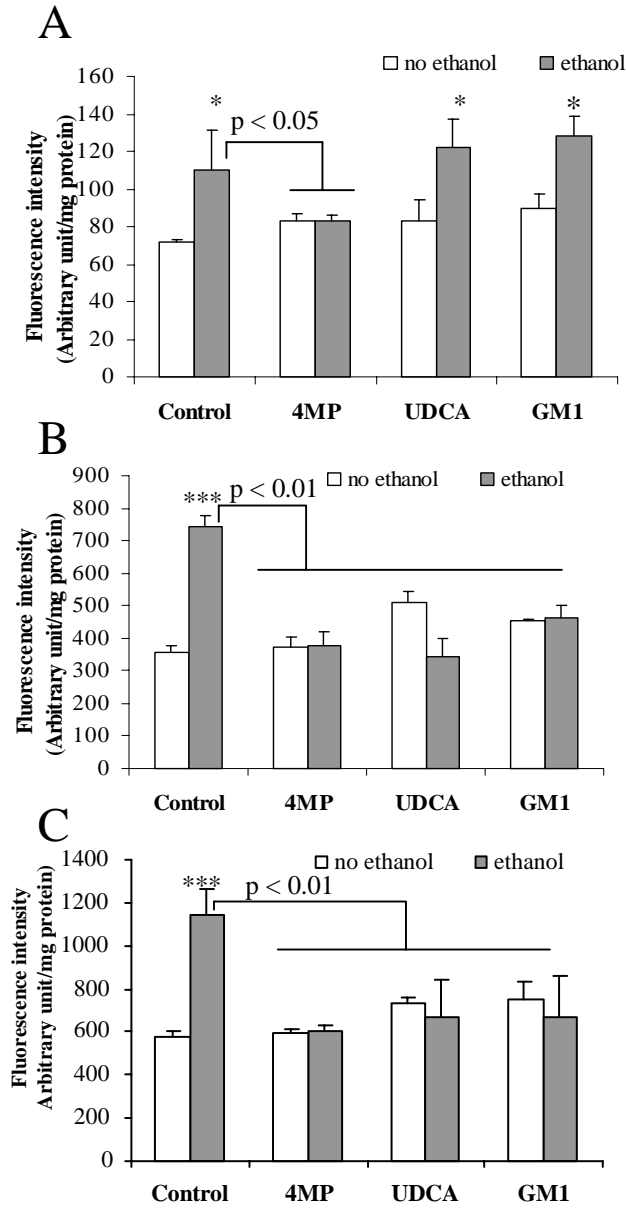


Figure 3

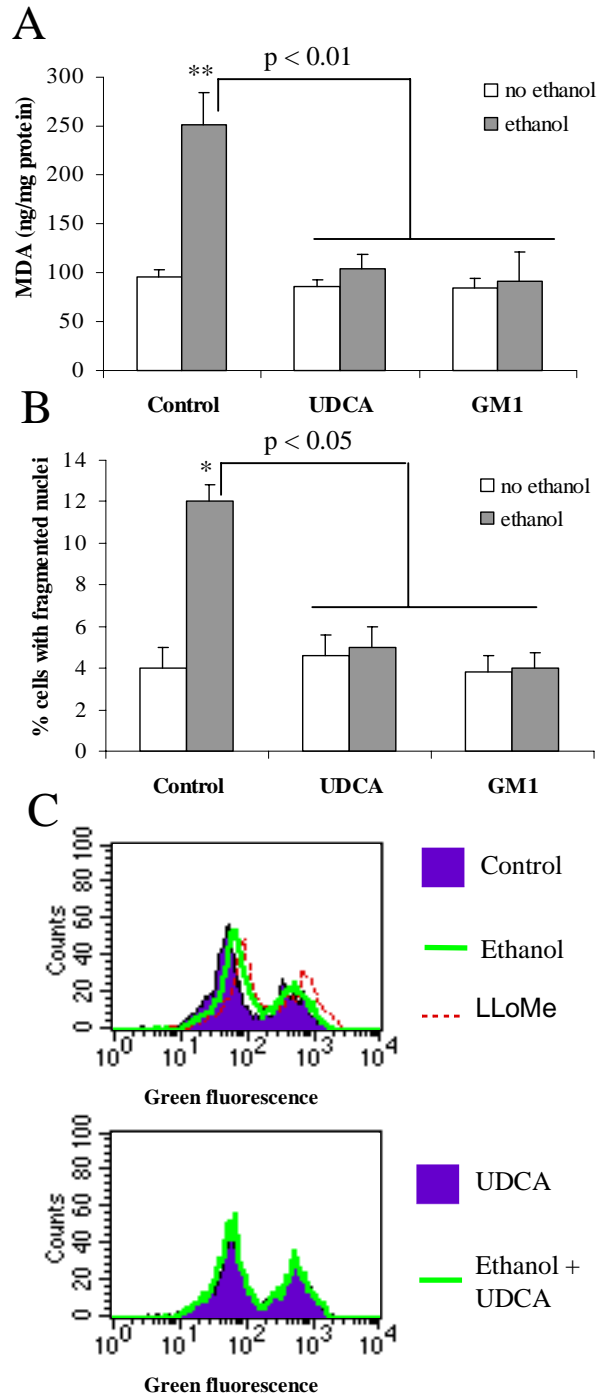


Figure 4

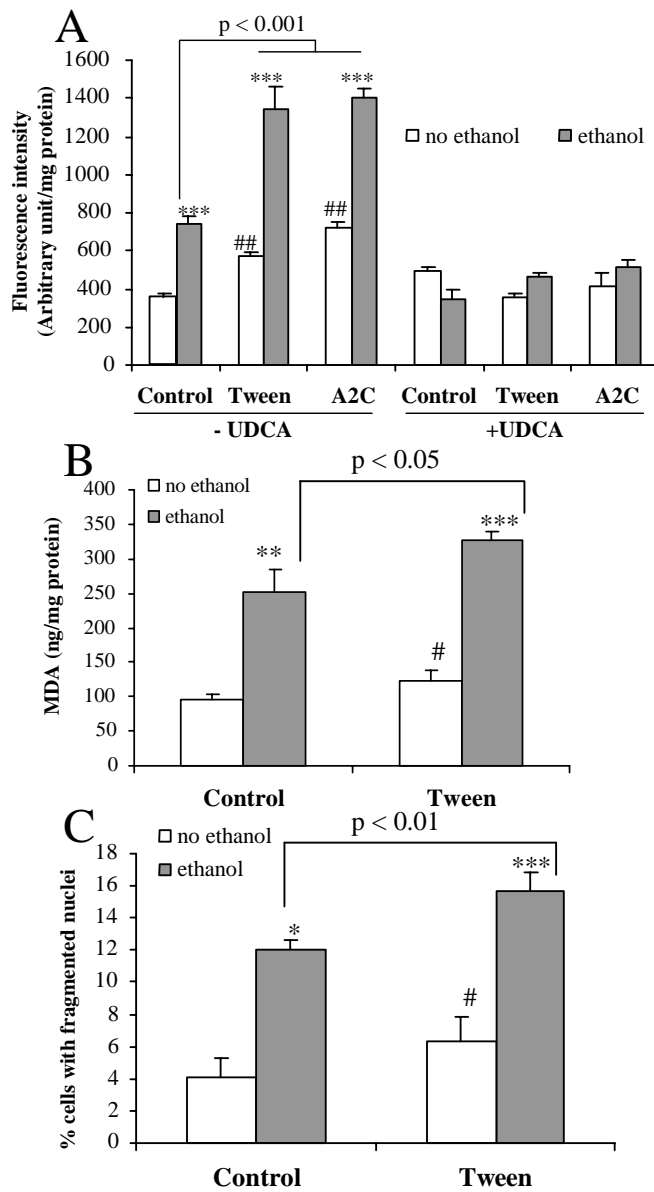


Figure 5

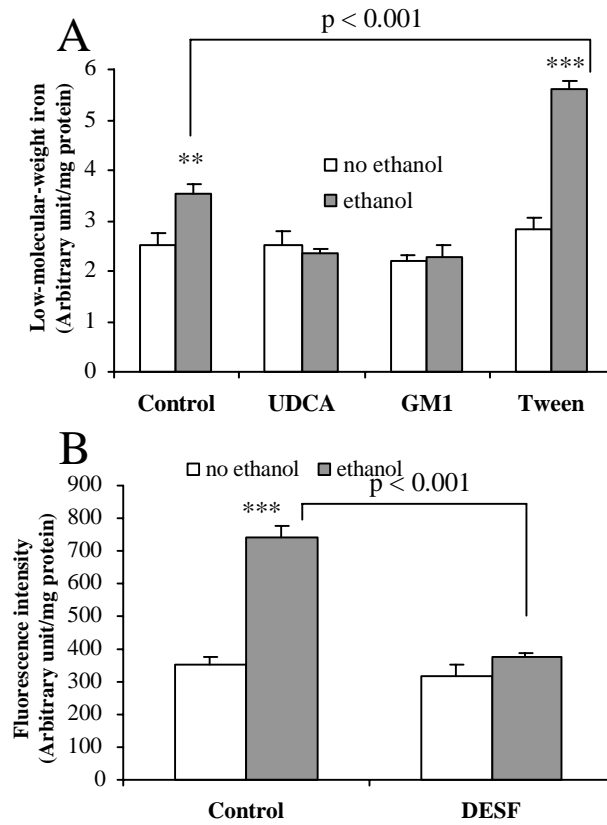


Figure 6

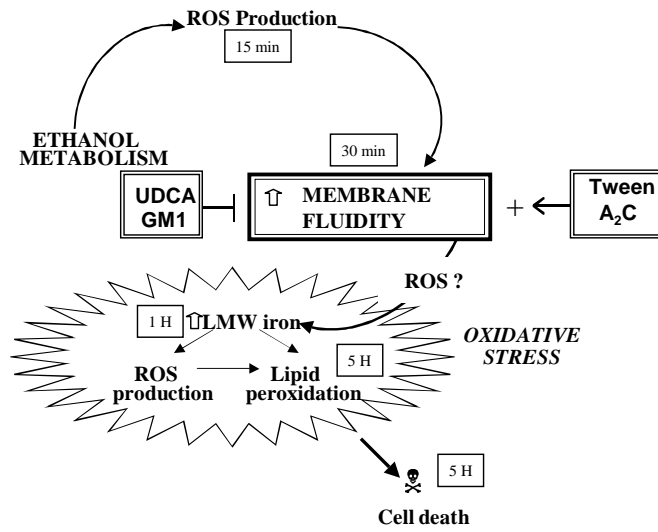


Figure 7