

## Palmitoleate attenuates palmitate-induced Bim and PUMA up-regulation and hepatocyte lipoapoptosis<sup>☆</sup>

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**Background & Aims:** Saturated free fatty acids induce hepatocyte lipoapoptosis. This lipotoxicity involves an endoplasmic reticulum stress response, activation of JNK, and altered expression and function of Bcl-2 proteins. The mono-unsaturated free fatty acid palmitoleate is an adipose-derived lipokine which suppresses free fatty acid-mediated lipotoxicity by unclear mechanisms. Herein we examined the mechanisms responsible for cytoprotection.

**Methods:** We employed isolated human and mouse primary hepatocytes, and the Huh-7 and Hep 3B cell lines for these studies. Cells were incubated in presence and absence of palmitate (16:0), stearate (18:0), and or palmitoleate (16:1, n-7).

**Results:** Palmitoleate significantly reduced lipoapoptosis by palmitate or stearate in both primary cells and cell lines. Palmitoleate accentuated palmitate-induced steatosis in Huh-7 cells excluding inhibition of steatosis as a mechanism for reduced apoptosis. Palmitoleate inhibited palmitate induction of the endoplasmic reticulum stress response as demonstrated by reductions in CHOP expression, eIF2- $\alpha$  phosphorylation, XBP-1 splicing, and JNK activation. Palmitate increased expression of the BH3-only proteins PUMA and Bim, which was attenuated by palmitoleate. Consistent with its inhibition of PUMA and Bim induction, palmitoleate prevented activation of the downstream death mediator Bax.

**Conclusions:** These data suggest palmitoleate inhibits lipoapoptosis by blocking endoplasmic reticulum stress-associated increases of the BH3-only proteins Bim and PUMA.

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### Introduction

The metabolic syndrome, characterized by obesity and insulin resistance, is associated with elevated levels of circulating free fatty acid (FFA) [1,2]. The excess serum FFA in the context of insulin resistance saturates the transport and storage capacity of adipocytes leading to their uptake by liver, skeletal muscle, heart, and pancreatic  $\beta$ -cells [2]. The surfeit of FFA results in their participation in non-oxidative pathways with potential deleterious consequences for the non-adipocyte including cellular demise, termed lipoapoptosis [3]. This phenomenon is particularly relevant to the liver where hepatocyte lipotoxicity contributes to the syndrome of nonalcoholic fatty liver disease (NAFLD) [4]. Indeed, hepatocyte lipoapoptosis is a pathologic feature of NAFLD and correlates with disease severity [5,6]. Thus, mechanistic insights regarding the initiation and prevention of hepatocyte lipoapoptosis are of biomedical interest.

Intracellular FFA are trafficked to and esterified within the endoplasmic reticulum (ER), and not surprisingly, inundation of the liver with FFA disturbs ER function resulting in an ER stress response [7], which is well documented in NAFLD [8]. A potent transducer of ER stress response in NAFLD is PERK [9]. PERK activation induces the transcription factor CHOP [10], which is increased in liver and hepatocytes from dietary models of hepatic steatosis [11]. Another transducer of ER stress is IRE-1, which leads to activation of JNK [10]. Consistent with an ER stress-induced pathway of FFA-mediated cytotoxicity, hepatocyte lipoapoptosis is also associated with JNK activation in both rodent and human steatohepatitis, and JNK inhibition attenuates lipoapoptosis in these models [12,13]. Thus, ER stress-associated JNK activation is a potential cellular mechanism contributing to hepatocyte lipoapoptosis.

Bcl-2 protein family member can act to induce or prevent apoptosis [14]. JNK activation can be linked to dysregulation of

**Keywords:** Apoptosis; Bcl-2 proteins; Endoplasmic reticulum stress; Human hepatocytes; Nile Red; Steatosis.

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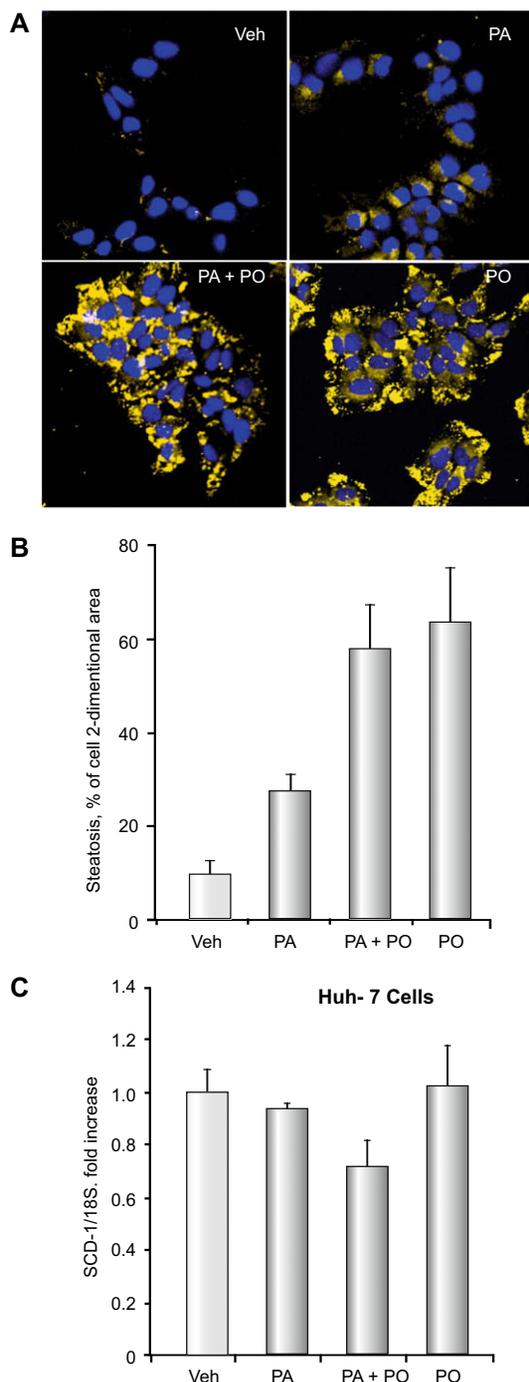
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**Abbreviations:** FFA, free fatty acid; NAFLD, nonalcoholic fatty liver disease; ER, endoplasmic reticulum; PERK, protein kinase RNA-like ER kinase; CHOP, CCAAT/enhancer binding homologous protein; IRE-1, inositol-requiring protein-1; JNK, c-Jun-N-terminal kinase; BH3, Bcl-2 homology 3; PUMA, p53-upregulated mediator of apoptosis; Bim, Bcl-2-interacting mediator of cell death; PA, palmitate; SA, stearate; PO, palmitoleate; SCD-1, stearoyl-CoA desaturase-1; DMEM, Dulbecco's modified Eagle's medium with high glucose; PCR, polymerase chain reaction; GADD 34, growth arrest and DNA damage gene 34; Bax, BCL2-associated X protein; XBP-1, X Box binding protein-1; eIF2- $\alpha$ , eukaryotic initiation factor 2- $\alpha$ ; DAPI, 4',6-diamidino-2-phenylindole.



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**Fig. 1. PO does not attenuate PA-mediated steatosis.** Nile Red staining was performed on Huh-7 cells treated with vehicle (Veh), 200  $\mu$ M PA, 200  $\mu$ M PO plus 200  $\mu$ M PA, or 200  $\mu$ M PO alone for 18 h. (A) Representative fluorescent photomicrographs (x 60) are depicted. Nile Red fluoresces as a yellow-gold at about 510 nm; cells were counter-stained for nucleic acids by DAPI (blue). (B) Cellular steatosis was quantified in 5 random low power fields for each condition with image analysis software. Total area of lipid per cell (pixels above threshold) is represented. The data represent the mean  $\pm$  SEM for  $n = 3$  studies. (C) Huh-7 cells were treated with vehicle (Veh), 800  $\mu$ M PA, 400  $\mu$ M PO plus 800  $\mu$ M PA, or 400  $\mu$ M PO alone for 8 h. SCD-1 mRNA was quantified by real time PCR. Fold induction was determined by normalization to 18S ribosomal RNA. Data represent the mean  $\pm$  SEM of three independent experiments.

this core cell death machinery, promoting cell death [4]. In particular, JNK-1 but not JNK-2 activation by toxic FFA results in increased cellular levels of the pro-apoptotic BH3-only protein members of the Bcl-2 protein PUMA, and silencing this death mediator attenuates lipoapoptosis [15]. JNK is also known to activate Bim [16], which is another BH3-only protein contributing to lipoapoptosis [12]. Thus, ER stress can be directly coupled to dysregulation of Bcl-2 proteins which in turn trigger the mitochondrial pathway of apoptosis. Taken together, these observations suggest that FFA induce lipoapoptosis through both induction of PUMA and Bim, which in turn results in activation of the downstream death mediator Bax. Oligomerization of Bax within the outer mitochondrial membrane triggers mitochondrial dysfunction and cell death [17].

FFA and not their esterified product (triglyceride) appear to mediate lipotoxicity [18]. Experimental evidence indicates that saturated FFA such as PA (a 16 carbon FFA with no carbon-carbon double bonds, indicated 16:0) and stearate (18:0; SA) are more toxic than unsaturated FFA [12]. The mono-unsaturated FFA palmitoleate (PO; 16:1, n-7), is a unique product of adipocytes and functions as a lipid hormone, called a lipokine [19]. Although PO itself may effect minimal cytotoxicity, it is far less compared to saturated free fatty acids [12]. Furthermore, PO exerts a salutary effect in a murine model of the metabolic syndrome [19], in part by reducing expression of SCD-1, an enzyme which converts saturated FFA into mono-unsaturated FFA, a key step in channeling FFA into triglyceride synthesis [20]. PO has also been reported to reduce toxic FFA acid-induced apoptosis in rat hepatoma cell lines [21]. However, the mechanisms by which PO exerts its cytoprotective effects remain unclear and have not been directly examined in human hepatocytes. The elucidation of how this lipokine mitigates hepatocyte lipoapoptosis may help identify treatment strategies for human NAFLD.

The current work addresses the question of how PO reduces hepatocyte lipoapoptosis by toxic saturated FFA *in vitro*. We identify a pathway that involves PO inhibition of ER stress, and PUMA and Bim induction by PA. Inhibition of ER stress-mediated dysregulation of Bim and PUMA by PO and/or analogues may be salutary in human NAFLD.

**Materials and methods**

**Cells.** The human hepatocellular carcinoma cell lines, Huh-7, and Hep3B cells, and primary hepatocytes were employed for these studies. Detailed information regarding the culture conditions is in the [Supplementary Materials And Methods Section](#).

**Fatty acid treatment.** Palmitic acid (catalog # P5585) and palmitoleic acid (catalog # P9417) were obtained from Sigma-Aldrich (St. Louis, MO). Free fatty acids were dissolved in isopropanol at a concentration of 20–80 mM. FFA were added to DMEM containing 1% bovine serum albumin to assure a physiologic ratio between bound and unbound FFA in the media [22]. The concentrations of individual FFA used in the experiments (200–800  $\mu$ M) are similar to the fasting total FFA plasma concentrations observed in human nonalcoholic steatohepatitis [23–25].

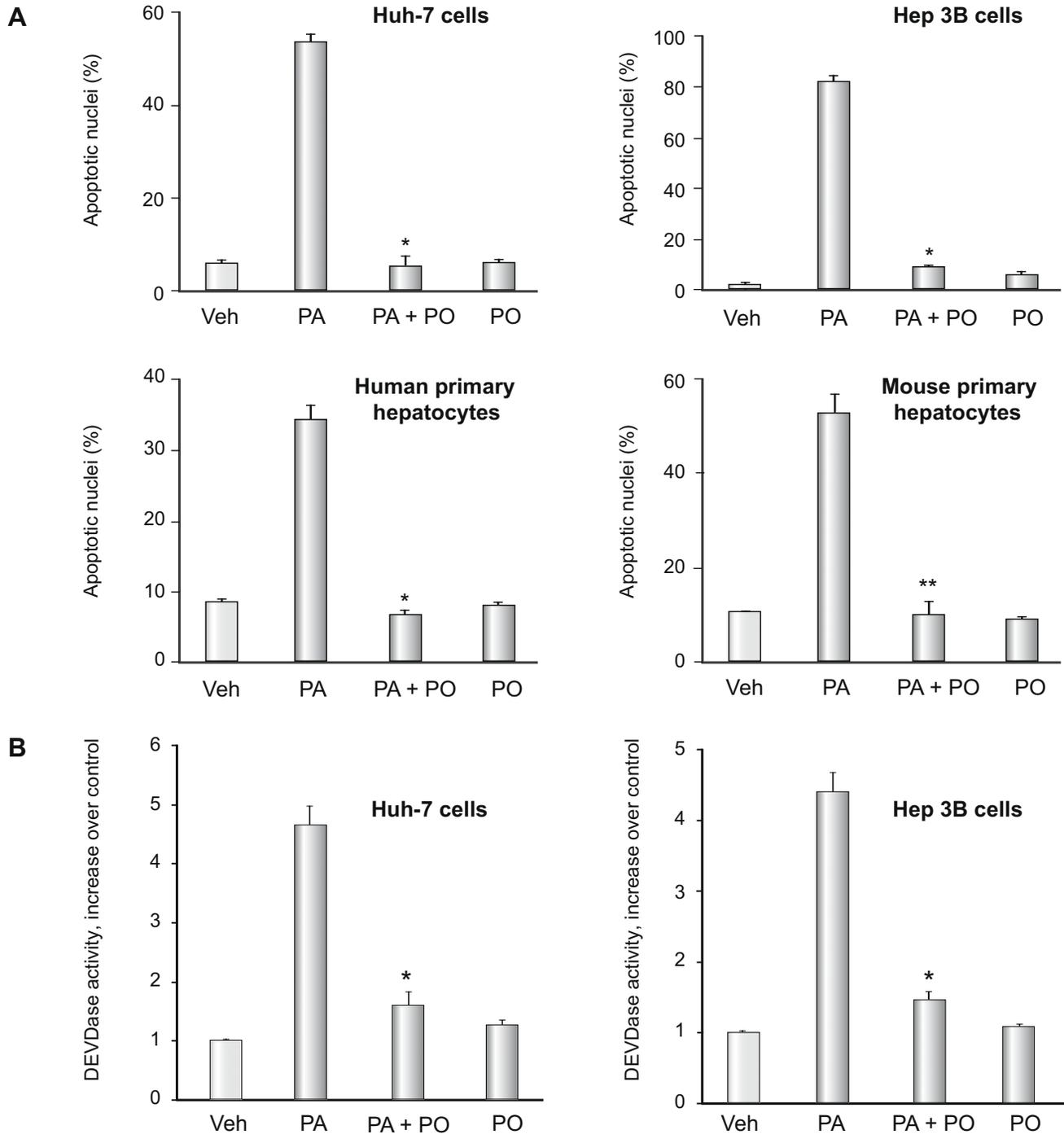
**Quantification of apoptosis.** Apoptosis was quantified by assessing the characteristic nuclear changes of apoptosis using the nuclear binding dye DAPI (Molecular Probes, Eugene, OR) and fluorescence microscopy (Zeiss LSM 510, Carl Zeiss, Jena, Germany). Caspase 3/7 activation in cell cultures was measured using Apo-ONE homogeneous caspase 3/7 kit (Promega, Madison, WI) according to the manufacturer's instructions.

**Nile Red staining.** Huh-7 cells were grown on glass coverslips. Intracellular neutral lipid was stained with Nile Red (1  $\mu$ g/ml) for 5 min at room temperature. Cells were then fixed with 3.7% paraformaldehyde for 15 min at room temperature. After washing with PBS, cells were mounted in Prolong Antifade (Invitrogen,

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Camarillo, CA) and visualized using an inverted laser-scanning confocal microscope (Zeiss LSM 510, Carl Zeiss, Jena, Germany) with wavelength of 480 nm for excitation and greater than 505 nm for emission for lipid stain [26]. Cellular

fluorescence was quantitated using Zeiss KS400 image analysis software (Carl Zeiss, Inc., Oberkochen, Germany) and expressed as percent of Nile Red positive area per cell.



**Fig. 2. PO attenuates PA-mediated apoptosis.** (A) Cells were treated with free fatty acids. The concentration of PA was 800  $\mu$ M for Huh-7 cell, 400 $\mu$ M for Hep 3B cells, and 200  $\mu$ M for primary hepatocytes. The ratio of PA: PO was 2:1 for Huh-7 cells and 1:1 for the remainder of the cell types. Apoptosis was assessed by morphological criteria after DAPI staining. The data represent the mean  $\pm$  SEM for  $n = 3$  studies.  $p < 0.01$ ,  $p < 0.05$ , PA-treated cells vs. PA plus PO-treated cells. (B) After Huh-7 cells were treated as in (A), activity of effector caspases 3 and 7 was measured by a fluorogenic assay. Data are expressed as fold-increase of relative fluorescence units (RFLU) over control value (untreated cells), which was arbitrarily set to 1, and represent the mean  $\pm$  SEM for  $n = 3$  studies each performed in triplicate.  $p < 0.05$ , PA-treated cells vs. PA plus PO-treated cells.

**Real time polymerase chain reaction (PCR).** Total RNA was extracted from the cells using the Trizol reagent (Invitrogen) and was reverse-transcribed into complementary DNA with Moloney murine leukemia virus reverse transcriptase (Invitrogen) and random primers (Invitrogen). Quantification of the complementary DNA template was performed with real time PCR (LightCycler; Roche Applied Science) using SYBR green (Molecular Probes) as a fluorophore. PCR primers were as follows: for human SCD-1 forward (5'-CGCTAGACTTGTGACCTAGAA-3') and reverse (5'-CAAGCGTGGGACAGGATGAAGCA-3'), for human PUMA forward (5'-GACGACCTCAACGCACAGTA-3') and reverse (5'-AGGAGTCCCATGATGAGATTGT-3'), and for human GADD 34 forward (5'-CGACTGCAAAGCGGC-3') and reverse (5'-CAGGAAATGGACAGTGACCTTCT-3'). As an internal control, primers for 18S ribosomal RNA (rRNA) were used (Ambion, Austin, TX). The relative mRNA expression levels were expressed as a ratio of target mRNA /18S rRNA per each sample as previously described by us in detail [27]. CHOP real time PCR was performed using Taqman technology using commercially available primers (Hs00358796\_g1) from Applied Biosystems.

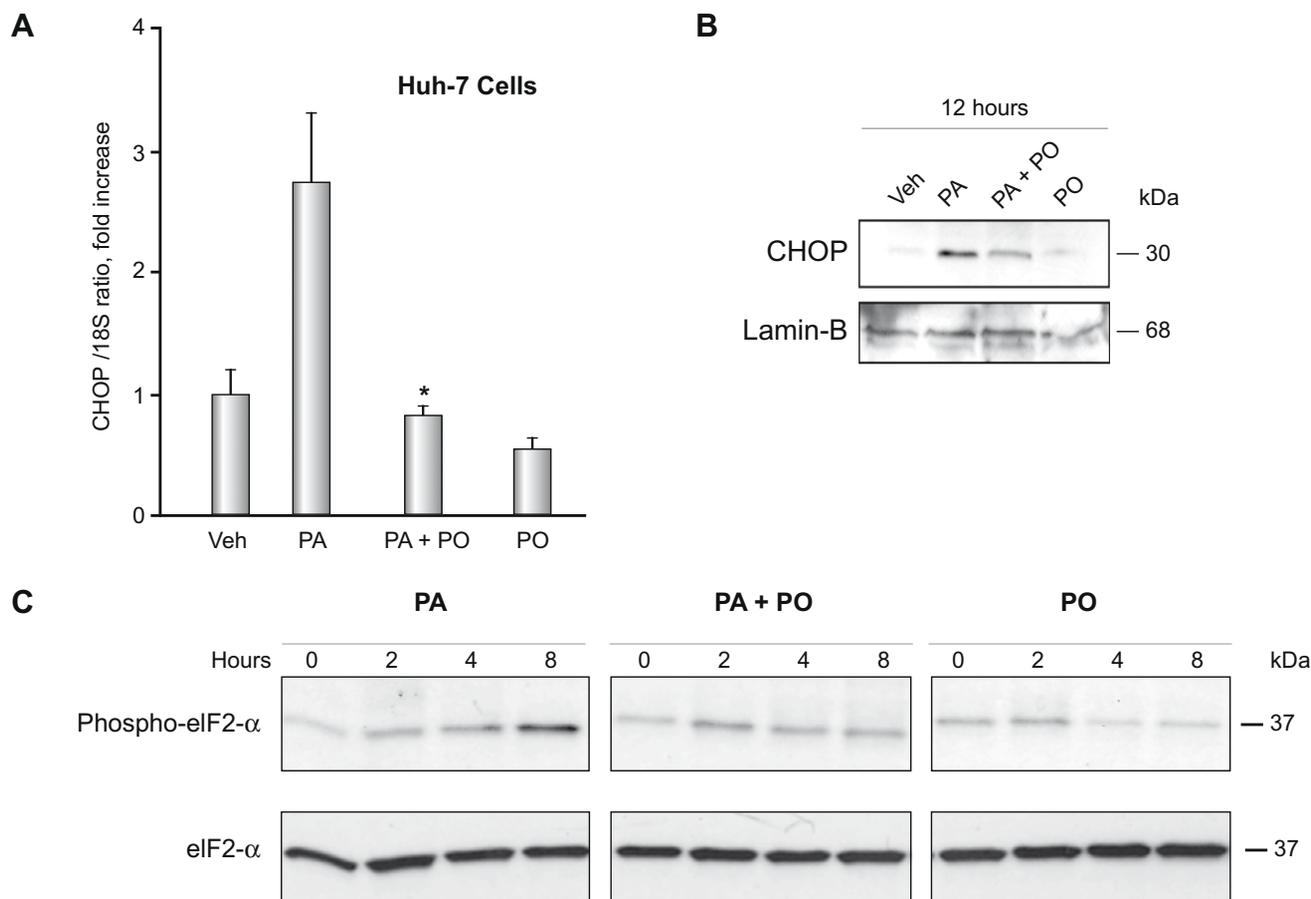
**Immunoblot analysis.** Whole cell lysates were prepared and subjected to immunoblot analysis as previously described in detail [27]. For CHOP protein analysis, nuclear extracts from whole cell lysates were obtained using Nuclear and Cytoplasmic Extraction Reagent (Thermo Scientific, Rockford, IL) following manufacturer's instruction. Samples containing 60 µg protein were resolved by 4–15% SDS-PAGE, transferred to nitrocellulose membranes, and incubated with primary antibodies at a dilution of 1:1000. Membranes were incubated with appropriate horseradish peroxidase-conjugated secondary antibodies (Biosource International, Camarillo, CA) at a dilution of 1:3000. Bound antibody was visualized using chemiluminescent substrate (ECL, Amersham, Arlington Heights, IL) and was exposed to Kodak X-OMAT film (Eastman Kodak, Rochester, NY).

**Immunocytochemistry for Bax activation.** Immunocytochemistry of activated Bax was performed using mouse anti-universal Bax (clone 6A7, 1:300 dilution, Exalpa Biologicals, Watertown, MA) as previously described in detail [15].

Detailed information on cells cultures and conditions, antibodies and reagents, analysis of XBP-1 splicing, and statistical analysis is in the Supplemental Materials and methods.

**Results**

**Despite accentuating cellular steatosis, PO attenuates PA-mediated lipoapoptosis.** We have previously reported that PA treatment of hepatocytes is associated with cellular steatosis [12], therefore, we initially examined the effect of PO on PA-associated cellular steatosis in Huh-7 cells. Cells were treated with either vehicle, 200 µM of PA, 200 µM of PO, or a combination of both. Unexpectedly, the magnitude of cellular steatosis was even greater with PO than PA (Fig. 1A and B). The combination resulted in steatosis similar to that observed with PO alone. Although PO is thought to inhibit hepatic steatosis *in vivo* by reducing SCD-1 expression [19], PO did not alter expression of SCD-1 mRNA in Huh-7 cells *in vitro* (PA 800 µM, PO 400 µM) (Fig. 1C). Thus, PO does not reduce the intracellular accumulation of neutral lipids when cells



**Fig. 3. PO inhibits PA-induced CHOP up-regulation and phosphorylation of eIF2-α.** (A) Huh-7 cells were treated with vehicle (Veh), 800 µM PA, 800 µM PA plus 400 µM PO, or 400 µM PO alone for 8 h. CHOP mRNA was quantified by real time PCR. Fold induction was determined by normalization to 18S. Data represent the mean and error of three independent experiments each performed in triplicate. *p* < 0.05, PA-treated cells vs. PA plus PO-treated cells. (B) Huh-7 cells were treated as above. Nuclear extracts were obtained from each experimental conditions and were subjected to immunoblot analysis for CHOP. Lamin B was used as a loading control. (C) Huh-7 cells were treated as above for the indicated time. Whole cell lysates were obtained and resolved by SDS-PAGE. Proteins were identified by Western blot analysis by using antisera specific for total and phospho-eIF2-α.

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are incubated with PA but rather increases steatosis in cultured Huh-7 cells.

Despite promoting increased lipid accumulation, PO attenuates PA-induced apoptosis. As maximal cytoprotective effect was observed at a PA:PO ratio of 2:1 in Huh-7 cells, and 1:1 in other liver cell lines and primary hepatocytes, these ratios were employed for all further studies (data not shown). As assessed by morphologic criteria, PO reduced PA-mediated apoptosis in Huh-7 (PA 800  $\mu$ M, PO 400  $\mu$ M) and Hep 3B cell lines (PA 400  $\mu$ M, PO 400  $\mu$ M), and primary mouse and human hepatocytes (PA 400  $\mu$ M, PO 400  $\mu$ M) (Fig. 2A). This cytoprotective effect of PO was dose-dependent (Supplemental Fig. 1). Apoptosis was also confirmed biochemically in Huh-7 cells and Hep 3B cells by measuring caspase 3/7 activity which yielded results virtually identical to the morphologic studies (Fig. 2B). This anti-apoptotic effect of PO was also observed in stearate (SA)-treated cells (SA 800  $\mu$ M, PO 400  $\mu$ M) (Supplemental Fig. 2A, B). Taken together, these data indicate that PO potently suppresses saturated FFA cytotoxicity despite enhancing steatosis. Given that PO cytoprotection was similar in cell lines and primary hepatocytes, we employed the Huh-7 cell line for further mechanistic studies.

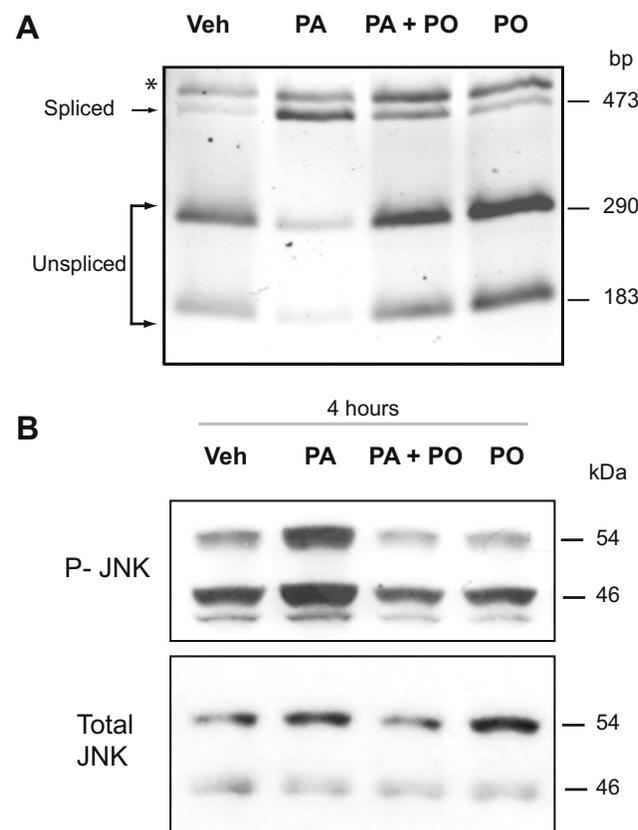
*PO attenuates ER stress-induced by PA.* Previous work by Pagliassotti and co-workers indicates that FFA-induced lipoapoptosis occurs via an ER stress pathway [8]. Therefore we explored the effect of PO on ER stress induced by PA. First, we examined activation of the PERK response system of the ER stress pathway [10], which is characterized by CHOP induction [28]. PA-mediated induction of CHOP mRNA and protein expression was reduced in the presence of PO (Fig. 3A and B). PO also attenuated induction of GADD 34 mRNA, which is also upregulated by ER stress downstream of CHOP [10] (Supplemental Fig. 3). Furthermore, PO also attenuated phosphorylation of eIF2- $\alpha$ , which is also activated by PERK [10] (Fig. 3C). Next, we examined the ER stress response transduced by IRE-1, which is characterized by XBP-1 splicing and JNK activation [10]. PA treatment of Huh-7 cells induced XBP-1 splicing, consistent with activation of IRE-1 endonuclease activity (Fig. 4A). This XBP-1 splicing was inhibited by PO (PA 800  $\mu$ M, PO 400  $\mu$ M) (Fig. 4A). Activating phosphorylation of JNK by PA was also reduced in the presence of PO (PA 800  $\mu$ M, PO 400  $\mu$ M) (Fig. 4B). These results indicate that PO inhibits multiple ER stress pathways initiated by PA. Finally, we ascertained if PO also reduces ER stress by thapsigargin or tunicamycin, which are classic cell biological approaches for inducing ER stress [29]. PO did not, however, inhibit thapsigargin nor tunicamycin-induced CHOP mRNA expression (Supplemental Fig. 4). Collectively, these data indicate that PO blocks ER stress by PA, an effect specific for cytotoxic FFA.

*PO reduces Bim and PUMA induction, and Bax activation by PA.* Consistent with our previous observation [15,27], PA increased PUMA and Bim cellular protein levels (Fig. 5A). In contrast, cellular levels of other BH3-only proteins (Noxa, Bik, Bad, Bid), pro-apoptotic multidomain Bcl-2 proteins (Bak, Bax), and the anti-apoptotic protein Bcl-X<sub>L</sub> were unaltered. Consistent with its cytoprotective effects, PO (PO 400  $\mu$ M and PA 400  $\mu$ M) attenuated Bim and PUMA induction by PA. In addition, PO also attenuated PUMA mRNA induction by PA (Fig. 5B). Activation of Bax, a known mediator of mitochondrial dysfunction, is required for induction of hepatocyte lipoapoptosis downstream of PUMA and Bim induction [12,15]. Indeed, both Bim and PUMA can directly activate Bax which in turn triggers mitochondrial dysfunction and cell death [14]. Activated Bax was identified by

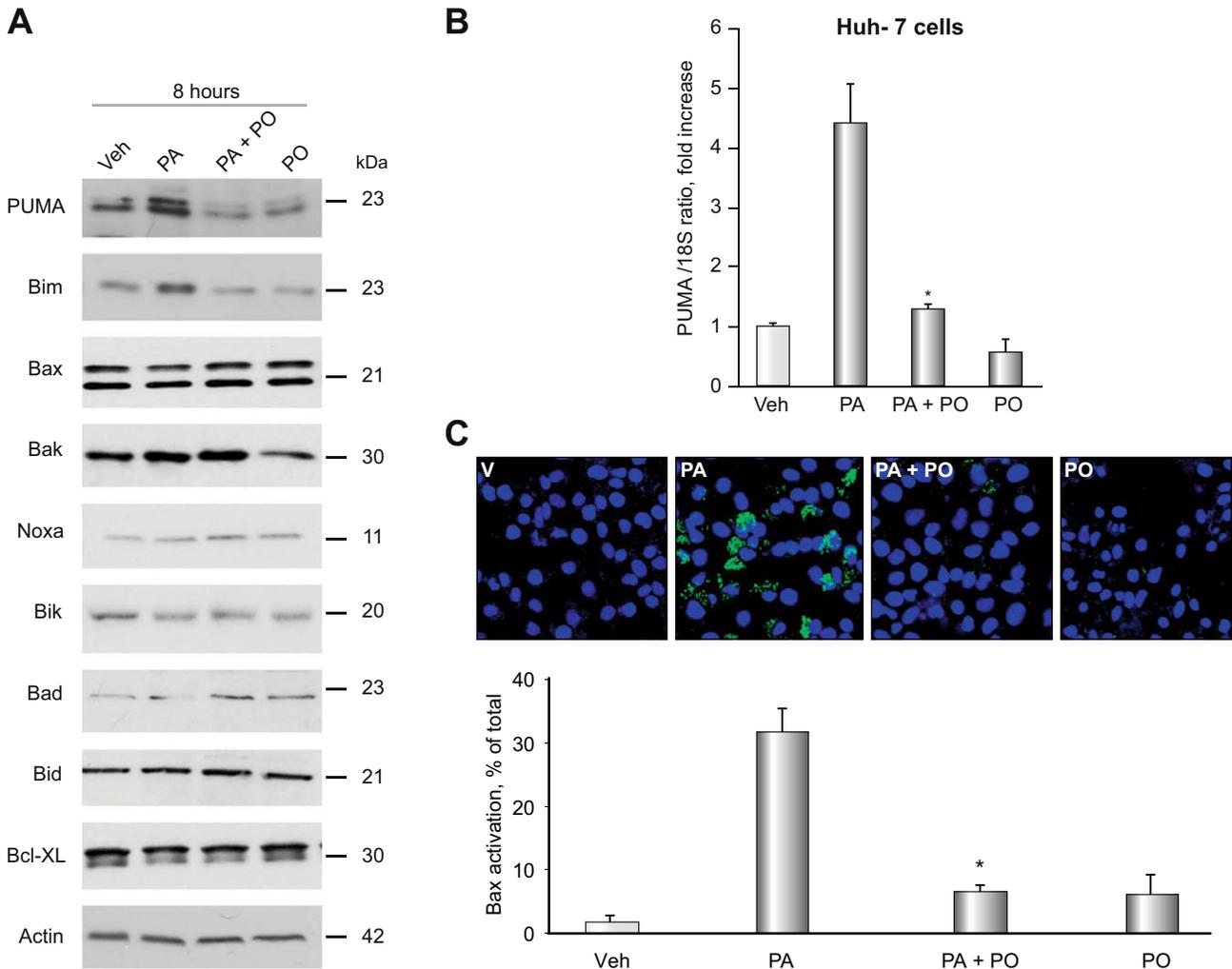
immunofluorescence using the 6A7 monoclonal antibody which detects the active conformational form of Bax [30]. Consistent with previous reports [12,15], Bax activation was observed in PA-treated cells, but this activation was attenuated when cells were incubated with PA plus PO (PA 800  $\mu$ M, PO 400  $\mu$ M) (Fig. 5C). Taken together, the data suggest that the inhibition of ER stress by PO also prevents dysregulation of Bcl-2 proteins by cytotoxic FFA.

## Discussion

Results of the present study provide new insights into the mechanisms of PO cytoprotection during FFA-induced lipoapoptosis. The principal findings of this study indicate that: (i) PO does not attenuate steatosis *in vitro*; (ii) PO inhibits saturated FFA-induced apoptosis in hepatocytes; (iii) PO inhibits PA-induced ER stress; and (iv) PO inhibits PA-induced dysregulation of pro-apoptotic Bcl-2 proteins. Each of these results is discussed in greater detail below.



**Fig. 4. PO inhibits PA-induced XBP-1 and JNK activation.** (A) Huh-7 cells were treated with either vehicle (Veh), 800  $\mu$ M PA, 800  $\mu$ M PA plus 400  $\mu$ M PO, or 400  $\mu$ M PO alone for 8 h. XBP-1 cDNA was amplified by PCR followed by 1 h-incubation with Pst1. Unspliced form of XBP-1 shows 290-bp and 180-bp product (which are mainly observed in Veh, PA + PO, PO-treated cells). Spliced form shows single 473-bp amplification product (which is mainly observed in PA-treated cells). Undigested PCR product. (B) Huh-7 cells were treated as above for 4 h. Whole cell lysates were obtained and resolved by SDS-PAGE. Proteins were identified by Western blot analysis by using antisera specific for total and active (phospho) members of JNK-1/-2.



**Fig. 5. PO inhibits PA-mediated Bim and PUMA induction, and Bax activation.** (A) (A and B) Western blot analysis was performed for Bcl-2 proteins using whole cell lysates from Huh-7 cells treated with vehicle (Veh), 800  $\mu$ M PA, 800  $\mu$ M PA plus 400  $\mu$ M PO, or 400  $\mu$ M PO alone for 8 h. (B) Huh-7 cells were treated with FFAs as described above. PUMA mRNA was quantified by real time PCR. Fold induction was determined by normalization to 18S. Data represent the mean and error of three independent experiments each performed in triplicate. \*  $p < 0.05$ , PA-treated cells vs. PA plus PO-treated cells. (C) Huh-7 cells were examined by immunofluorescence microscopy for activation of Bax following treatment with either vehicle (Veh), 800  $\mu$ M PA, 800  $\mu$ M PA plus 400  $\mu$ M PO, or 400  $\mu$ M PO alone for 16 h. The primary antibody employed recognizes the N-terminus of Bax which is exposed as an antigen upon Bax activation. Green fluorescence shows activated Bax and blue fluorescence shows DAPI staining. The graph shows quantification of five experiments. \*  $p < 0.01$ , PA-treated cells vs. PA plus PO-treated cells.

A recent study suggested that PO may function as a lipokine, a circulating lipid mediator, which modulates insulin sensitivity both in liver and muscle. Although PO accounts for a minority of the circulating FFA in healthy and in NASH patients, it is a potent signalling molecule [19,31]. For example, at physiological concentrations, PO improves the metabolic syndrome in a murine model, in part, by reducing hepatic SCD-1 [19]. In our reductionistic, cell culture model, PO actually promoted steatosis and had no effect on SCD-1 expression. These data suggest that SCD-1 expression in hepatocytes is not directly regulated by PO.

Despite promoting increased cellular steatosis, PO was cytoprotective during PA-mediated lipoapoptosis. This is consistent with prior observations reporting that unsaturated FFA are more efficiently esterified and incorporated into triglycerides [32]. Unsaturated FFA promote triglyceride generation likely due to their increased fluidity which facilitates their incorporation into lipid droplets [32]. Efficient incorporation of FFA

within neutral lipids appears to be a detoxification process minimizing the inherent toxicity of FFA [8,18]. These concepts help to explain, in part, the increased triglyceride accumulation in PO-treated cells and PO's ability to mitigate PA toxicity. In fact, other unsaturated FFA such as oleic acid and linoleic acid also inhibit cytotoxicity and ER stress by saturated FFA [8,29,33]. In this respect, the cytoprotective effects of PO mimic those of other unsaturated FFA [33]. Our studies extend the concept of cytoprotection by unsaturated FFA, by demonstrating PO cytoprotection in primary human hepatocytes, an important translational research observation. The observation that human hepatocytes undergo lipoapoptosis by PA and that PO is cytoprotective in this paradigm helps, in part, to validate prior studies of lipoapoptosis in hepatocyte derived cell lines and in primary rodent hepatocyte cultures.

Involvement of ER stress has been implicated in saturated FFA-mediated apoptosis in liver cells [8,29], and saturated FFA,

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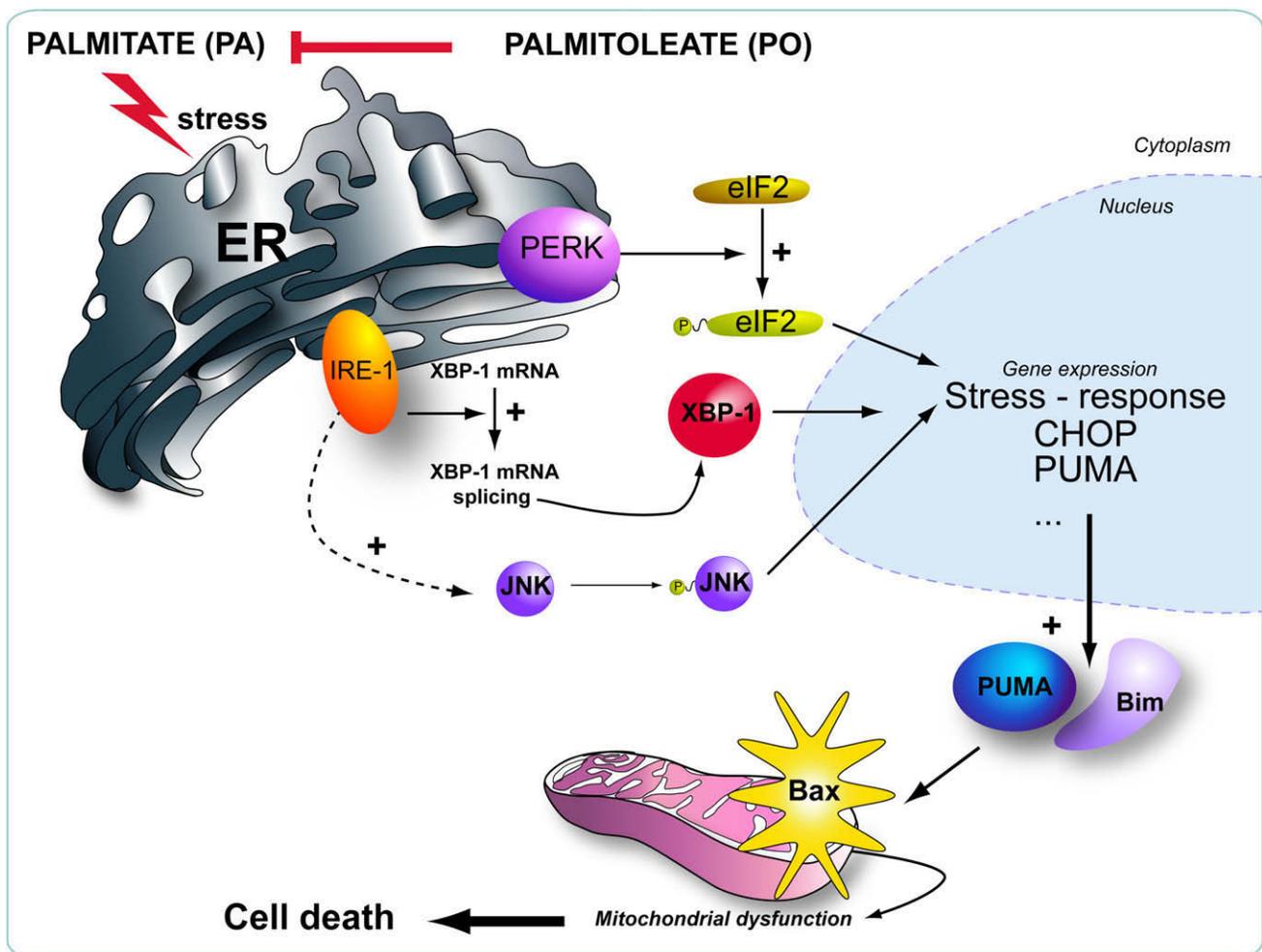
but not unsaturated FFA induce ER stress *in vivo* [11]. Our current results indicate that PO inhibits induction of a pivotal ER stress markers, in particular CHOP induction. This mediator of ER stress has been implicated in multiple models of ER stress-associated apoptosis. For example, ER stress-induced apoptosis is reduced in CHOP knockout mice compared to wild type animals [34]. Genetic deletion of CHOP also reduces Bim induction during ER stress [35]. These and our current observations suggest that Bim induction during lipotoxicity is due to downstream ER stress.

We note that in our present study, PO did not inhibit thapsigargin nor tunicamycin-induced CHOP up-regulation in Huh-7 cells. These data indicate that PO is not a general inhibitor of the ER stress response, but rather specifically antagonizes ER stress-induction by cytotoxic FFA. This information implies that ER stress is not a single, standardized signal, but rather that it is due to different activators that act through individualized, specific pathways. Further studies are necessary to identify how FFA modulate this unique ER stress response.

Prior studies on lipoapoptosis have not delineated the downstream consequences of FFA-mediated ER stress. PO attenuation of the ER stress response permits further dissection of these downstream events. A key downstream mediator of ER stress is

JNK which has been implicated in human and murine steatohepatitis [36]. For example, prior studies have highlighted the importance of JNK-1 activation leading to PUMA protein induction during lipoapoptosis [15]. In these studies, genetic knockdown of PUMA attenuates hepatocyte lipoapoptosis [15]. The current study extends these observations by demonstrating that inhibition of ER stress with PO attenuates this JNK-dependent dysregulation of pro-apoptotic Bcl-2 proteins. These cytotoxic responses to saturated FFA appear to be downstream of ER stress. An emerging picture of lipoapoptosis is developing, with ER stress upstream of JNK activation which then, likely in concert with other mediators, such as CHOP, contributes to increased PUMA transcription and Bim activation [35]. These BH3-only proteins then trigger Bax activation resulting in the mitochondrial pathway of cell death (Fig. 6).

Collectively, our present findings suggest that the lipokine PO attenuates saturated FFA-induced cell death in hepatocytes by inhibiting ER stress-associated dysregulation of pro-apoptotic Bcl-2 proteins. These data link PO cytoprotection to a beneficial effect on the core-apoptotic machinery of the cell. Given this mechanistic insight, it is tempting to speculate that PO and/or potent PO analogues could prove beneficial in human NAFLD.



**Fig. 6. Schematic representation of the proposed model for the mechanism of PO inhibiting PA-induced apoptosis.** Palmitoleate (PO) inhibits palmitate (PA)-induced ER stress, thereby preventing induction of the BH3-only proteins PUMA, Bim, and Bax activation.

**Acknowledgements**

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**Appendix A. Supplementary data**

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhep.2010.01.003.

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