p66^{Shc} plays a pivotal role in impaired liver regeneration in aged mice by a redox-dependent mechanism.

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Abstract:

Liver regeneration involves complicated processes and is affected by various patho-physiological conditions. The present study was designed to examine the molecular mechanisms underlying the aging-associated impairment of liver regeneration. Male C57BL/6J mice were used as young and aged mice (<10 weeks and >20 months old, respectively). These mice were subjected to 70% partial hepatectomy (PH). Liver regeneration and liver injury/stresses were evaluated chronologically after PH. Post-hepatectomy liver regeneration was markedly impaired in aged mice. Though the extent of hepatocyte proliferation in the regenerating liver was similar in aged and young mice, cell growth was absent in aged mice. Oxidative stress (OS) was observed immediately after hepatectomy, followed by marked apoptosis in aged mice. Signaling molecules regarding cell proliferation (MAPK, STAT-3, p46/52^{Shc}) and anti-oxidation (catalase, SOD, Ref-1, GPx) were expressed/activated after hepatectomy in livers of both aged and young mice. Akt was not activated in aged-mouse liver, but its expression was similar to that in young mice. p66^{Shc}, known as an age-/oxidant-associated protein, was strongly phosphorylated. By knocking-down p66^{Shc}, the impairment of liver regeneration was normalized. OS

immediately after hepatectomy induced subsequent liver injury (apoptosis), and deletion of p66^{Shc} suppressed both OS and hepatocyte apoptosis in the regenerating liver of aged mice. Though we need additional data in other animal models to fully understand the mechanism, p66^{Shc} may play a pivotal role in the impairment of liver regeneration in aged mice by triggering OS and subsequent apoptosis. The present data may provide a clue to understanding the mechanism underlying the association between aging and the impairment of liver regeneration.

Keywords: p66^{Shc}, Akt, caspase-3,apoptosis, oxidative stress, in vivo imaging

Liver regeneration is a series of physio-pathological phenomena resulting in quantitative recovery from loss of liver mass to compensate for decreased hepatic volume and impaired function. The liver has a unique ability to restore lost volume, which is rarely seen in other organs.[1,2,3] It is well established that normal adult hepatocytes are usually quiescent but have the potential ability to replicate. After surgical procedures that reduce liver mass, such as partial hepatectomy (PH) or live donor-liver transplantation, rapid enlargement of the residual or grafted liver commonly takes place to restore liver mass and function. Clinically, liver regeneration has important implications because many therapeutic strategies for surgical treatment of liver diseases, such as removal of liver tumors and liver transplantation, depend on the ability of the liver to regenerate physically and functionally. Poor or insufficient liver regeneration may be potentially fatal for these patients.[4,5,6] Therefore, better understanding of the patho-physiological features of liver regeneration could lead to clinical benefits.

In Western countries, the last two decades have seen a progressive increase in the mean life expectancy of the general population, resulting in higher percentages of aged people.[7,8] Ageing is an issue of growing concern in modern surgery and one which must be resolved in the near future. The influence of ageing on the outcome of surgery has already been extensively analysed and reported in some fields such as liver surgery. Hepatic resection is a common surgical treatment for a wide range of liver diseases.[7,9,10]

Recently, more hepatic resections have been performed in patients over the age of 60, with encouraging results.[7,11] The aged population, however, is

predisposed to a variety of diseases and pathological conditions, which may contribute to a marked increase in morbidity in this subpopulation.[12] The incidence of liver disease increases with age, but the cellular and subcellular mechanisms that underlie this suspected predisposition to pathology remain unresolved. Several age-related changes have been documented, including reductions in liver volume, metabolism, expression of a variety of proteins, and hepatobiliary function.[12,13] Changes such as reduced response to Oxidative stress (OS), reduced expression of growth-regulatory genes, diminished rates of DNA repair, and telomere shortening may contribute to reduced hepatic regenerative capacity, shorter post-liver transplant survival, and increased susceptibility to certain liver diseases among the aged.[12]

Src Homology 2 Domain Containing (Shc) proteins are classified into three families, designated ShcA, ShcB and ShcC in mammals.[14] Although the expression of ShcB and ShcC appears to be restricted to neuronal cells, ShcA is ubiquitously expressed except for in the brain and in neurons.[14,15] ShcA (here after referred to simply as 'Shc') was identified in 1992 as an adaptor molecule coupling the activated Epidermal Growth Factor receptor to Ras and the Mitogen-Activated Protein Kinase (MAPK) cascade.[15] Shc proteins have been studied mainly regarding the mechanisms of their mitogenic properties. However, p66^{Shc} inhibits activation of the Ras/MAP kinase pathway by competing with p46^{Shc} and p52^{Shc} for binding to Grb2.[14-18] Recent studies have reported that p66^{Shc} contributes to the regulation of cellular OS and apoptosis.[19,20,21] Fibroblasts and hepatocytes without p66^{Shc} have increased

resistance to OS and apoptosis with increased levels of Mn-Superoxide Dismutase (SOD), Redox Factor-1 (Ref-1) and Bcl-xL.[19,21] Furthermore, p66$^{Shc-/-}$ mice are protected against acute tissue damage following hind limb ischemia and following generation of reactive oxygen species caused by ischemia/reperfusion.[22] Although elevated levels of cellular reactive oxygen species have also been implicated in ageing, p66$^{Shc-/-}$ mice show a greater resistance to OS and up to 30% longer lifespan compared to their wild-type counterparts.[20]

The present study was designed to examine the role of p66^{Shc} and associated molecules in liver regeneration in aged mice. To this end, we analyzed mechanisms of liver regeneration in the context of cell proliferation, growth, OS, and apoptosis in liver regeneration. Here, we report that p66^{Shc} plays a pivotal role in the impairment of liver regeneration by inducing OS and injury (apoptosis) in the aged mouse PH model.

Materials and Methods

Animal experiments. C57BL/6 male mice (8-10 weeks, >13 months, and >20 months old; young, middle-aged and aged mice, respectively) were used for simple 70% PH experiments. Anesthesia was induced with an intraperitoneal injection of Nembutal (pentobarbital sodium, 60 mg/100 g body weight). Mice were fasted overnight prior to the experiments. After laparotomy, the left and median liver lobes were surgically resected. The mice were sacrificed for collection of liver specimens at the indicated time points before or after hepatectomy, and the liver/body weight ratios were calculated to estimate the

recovery of liver mass. The surgical procedure (PH) in this study was done by the single skillful researcher. We have preliminarily examined/confirmed the accuracy of the procedure using 5 mice. We calculated resection rate by [the resected liver]/[the whole liver], which showed 65.8 ± 0.17 (%) (mean +/- SD). In order to deliver the specific gene to mice liver, adenoviruses were administered intravenously via the tail vein 72 hours prior to the experiments. The recombinant adenovirus Ad*p66^{Shc}RNAi* encodes a short hairpin loop RNA with a 19-mer N-terminal CH2 domain sequence corresponding to bases 45–63 of the cDNA of p66^{Shc}.[23] Ad*LacZ*, an adenovirus vector encoding *β-galactosidase*, was used as a control.

The animals were maintained under standard conditions and treated according to the Guidelines for the Care and Use of Laboratory Animals of Hokkaido University.

Cell proliferation assay. In order to evaluate proliferation of hepatocytes following PH, Proliferating Cell Nuclear Antigen (PCNA)-positive and mitotic hepatocytes were counted. Liver tissues were removed prior to, and 72 hours post-hepatectomy (for PCNA and mitosis), fixed in 10% buffered formalin and paraffin-embedded. Hematoxylin and eosin staining and immunohistochemical staining with anti-PCNA were performed. At least 500 hepatocytes were counted for mitotic index or PCNA-positivity at least 3 times in different sections in each group.

Measurement of cell size (hepatocytes). The method to measure the size of hepatocytes in liver sections was described previously.[24] Briefly, individual hepatocytes were outlined and cross-sectional area was determined with a

computer-assisted image analysing system (LSM Image Browser, Carl Zeiss GmBH, Jena, Germany). Cell areas of at least 500 hepatocytes were randomly selected in zone 2 and calculated in triplicate using different sections in each group.

Western blot analysis. Whole liver protein extract (30 μg) was separated by 10% SDS-PAGE and transferred to a PVDF membrane. The following antibodies were used as the primary antibodies**:** Shc/phospho-Shc, p44/42-MAPK, phospho-p44/42-MAPK, Signal Transducer and Activator of Transcription protein 3 (STAT3)/phospho-STAT3, Akt/phospho-Akt, Caspase-3, FADD-Like Interleukin 1β-Converting Enzyme (FLICE) (Cell Signaling, MA), FLICE-Inhibitory Protein (FLIP), Ref-1, Mn-SOD (BD Transduction Laboratories, NJ), CuZn-SOD, Bcl-2/xL, Glutathione Peroxidase (GPx) (Santa Cruz, CA).

In vivo imaging of mouse liver oxidative stress and injury (caspase-3 activity). Redox-sensitive fluorescent probe of GFP (Reduction/Oxidation–Sensitive Green Fluorescent Protein, roGFP) which allows real-time visualization of the oxidation/reduction potentials of various cells in vitro*,* has been developed and reported recently.[25,26] We developed recombinant adenoviral vector coding for roGFP. Disulfide bond formation between the cysteine residues promotes protonation of the chromophore, reducing the excitation spectrum peak near 480 nm. By calculating the ratios of fluorescence intensities from excitation at 480 nm, an indication of the redox potential can be measured and hence, the extent of oxidation. Three days before each experiment, Ad*roGFP* was administered intravenously via the tail

vein in a volume of 100 μl (5 x 10^7 pfu/body) using a 31G needle. For *in vivo* liver imaging, the organ was exposed under anesthesia to enable a CCD camera to record liver images directly.[27] *In vivo* imaging of the mouse liver was performed using a *Photon Imager* (Biospace Co, France). Fluorescence intensities at 530 nm from excitation at 480 nm were measured and reciprocally plotted [1/(em. 530 at ex. 480 nm)]. This allows the signal to increase with oxidation and to decrease with reduction, and can be used as an index of *in vivo* redox state.

The optic probe, termed pcFluc-DEVD, sensing real-time Caspase-3 activity has been developed.[28] Split the N- and C-terminal end of firefly Luciferase (Fluc) is connected with the substrate sequence for Caspase-3, DEVD. then pcFluc-DEVD makes cyclic Fluc indicative of the inactive form. Once caspase-3 is activated in cells, Fluc changes into an active form and luminescence activity is restored. We developed recombinant adenoviral vector cording for pcFluc-DEVD, and infected it to mouse (5 x 10^7 pfu/body). D-Luciferin, a luciferase substrate, was injected intraperitoneally at a dose of 3 mg/100 μl in PBS. *In vivo* imaging of the mouse liver was performed using an in vivo imager for 5 minutes, from 5 to 10 minutes after injection.

Biochemical measurement of oxidative stress and apoptosis in liver tissue

For evaluation of apoptotic cell death in liver tissue, an ELISA kit (Cell Death Detection ELISA^{PLUS}; Roche, Basel, Switzerland) was used according to the manufacturer's instructions. Biochemical analyses, such as tissue 4-Hydroxy-2-Nonenal (4-HNE) as a peroxidation index and serum GOT/GPT/LDH

levels as liver damage indices, were performed at the time points indicated before and after reperfusion. For western blot analysis, anti-4-HNE was purchased from Japan Institute for the Control of Aging (JaICA, Shizuoka, Japan).

Statistical Analysis. Results are expressed as means ± SEM. Statistical analyses were performed with Fishers' test and *p* values less than 0.05 were considered significant.

Results

Liver regeneration was impaired after partial hepatectomy (PH) in aged mice.

We first examined liver recovery after 70% PH in the young, middle-aged, and aged mice (8-10 weeks, >13 months, and >20 months old, respectively) (Figure 1). In the young mice, liver recovery occurred immediately after PH and continued until at least 2 weeks post-PH. In the middle-aged mice, liver recovery was insufficient at 72 hours-post-PH, but there was partial recovery by day 14 post-PH. In the aged mice (>20 months old), liver recovery was markedly impaired until 14 days post-PH, though recovery was somewhat observed. Liver mass recovery was impaired according to age.

In order to examine the mechanism of impaired liver regeneration associated with aging, we compared young and aged mice in further studies.

Post-PH mitotic response occurred equally in the young and aged mice.

Histological examination revealed that post-PH proliferation of hepatocytes occurred equally in the young and aged mice. The marked mitotic response terminated by day 14 post-PH in both groups. The mitotic hepatocytes were equally observed and peaked at 3 days post-PH in the young and aged mice (Figure 2a). Western blot and immunohistochemical analyses for PCNA also showed a peak at 72 hours post-PH and a decrease thereafter (Figure 2a).

It has been reported that responsive cell growth (increase of cell size) mediated by Phosphoinositide-Dependent Protein Kinase 1 (PDK1)-Akt is critical for good liver regeneration in some physio-pathological situations.[24,29] Therefore, we compared the cell size of the hepatocytes in young and aged mice before and after PH. Hepatocytes were equal in size before PH both in the young and aged mice. Hepatocytes became larger in size in response to PH in the young mice, but not in the aged mice (Figure 2b). The defective cell growth of hepatocytes in the aged mice may partly account for the impaired liver

regeneration.

Liver was damaged immediately after PH in aged mice.

In the aged mice, liver injury occurred immediately after PH. Apoptotic cell death in the liver occurred 4 hours post-PH in the aged mice (Figure 3a). Serum levels of GOT and GPT were also elevated at 4 hours and 72 hours post-PH, and bilirubin at 72 hours post-PH. These parameters recovered to baseline levels by day 14 post-PH (Figure 3b and c). Interestingly, mild apoptosis occurred 14 days post-PH in the aged mice, but did not affect serum markers of liver injury.

Hepatic signal transduction associated with cell proliferation/survival, apoptosis, and oxidative stress.

To elucidate the mechanisms of apoptotic liver injury immediately following PH and the impaired liver regeneration in aged mice, we examined the signaling molecules involved in proliferation, survival, apoptosis, and anti-oxidation.

p42/44-MAPK, STAT3, and p46/52^{shc}, which are associated with cell

proliferation, were equally expressed but activated more in the liver of aged ice immediately after PH (Figure 4a and e). Akt was also expressed in the liver of aged mice but was not activated, in contrast with liver from young mice.

FLICE and FLIP were expressed equally in liver from young and aged mice (Figure 4b). Bcl-2 was markedly expressed in aged mice even before PH, whereas Bcl-xL expression was slightly suppressed. Caspase-3 was activated 4 hours and 14 days post-PH in aged-mouse liver, but only at 14 days post-PH in young-mouse liver.

Antioxidant proteins, catalase, Mn-/CuZn-SOD, Ref-1, and GPx were equally expressed in the young- and aged-mouse liver (Figure 4c). Elevated expression of 4-HNE, a byproduct of lipid peroxidation, showed strong OS in the aged mice especially post-PH (Figure 4d). Shc protein was expressed slightly more in the liver of young mice. p66^{Shc}, an age/redox-associated protein, was markedly phosphorylated at serine 36 immediately after PH (Figure 4e), which has been reported to be associated with Akt activity and OS.[21]

Post-PH liver regeneration was recovered by ablating hepatic p66^{Shc} in the aged mice.

Following PH in aged mice, liver injury markers (apoptosis, sGOT/GPT,

caspase-3 activity, and OS) were all elevated in parallel with age-associated p66^{Shc} activation. These observations prompted us to study the role of p66^{Shc} in the liver injury and impaired regeneration after PH in aged mice.

Ablation of hepatic p66^{Shc} did not affect post-PH liver regeneration in young mice, but remarkably improved liver regeneration in aged mice (Figure 5a). By ablating hepatic p66^{Shc}, the liver in aged mice recovered post-PH equally to that in young mice. This suggests that p66^{Shc} and its activation play a pivotal role in the impairment of regeneration in the aged liver, possibly by inducing OS and injury (apoptosis). As expected, Akt, a pro-survival/anti-apoptotic/antioxidant protein, was also activated by ablating p66^{Shc} in the liver post-PH in aged mice (Figure 5b).

Ablation of p66^{Shc} protected post-PH liver from oxidative stress and injury in the aged mice.

To examine the role of p66^{Shc} in liver regeneration in aged mice, we evaluated OS and injury (apoptosis) after PH. By transfecting roGFP and the functional bioluminescent probe for caspase-3 to liver, we measured hepatic OS and apoptosis non-invasively and chronologically in live mice.

In aged mice, marked hepatic OS was observed within 1 hour post-PH and OS returned to baseline level by 4 hours post-PH. In contrast, OS post-PH was not observed until at least 4 hours post-PH in young mice. Ablation of p66^{Shc} suppressed post-PH OS to pre-PH baseline level in aged mice (Figure 6a). This may indicate that p66^{Shc} is conclusively and specifically involved in the generation of reactive oxygen species in the post-PH liver.

In vivo imaging of hepatic caspase-3 activity in the post-PH liver revealed that hepatic damage was initiated and peaked 2 hours and 8 hours post-PH, respectively, in aged mice, whereas the liver was not damaged at all in young mice. Knock-down of p66^{Shc} reduced damage in the post-PH liver in aged mice, though gradual liver damage occurred until 24 hours post-PH (Figure 6b). This was also confirmed by apoptosis assay of post-PH liver (Figure 6c). Ablation of hepatic p66^{Shc} did not affect the size of hepatocytes post-PH (data not shown).

Discussion

In the present study, we demonstrated that p66^{Shc} primarily plays a pivotal role in impaired liver regeneration in aged mice by inducing OS and

damage (apoptosis) immediately after hepatectomy. Hepatocytes proliferated in response to PH equally in young and aged mice. Hepatocyte proliferation assessed by mitotic index and PCNA-positivity in liver tissue did not show any difference between young and aged mice. Acute liver injury following PH occurred only in the aged mice and was the main cause for the insufficient liver regeneration. Immediate post-PH**,** injury was caused mainly by OS-mediated apoptosis, which was regulated by age-associated p66^{Shc}. It also has been reported that responsive cell growth (increase of cell size) following PH is critical for normal liver regeneration in some patho-physiological situations and is regulated by the PDK1-Akt pathway.[24,29] These findings support our present data that hepatocytes lacking Akt activity failed to increase their size following PH in the aged mice. Taken together, acute liver injury and lack of cell growth are the most conceivable causes for the impaired liver regeneration in aged mice. p66^{Shc}, an age/redox-associated molecule, played a pivotal role in the impairment of liver regeneration by up-regulating post-PH OS/injury and reducing Akt activity/cell size.

Analyses of signals in the regenerating liver revealed that cell proliferation-associated molecules (MAPK, STAT3, p46/52^{Shc}) were all activated

in response to PH even in aged mice and actually induced hepatocyte proliferation to a degree comparable to that of young mice. There were no differences in the expression of the apoptosis-associated proteins such as FLICE and FLIP. Although Bcl-XL expression was slightly reduced, Bcl-2 expression was markedly increased in aged-mouse liver. It is not clear why these two proteins were differentially expressed in aged mice. Strong expression of Bcl-2 may have occurred in response to chronic OS in the liver of aged mice (Figure 4d), though aged mice liver expressed antioxidant proteins such as Catalase, Mn-/CuZn-SOD, Ref-1, GPx to a degree comparable to those of young mice liver.

p66^{Shc}, an ageing- and OS-associated molecule, was markedly phosphorylated at serine 36 in the liver of aged mice liver, although phosphorylation at tyrosine 317 was weak. Phosphorylation of p66^{Shc} at serine 36 has been reported to induce cellular OS by regulating (suppressing) Akt activity and catalase expression,[21] which be a mechanism underlying post-PH liver damage in aged mice. In young mice, PH caused liver damage as a result of surgical stress but did not induce OS and apoptosis immediately post-PH (Figure 3) and did not activate p66^{Shc}.

In the present study, phosphorylation of p66^{Shc} at serine 36 occurred in

response to PH only in aged mice, although the expression of major antioxidant molecules examined was not changed. Knocking-down of liver p66^{Shc} led to marked recovery of liver regeneration after PH in aged mice but did not affect regeneration in young mice. Also, deletion of p66^{Shc} reduced OS and caspase-3 activity and improved liver injury and regeneration post-PH in the liver of aged mice. These facts suggest that p66^{Shc} plays a pivotal role in the OS-mediated injury post-PH and the impaired liver regeneration in aged mice.

Akt was activated immediately after PH in liver of young but not aged mice. By ablating p66^{Shc}, Akt was phosphorylated/activated in the post-PH liver. Ablation of p66^{Shc} has previously been reported to phosphorylate Akt in some types of cells.[19,21,30] In the present study, knock-down of p66^{Shc} phosphorylated/activated Akt in the post-PH liver, similarly to the young mice. Because Akt is known as an antioxidant/pro-survival molecule,[31,32,33] Akt activation immediately after PH resulting from p66^{Shc}-knockdown may play a major role in suppressing post-PH OS/apoptosis and injury in the post-PH liver of aged mice.

In the present study, we elucidated the age-specific mechanisms of impaired liver regeneration following PH by identifying the role of p66^{Shc} in

post-PH OS and apoptosis. By regulating hepatic OS, p66^{Shc} may play a pivotal role in liver regeneration in aged mice. Further studies using other animal models are needed to more fully elucidate and conclude the mechanisms by which ageing leads to the impairment of liver regeneration. The present study, however, provide some potentially important clues to understand the relationship between ageing and liver regeneration.

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Disclosure/Duality of Interest:

The authors declare no conflict of interest.

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Abbreviations:

partial hepatectomy (PH); oxidative stress (OS); Src homology 2 domain containing (Shc); mitogen-activated protein kinase (MAPK); superoxide dismutase (SOD); redox factor-1 (Ref-1); proliferating cell nuclear antigen (PCNA); signal transducer and activator of transcription protein 3 (STAT3); FADD-like interleukin 1β-converting enzyme (FLICE); FLICE-inhibitory protein (FLIP); glutathione peroxidase (GPx); reduction/oxidation–sensitive green fluorescent protein (roGFP); firefly luciferase (Fluc); 4-hydroxy-2-nonenal (4-HNE); phosphoinositide-dependent protein kinase 1 (PDK1).

Figure legends

Figure 1

Liver regeneration was impaired after partial hepatectomy (PH) in aged mice. Liver regeneration was evaluated by the recovery of liver mass (wet weight) until 14 days post-PH in young (< 10 weeks), middle-aged (>12 months), and aged (>20 months) mice. At least 5 mice were used for each experiment. Data are expressed as mean ± SEM.

Figure 2

Post-PH mitotic response occurred equally in young and aged mice. (**a**) Histological examination (hematoxylin-eosin stain) revealed similar mitotic responses after PH in the liver of the young and aged mice. Mitotic cells were counted 72 hours and 14 days post-PH. Counts of PCNA-positive hepatocytes in the regenerating liver showed equivalent mitotic responses in young and aged liver. Western blot and immunohisotological analyses of PCNA confirmed the mitotic response in the liver of aged mice. Data are expressed as mean ± SEM. (**b**) Hepatocytes slightly increased in size in response to PH even in aged mice, although they increased in size more in the young mice.

Figure 3

Liver was damaged immediately after PH in aged mice. (**a**) Apoptotic cell death was observed markedly 4 hours post-PH only in aged mice, and mildly 14 days post-PH both in both young and aged mice. (**b**) Blood biochemistry showed immediate liver injury after PH in aged mice (GOT/GPT and bilirubin).

Figure 4

Signal transduction of hepatocytes associated with cell proliferation / survival, apoptosis, and oxidative stress. Expression and phosphorylation (activation) of signaling molecules were analysed by western blotting (cell proliferation-associated molecules (**a**), apoptosis-associated molecules (**b**), antioxidant-associated molecules (**c**), oxidized product (**d**) and p66^{Shc}, an age-associated molecule:p66^{Shc} (**e**). Whole cell extract from Fas-L (Jo2)-treated AML12 cells (1.25 μg/ml) were used as positive controls for FLICE/caspase-3 activation (b). And the whole cell extracts of MDA-MB231 breast cancer cells and AML12 liver cells were used as positive controls for FLIP and Bcl-2/-xL expressions (b).

Figure 5

Post-PH liver regeneration recovered as a result of ablating hepatic p66^{Shc} in aged mice. (**a**) Adenoviral transfection of p66^{Shc}-siRNA improved liver regeneration in aged mice. Note: post-PH liver regeneration was not affected in young mice. (**b**) By ablation of p66^{Shc}, phosphorylation/activation of Akt was induced in the liver of aged mice. Note: Ablation of p66^{Shc} by itself did not phosphorylated/activate Akt.

Figure 6

Ablation of p66^{Shc} protected post-PH liver from oxidative stress and injury in aged mice. (**a**) Bioimaging of liver OS after PH. UV Emission from roGFP from remnant right liver lobe were directly measured from the exposed liver surface and imaged 0, 1, 2 and 4 hours after PH and quantified. Each experiment was performed at least three times in each group and the photos are representative of at least three independent experiments. Data in the graph are expressed as mean ± SEM, and were expressed relative to the pre-PH control in each group. Note: signals (red color area) in aged mice were transiently reduced 1 hour

after PH, indicating liver OS. Ablation of p66^{Shc} reduced OS in the post-PH liver. (**b**) Bioimaging of liver caspase-3 activity after PH. Luciferase/luciferin-induced bioluminescent signals of remnant right liver lobe were measured from the body surface for 5 minutes (5 to 10 minutes after intraperitoneal injection of luciferin) and imaged 0, 2, 4, 8, and 24 hours after PH. Each experiment was performed at least three times in each group and the photos are the representative of at least three independent experiments. Data are expressed as mean ± SEM relative to the pre-PH control in each group.

(**c**) Apoptotic cell death was markedly suppressed 4 hours post-PH in p66^{Shc}-deleted aged mice. Results are expressed as mean ± SEM of three independent experiments. A p value < 0.05 was considered significant.

Figure 1

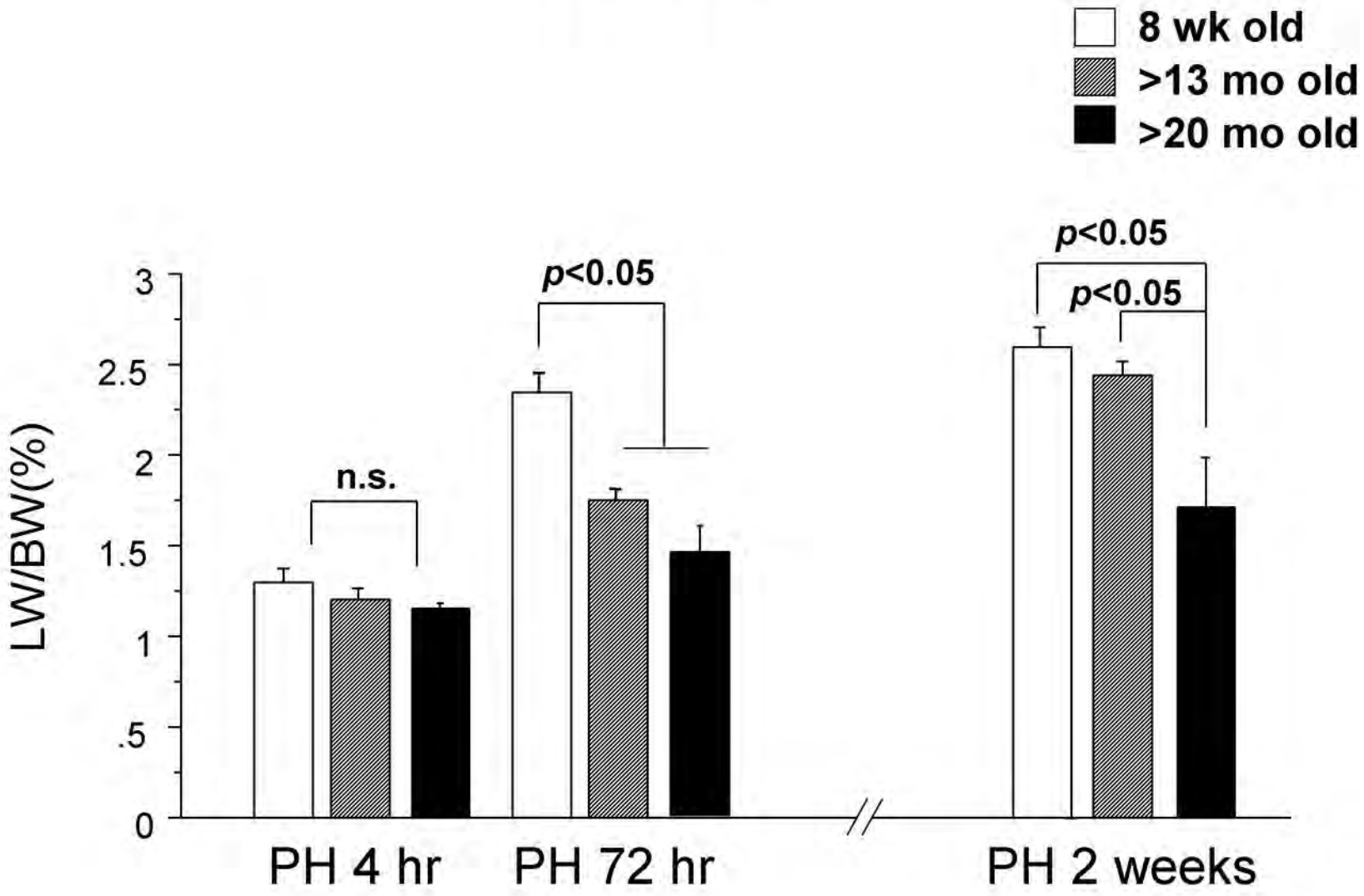
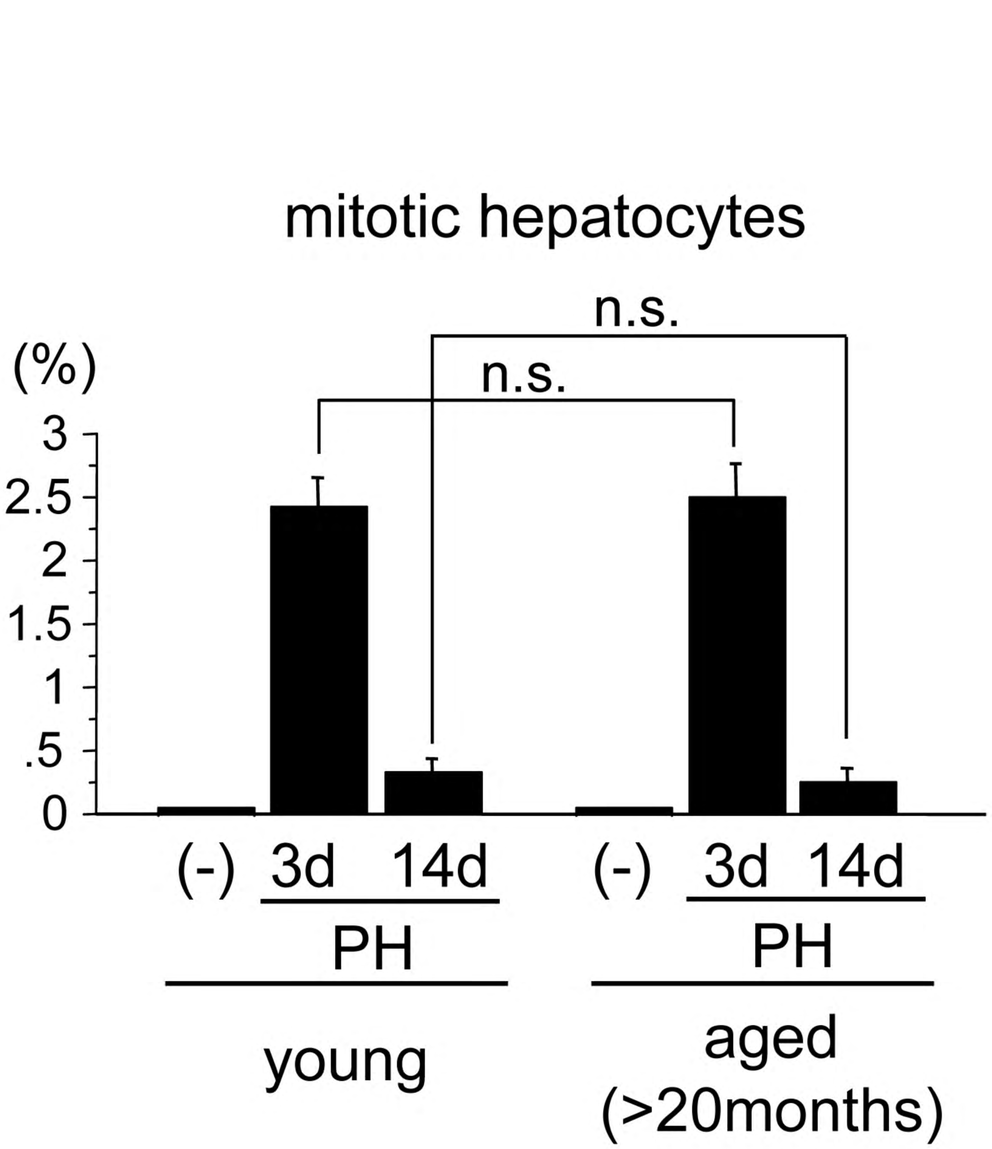
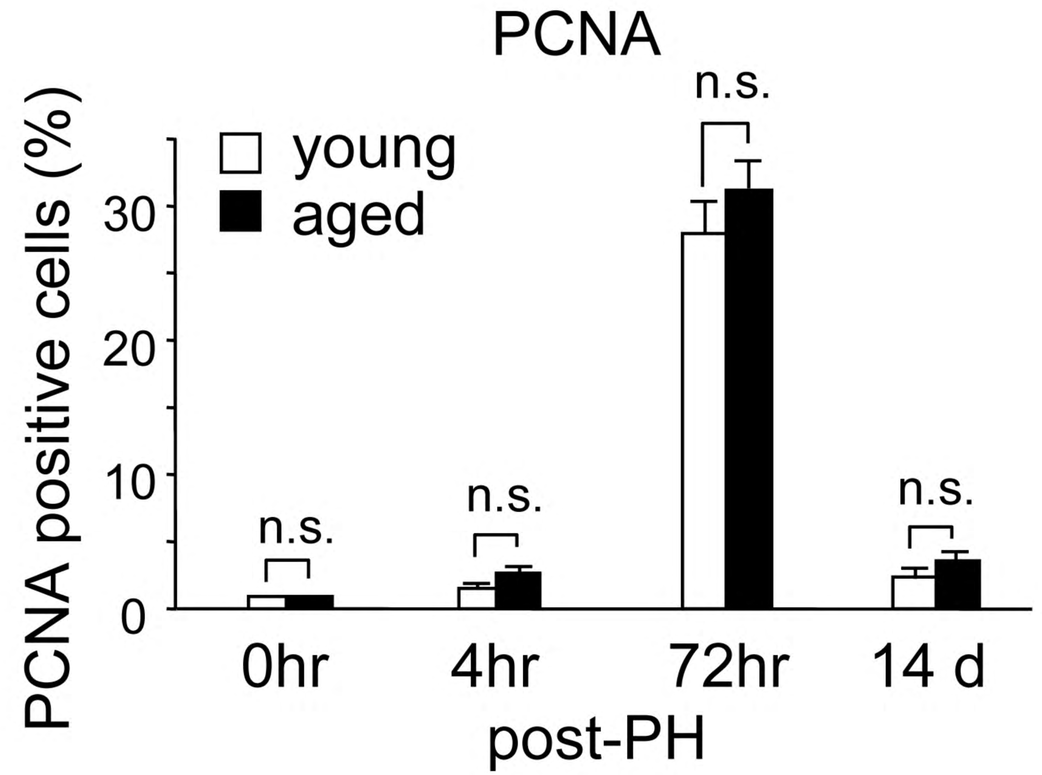

8 wk old
>13 mo old
>20 mo old
LW/BW(%)
3
2.5
2
1.5
1
.5
0
n.s.
p<0.05
p<0.05
p<0.05
PH 4 hr
PH 72 hr
PH 2 weeks

Figure 2a


mitotic hepatocytes
(%)
3
2.5
2
1.5
1
.5
0
n.s.
n.s.
(-)
3d
14d
PH
young
(-)
3d
14d
PH
aged
(>20months)


PCNA
PCNA positive cells (%)
young
aged
30
20
10
0
n.s.
n.s.
n.s.
n.s.
0hr
4hr
72hr
14 d
post-PH

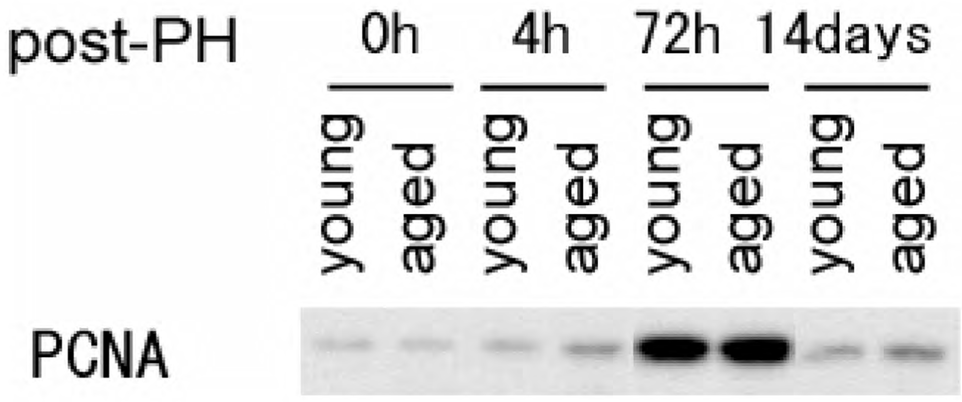

post-PH
0h
4h
72h
14days
young
aged
young
aged
young
aged
young
aged
PCNA

Figure 2b

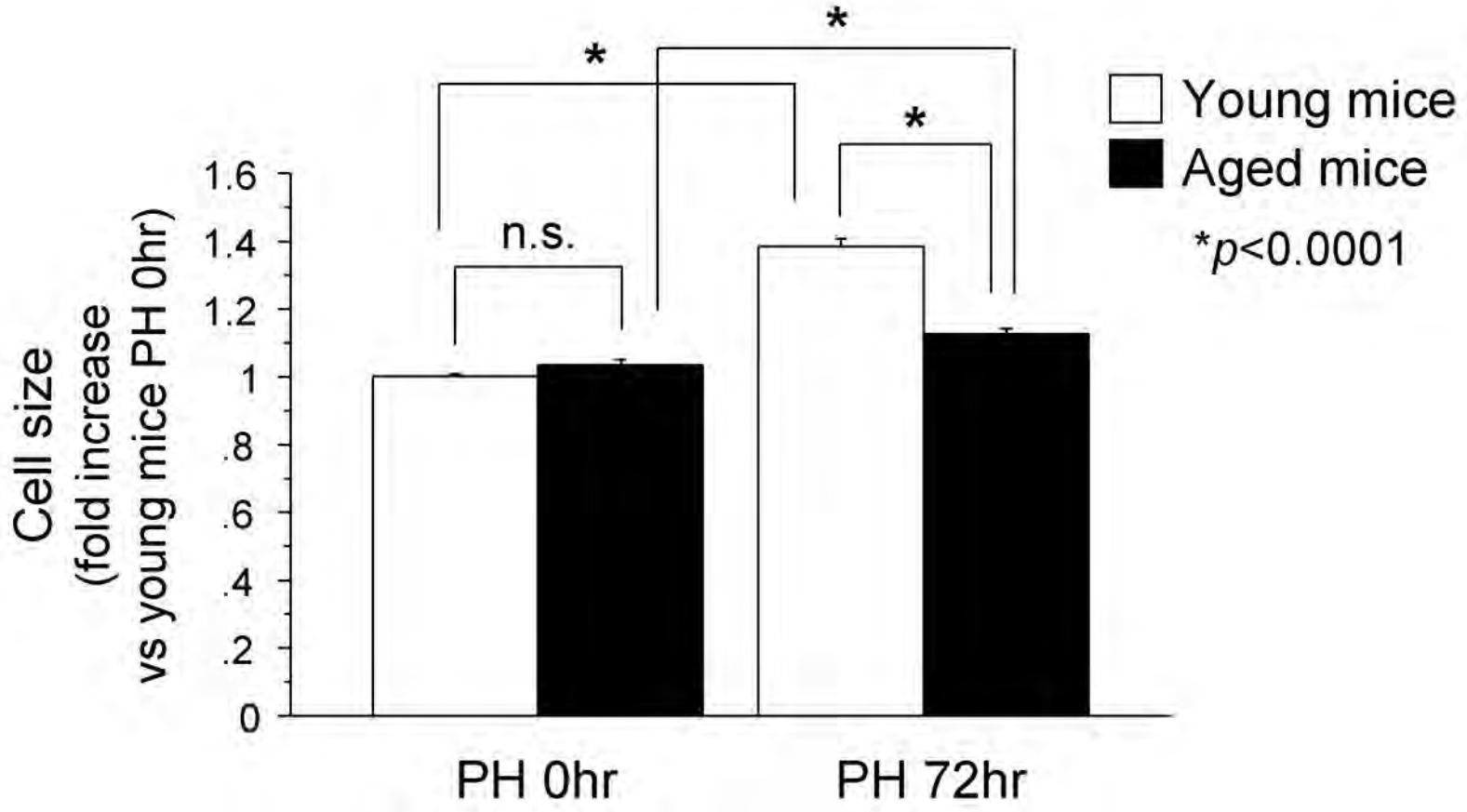

*
*
*
n.s.
Young mice
Aged mice
*p<0.0001
Cell size
(fold increase
vs young mice PH 0hr)
1.6
1.4
1.2
1
.8
.6
.4
.2
0
PH 0hr
PH 72hr

Figure 3

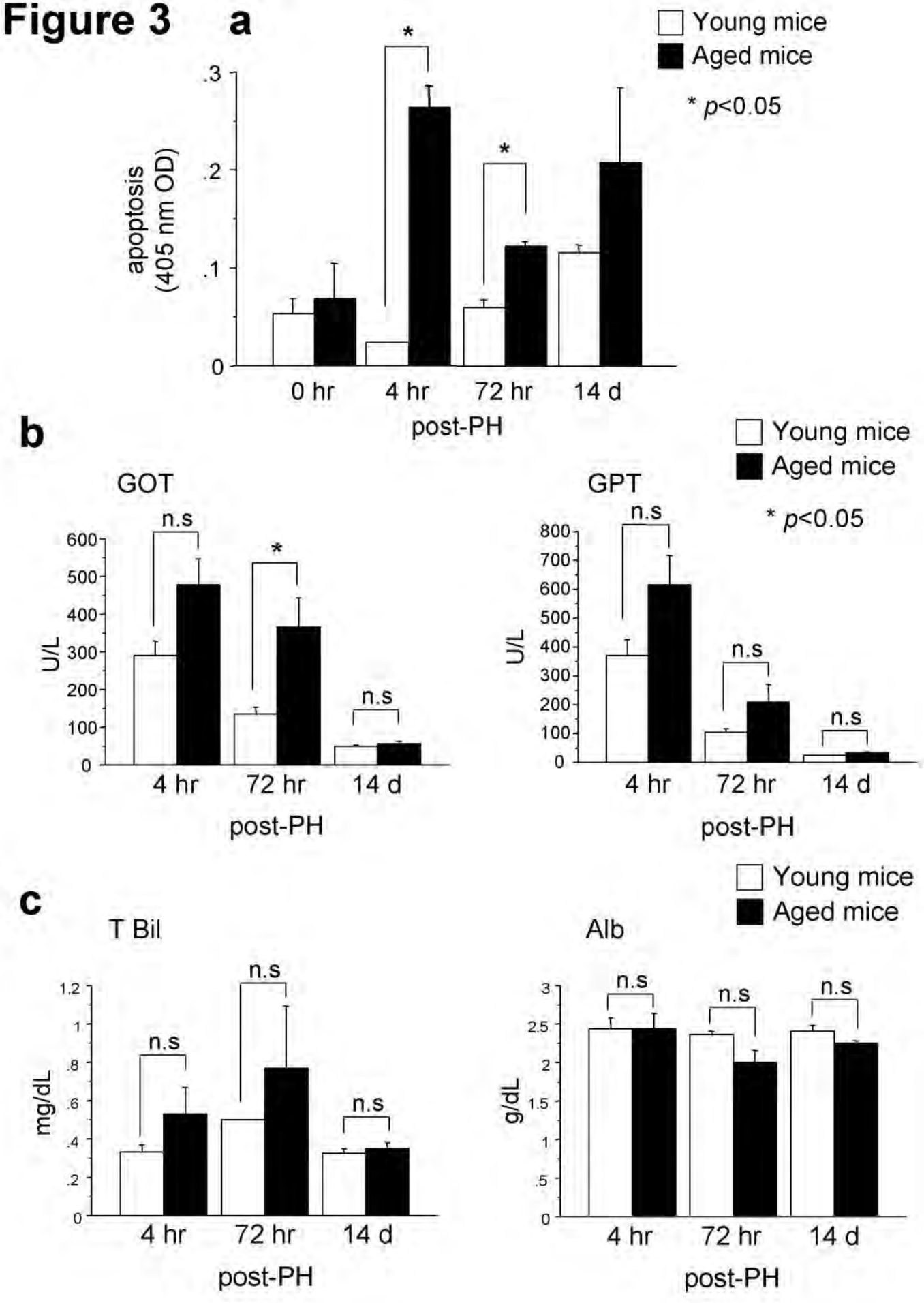
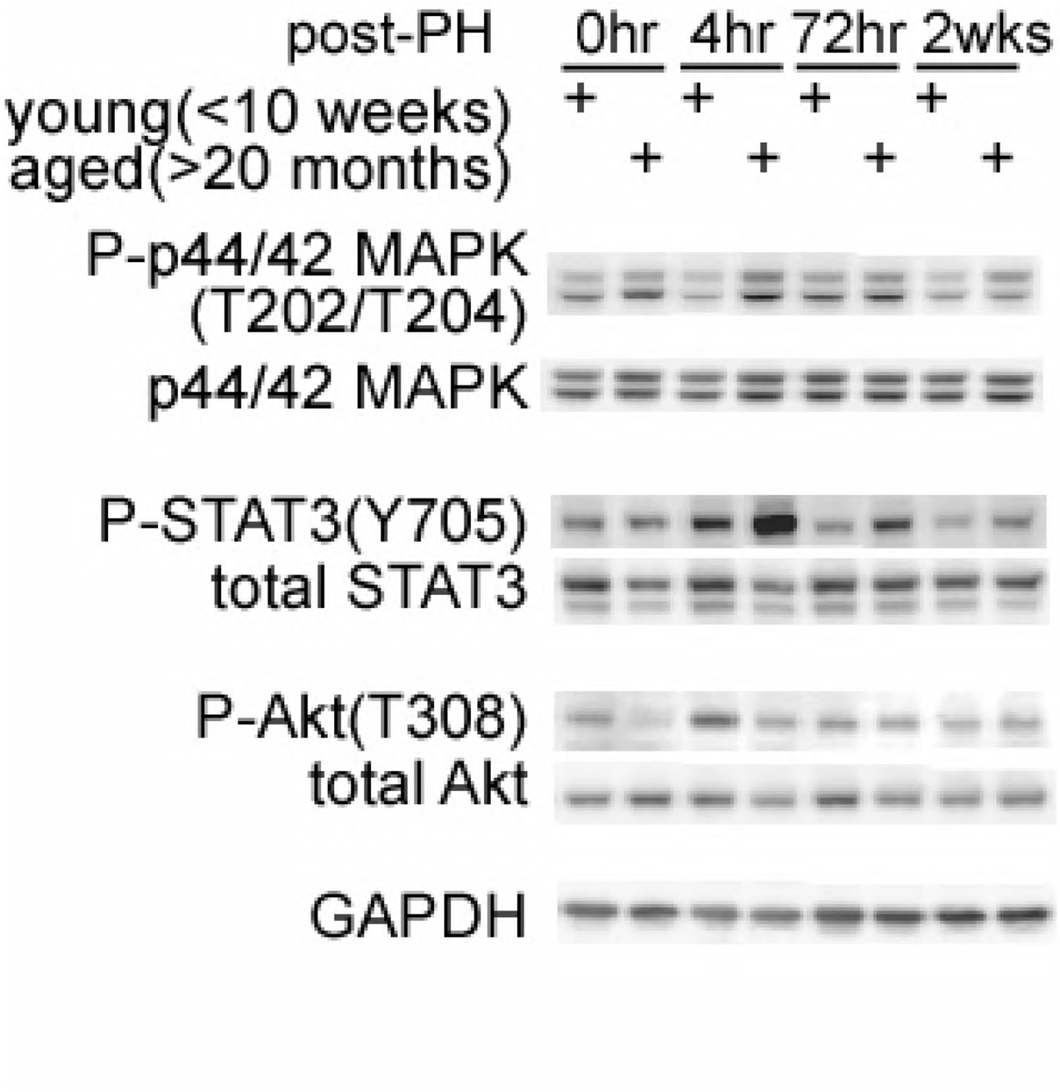
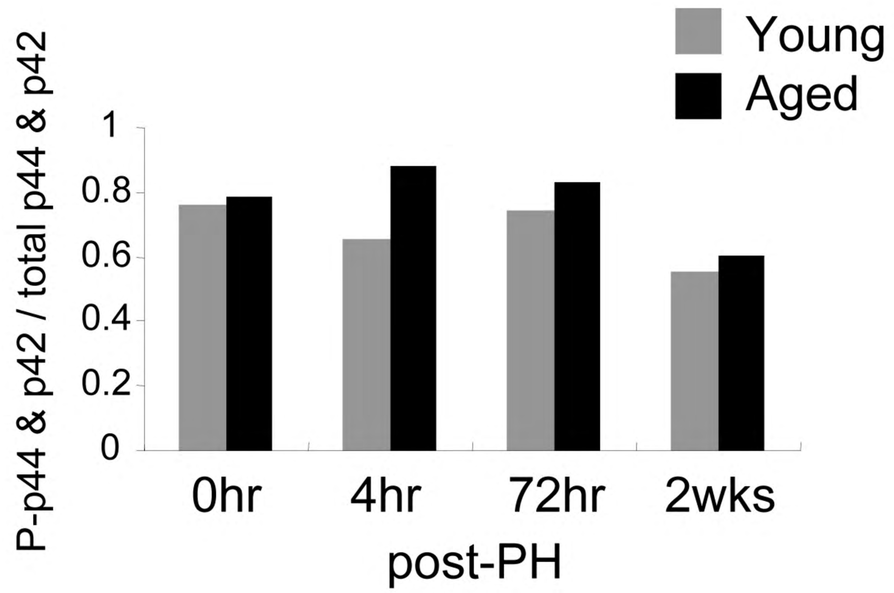
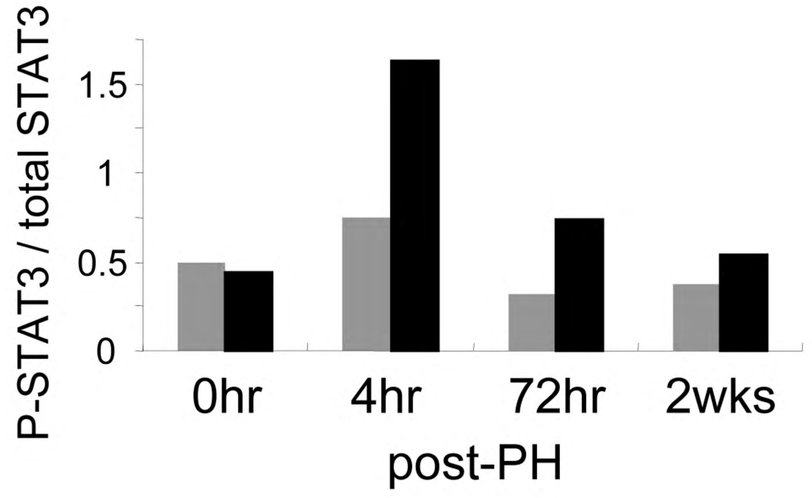

a
Young mice
Aged mice
* p<0.05
apoptosis (405 nm OD)
0
.1
.2
.3
*
*
0 hr
4 hr
72 hr
14 d
post-PH
b
Young mice
Aged mice
* p<0.05
GOT
U/L
0
100
200
300
400
500
600
n.s
*
n.s
4 hr
72 hr
14 d
post-PH
GPT
U/L
0
100
200
300
400
500
600
700
800
n.s
n.s
n.s
4 hr
72 hr
14 d
post-PH
c
Young mice
Aged mice
T Bil
mg/dL
0
.2
.4
.6
.8
1
1.2
n.s
n.s
n.s
4 hr
72 hr
14 d
post-PH
Alb
g/dL
0
.5
1
1.5
2
2.5
3
n.s
n.s
n.s
4 hr
72 hr
14 d
post-PH

Figure 4a


post-PH
0hr
4hr
72hr
2wks
young(<10 weeks)
aged(>20 months)
P-p44/42 MAPK
(T202/T204)
p44/42 MAPK
P-STAT3(Y705)
total STAT3
P-Akt(T308)
total Akt
GAPDH


Young
Aged
P-p44 & p42 / total p44 & p42
1
0.8
0.6
0.4
0.2
0
0hr
4hr
72hr
2wks
post-PH


P-STAT3 / total STAT3
1.5
1
0.5
0
0hr
4hr
72hr
2wks
post-PH

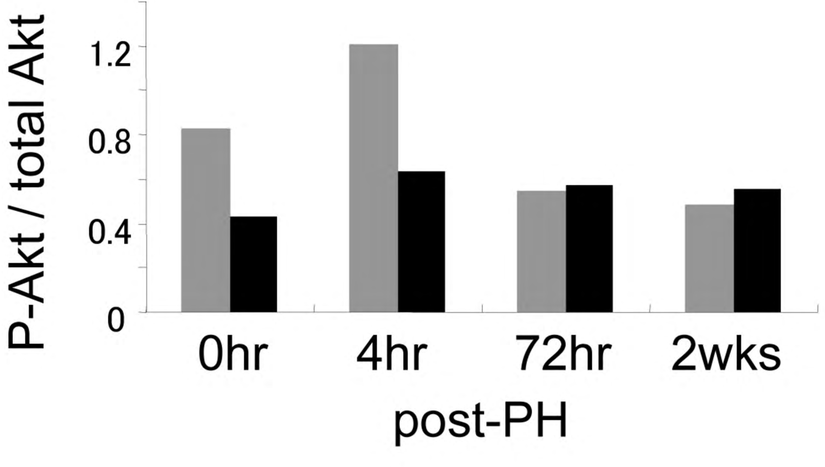
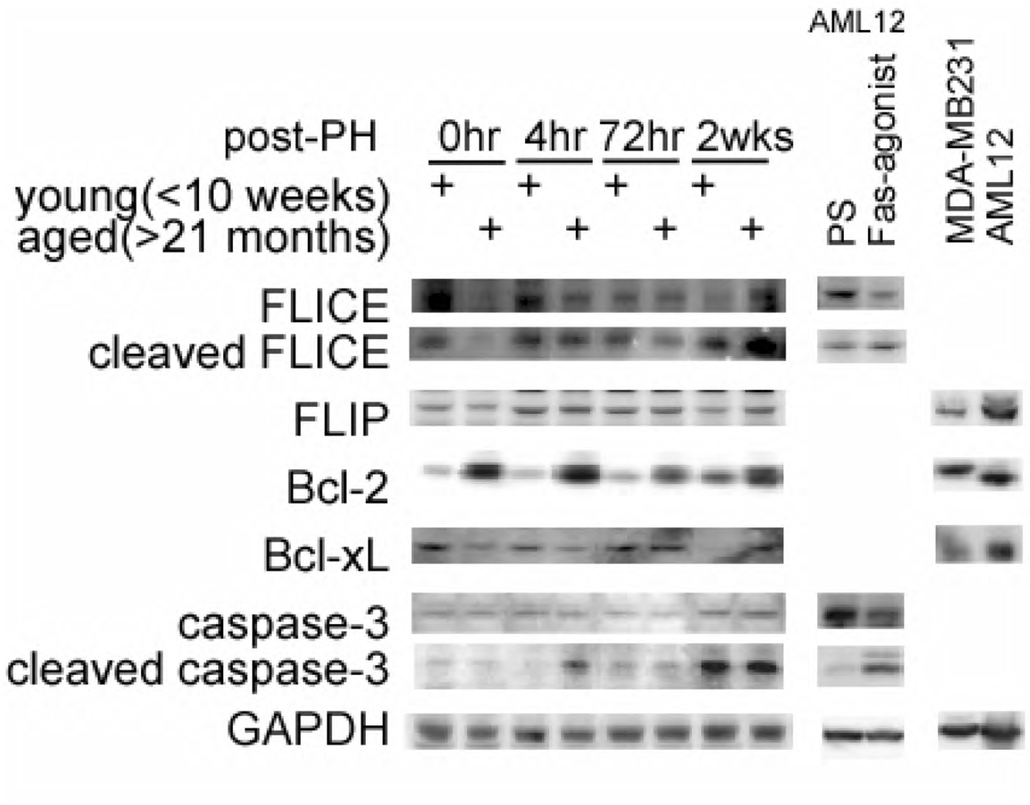
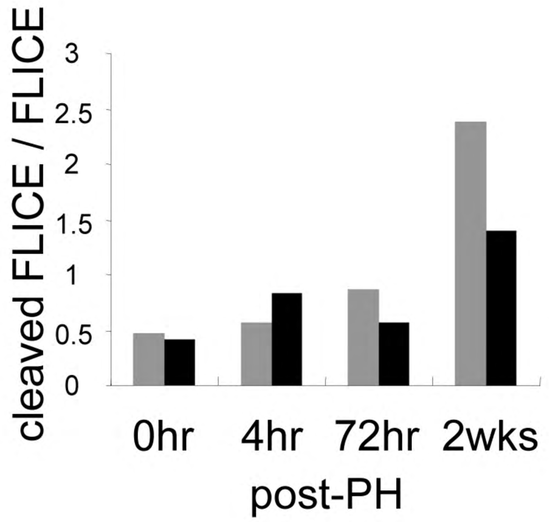
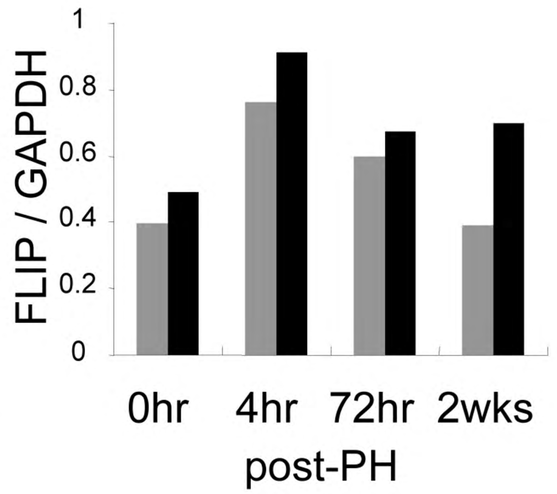
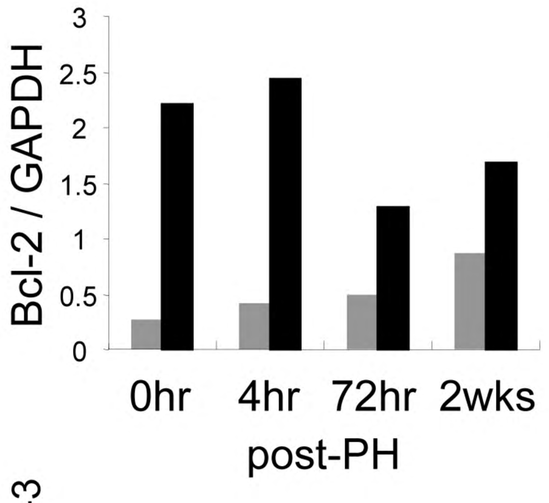

P-Akt / total Akt
1.2
0.8
0.4
0
0hr
4hr
72hr
2wks
post-PH

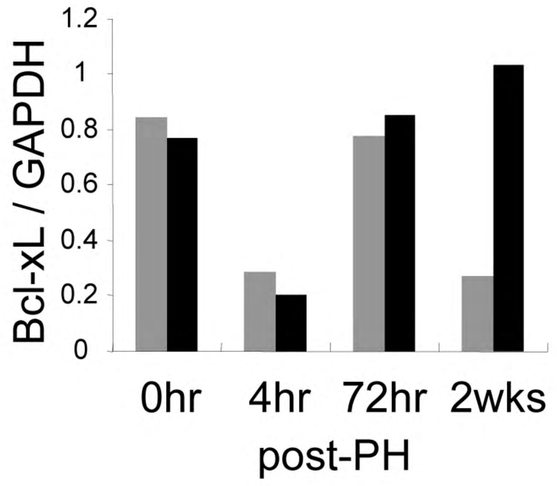
Figure 4b

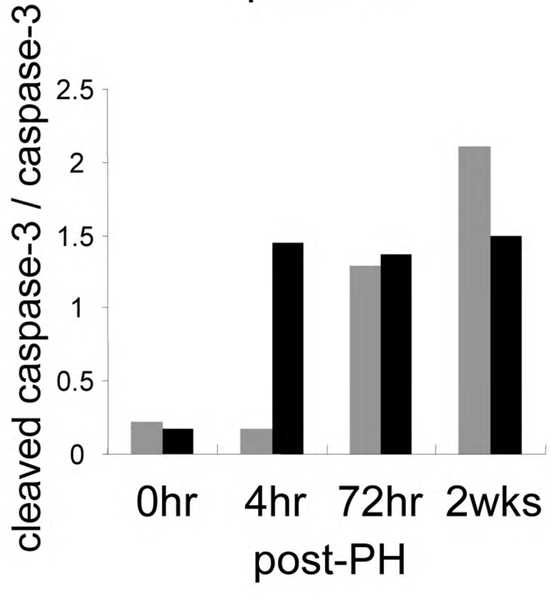

AML12
post-PH
0hr
4hr
72hr
2wks
young(<10 weeks)
aged(>21 months)
PS
Fas-agonist
MDA-MB231
AML12
FLICE
cleaved FLICE
FLIP
Bcl-2
Bcl-xL
caspase-3
cleaved caspase-3
GAPDH


cleaved FLICE / FLICE
0
0.5
1
1.5
2
2.5
3
0hr
4hr
72hr
2wks
post-PH


FLIP / GAPDH
0
0.2
0.4
0.6
0.8
1
0hr
4hr
72hr
2wks
post-PH

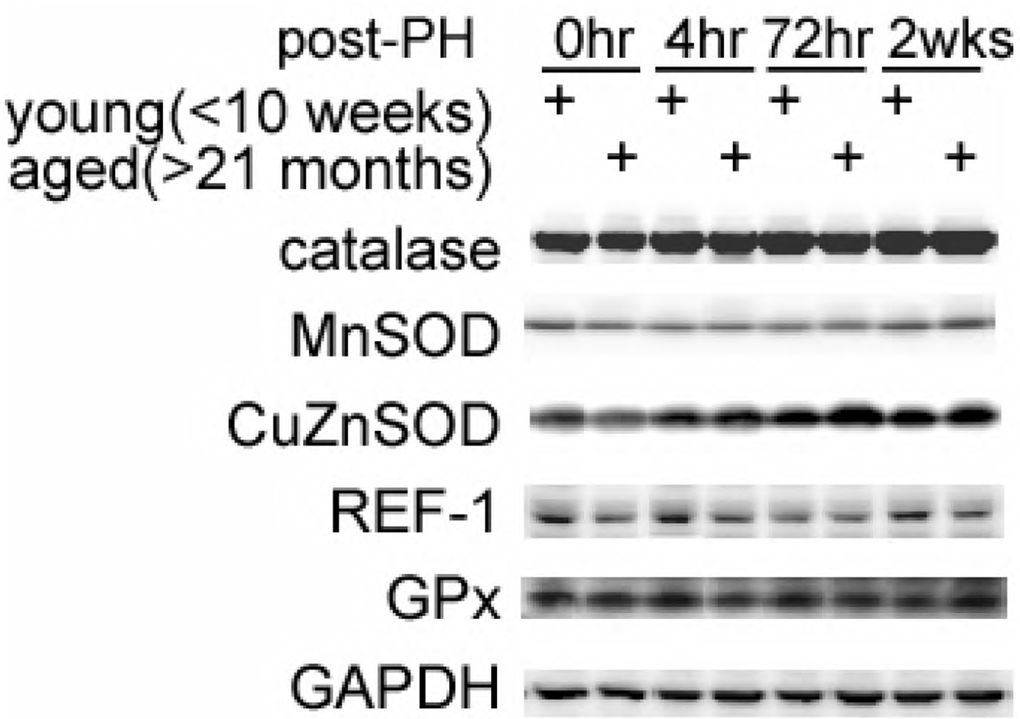

Bcl-2 / GAPDH
0
0.5
1
1.5
2
2.5
3
0hr
4hr
72hr
2wks
post-PH

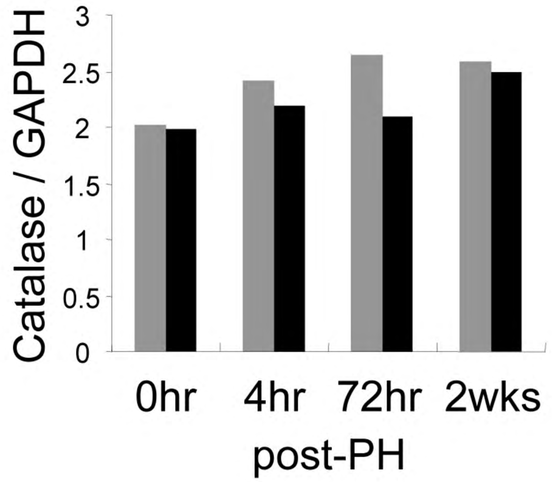

Bcl-xL / GAPDH
0
0.2
0.4
0.6
0.8
1
1.2
0hr
4hr
72hr
2wks
post-PH

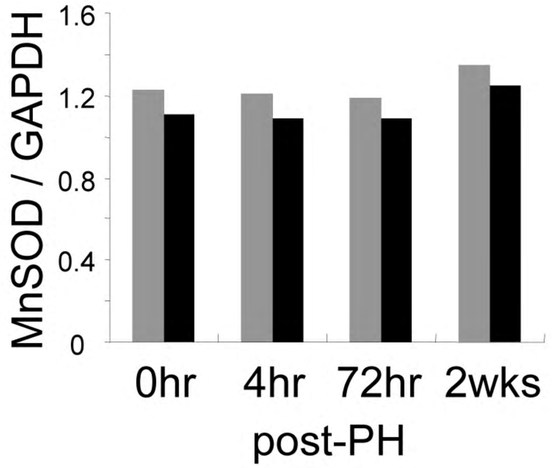

cleaved caspase-3 / caspase-3
0
0.5
1
1.5
2
2.5
0hr
4hr
72hr
2wks
post-PH

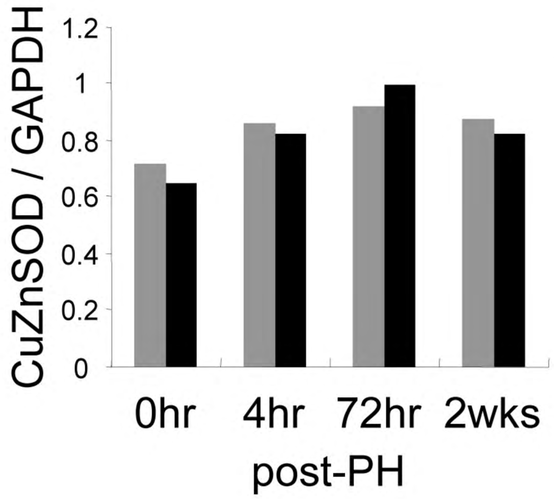

Young
Aged

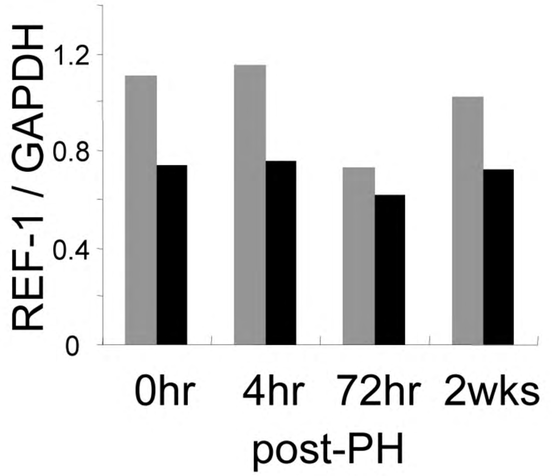
Figure 4c

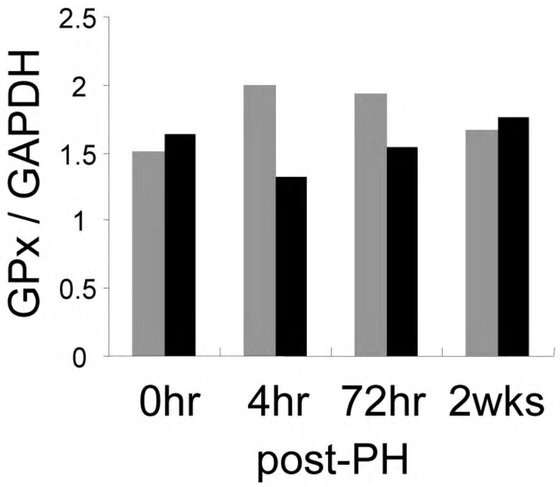

post-PH
0hr
4hr
72hr
2wks
young(<10 weeks)
aged(>21 months)
catalase
MnSOD
CuZnSOD
REF-1
GPx
GAPDH


Catalase / GAPDH
3
2.5
2
1.5
1
0.5
0
0hr
4hr
72hr
2wks
post-PH


MnSOD / GAPDH
1.6
1.2
0.8
0.4
0
0hr
4hr
72hr
2wks
post-PH

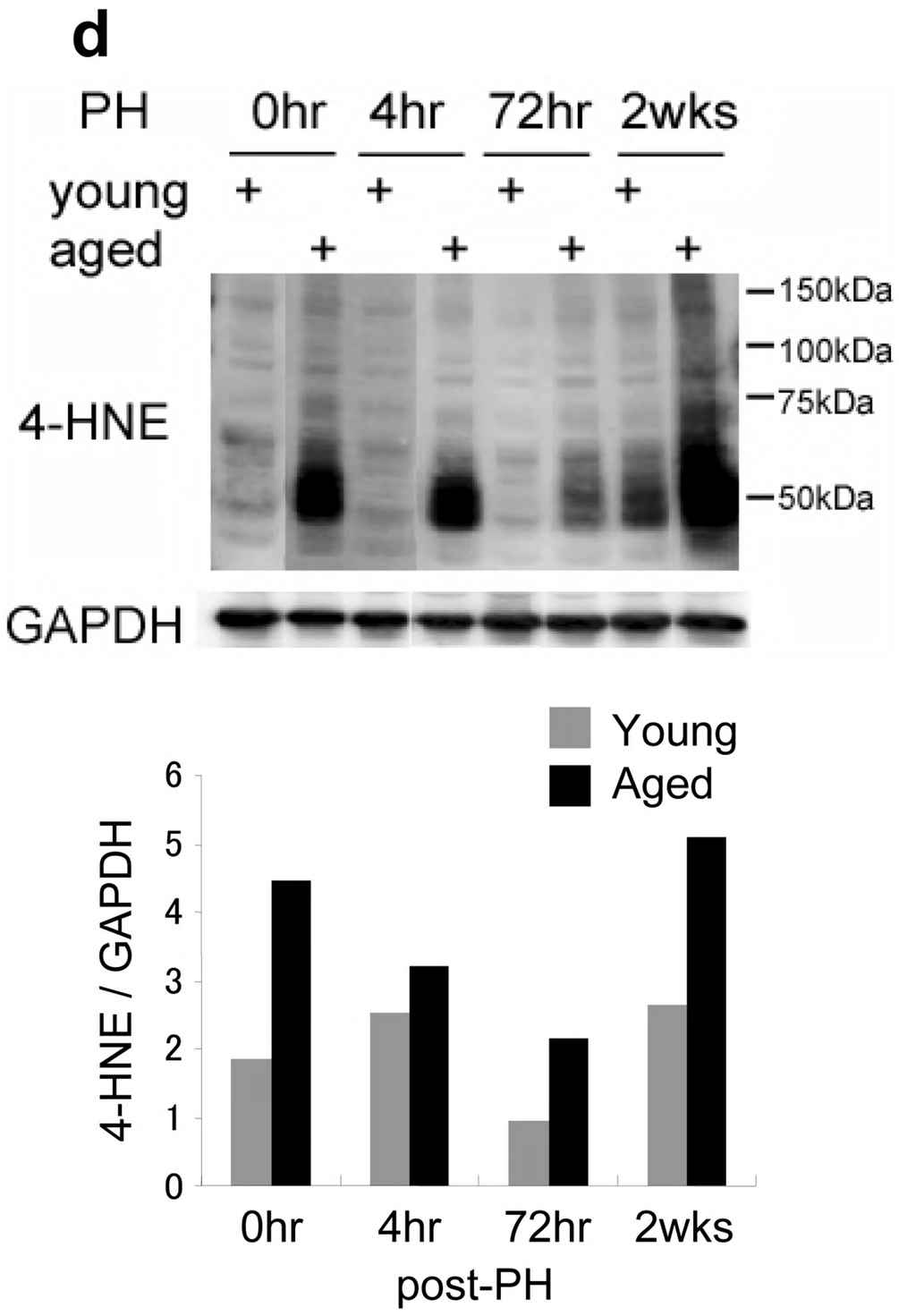

CuZnSOD / GAPDH
1.2
1
0.8
0.6
0.4
0.2
0
0hr
4hr
72hr
2wks
post-PH


REF-1 / GAPDH
1.2
0.8
0.4
0
0hr
4hr
72hr
2wks
post-PH


GPx / GAPDH
2.5
2
1.5
1
0.5
0
0hr
4hr
72hr
2wks
post-PH


Young
Aged

Figure 4


d
PH
0hr
4hr
72hr
2wks
young
aged
4-HNE
150kDa
100kDa
75kDa
50kDa
GAPDH
Young
Aged
4-HNE / GAPDH
0hr
4hr
72hr
2wks
post-PH

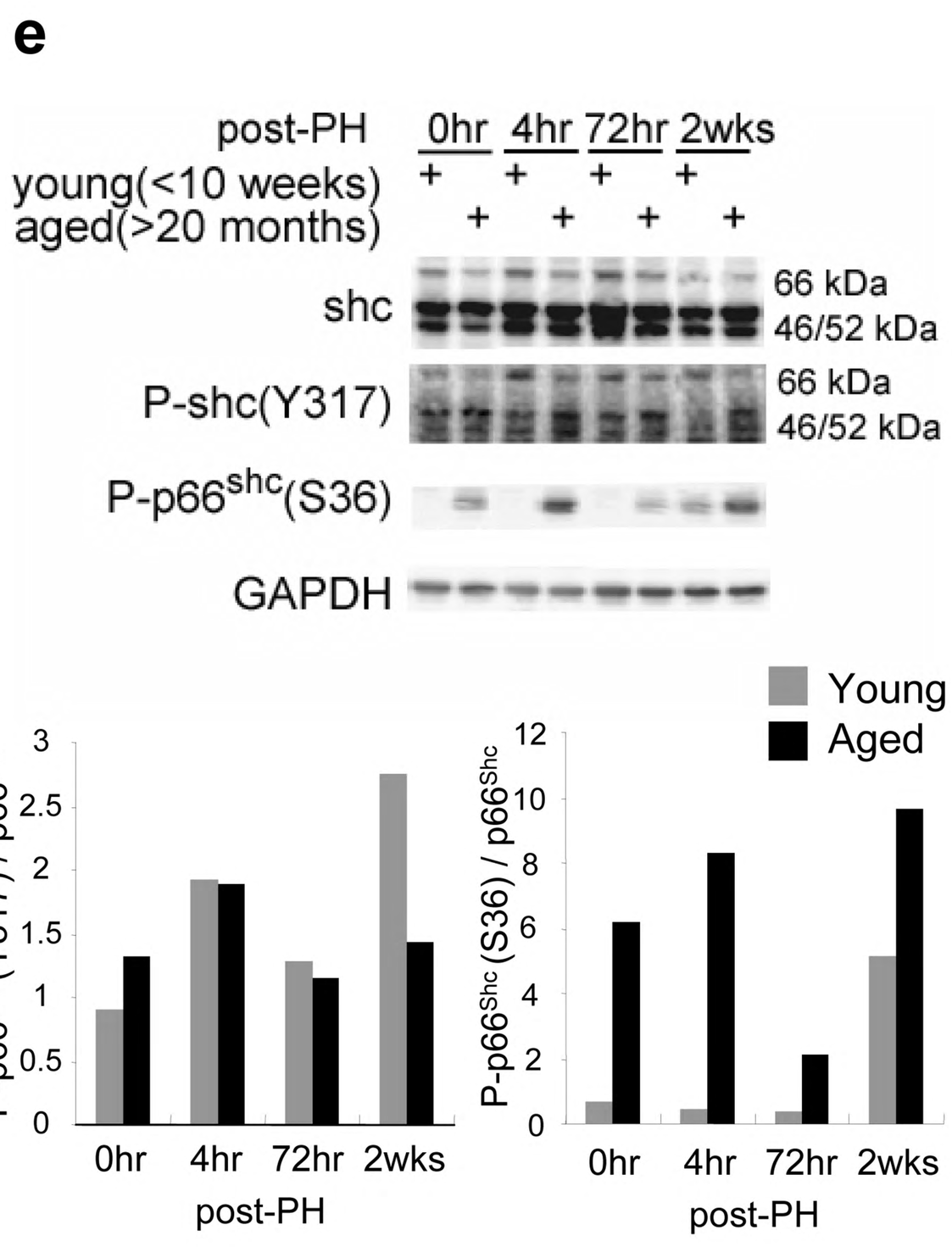
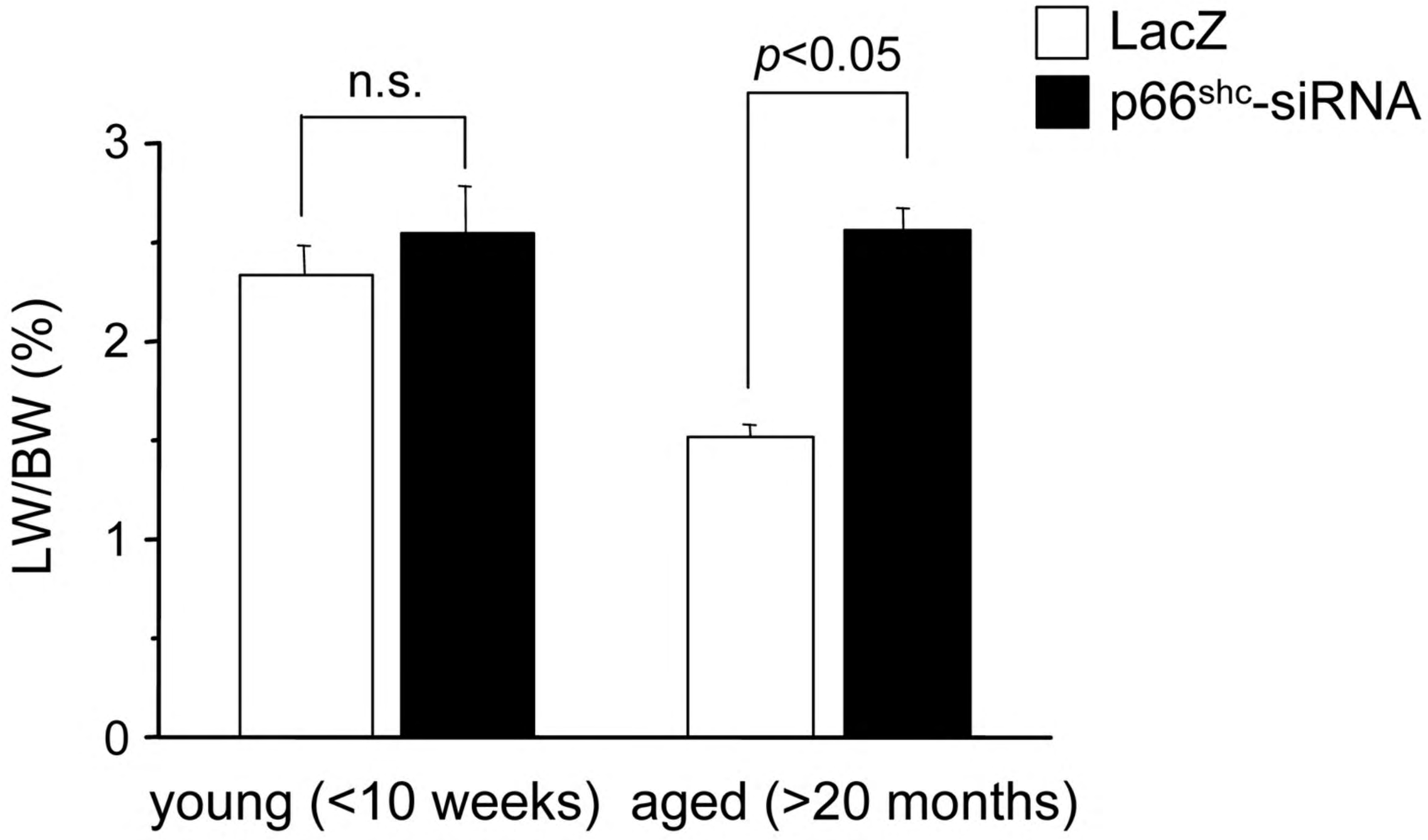

e
post-PH
0hr
4hr
72hr
2wks
young(<10 weeks)
aged(>20 months)
shc
66 kDa
46/52 kDa
P-shc(Y317)
66 kDa
46/52 kDa
P-p66shc(S36)
GAPDH
Young
Aged
P-p66Shc(Y317) / p66Shc
P-p66Shc (S36) / p66Shc
0hr
4hr
72hr
2wks
post-PH

Figure 5

a


n.s.
p<0.05
LacZ
p66shc-siRNA
3
2
1
0
LW/BW (%)
young (<10 weeks)
aged (>20 months)

b

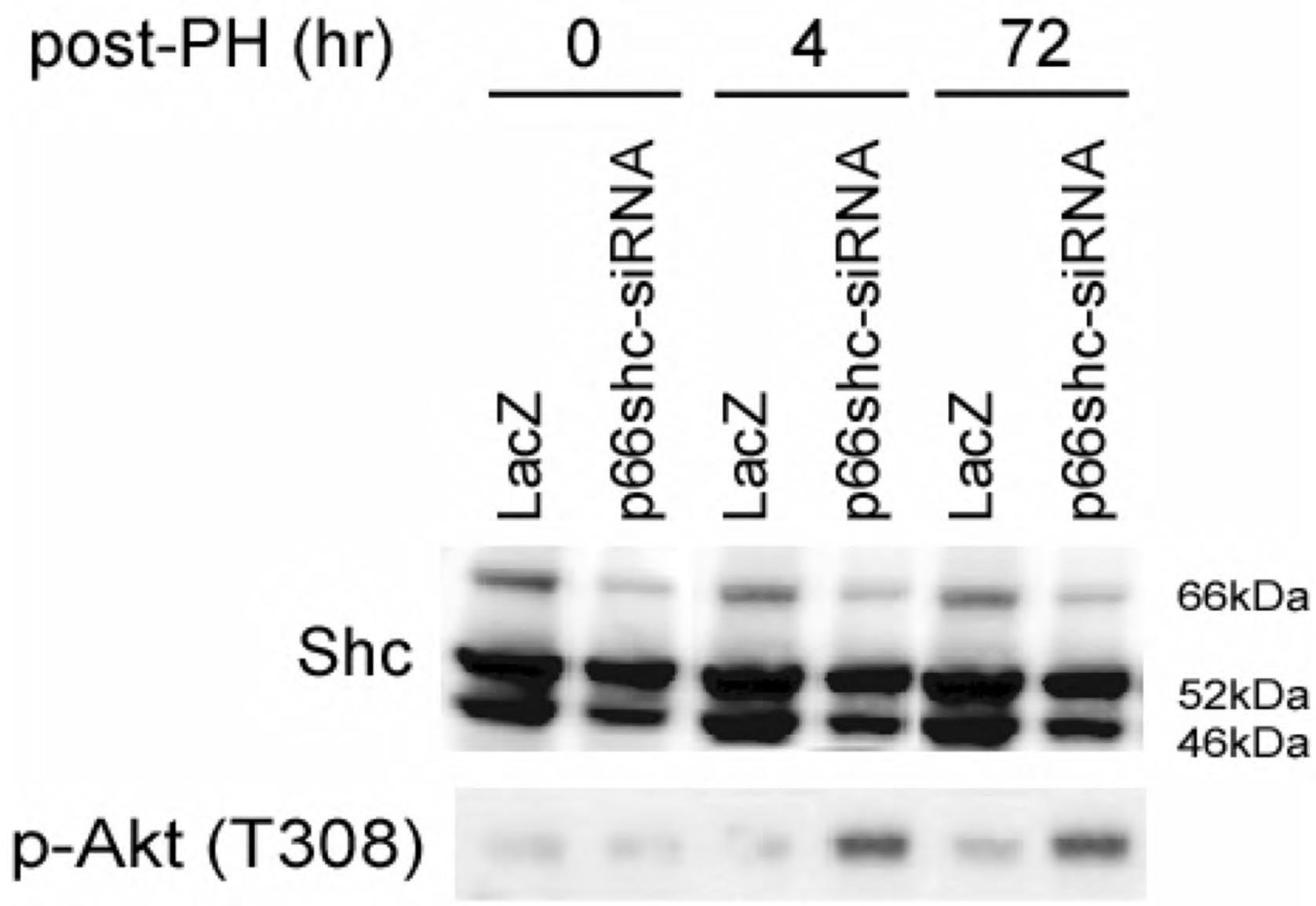
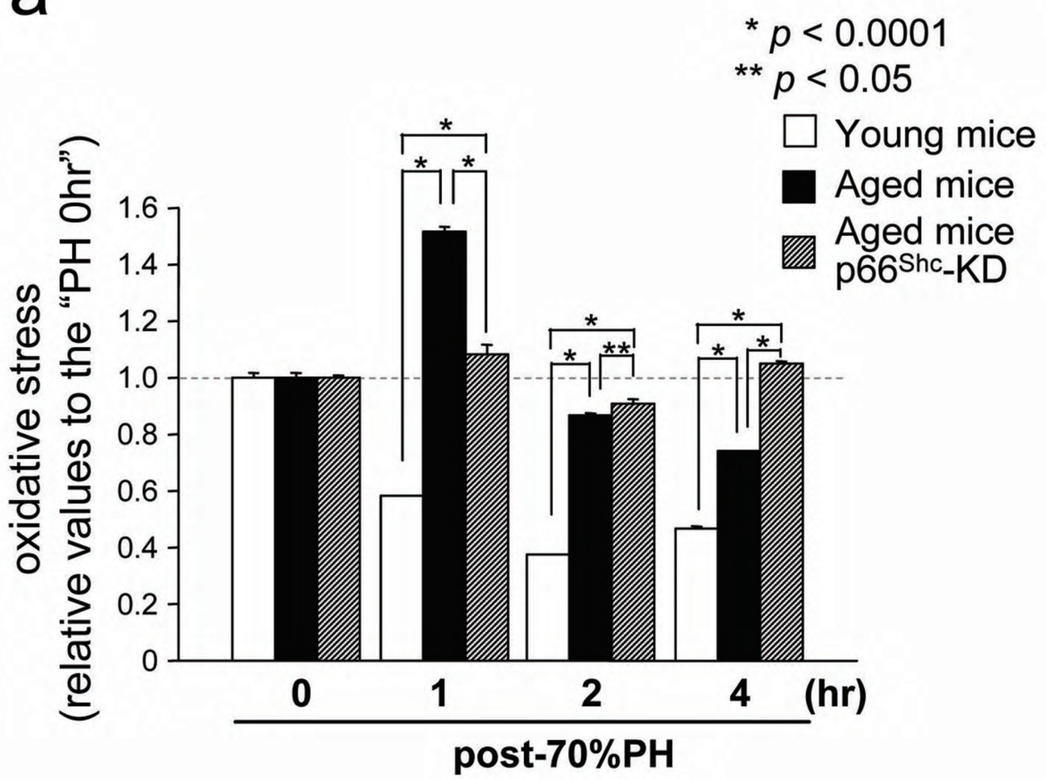
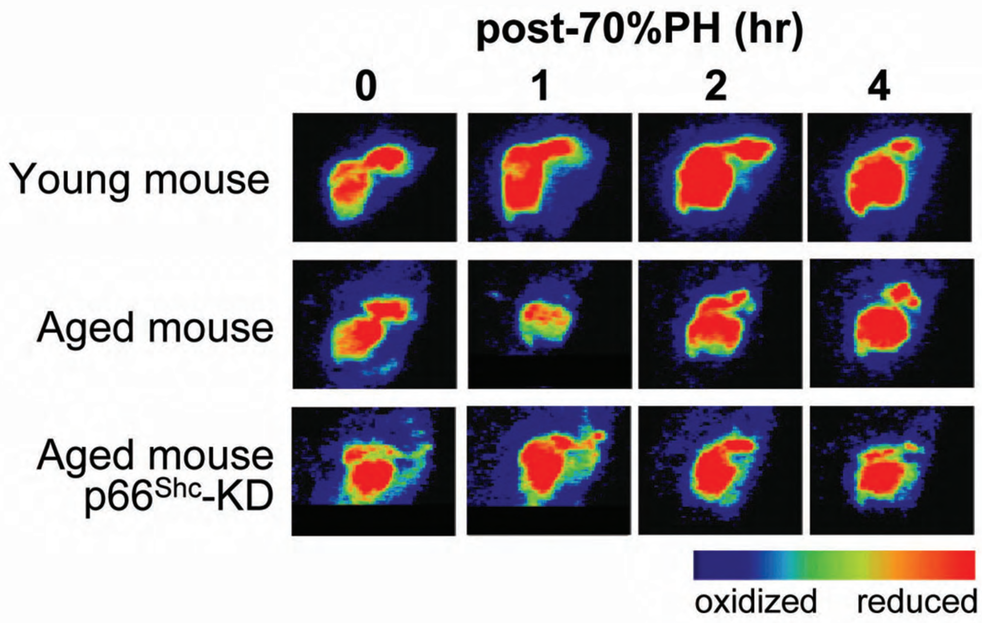

post-PH (hr)
0
4
72
LacZ
p66shc-siRNA
LacZ
p66shc-siRNA
LacZ
p66shc-siRNA
Shc
66kDa
52kDa
46kDa
p-Akt (T308)

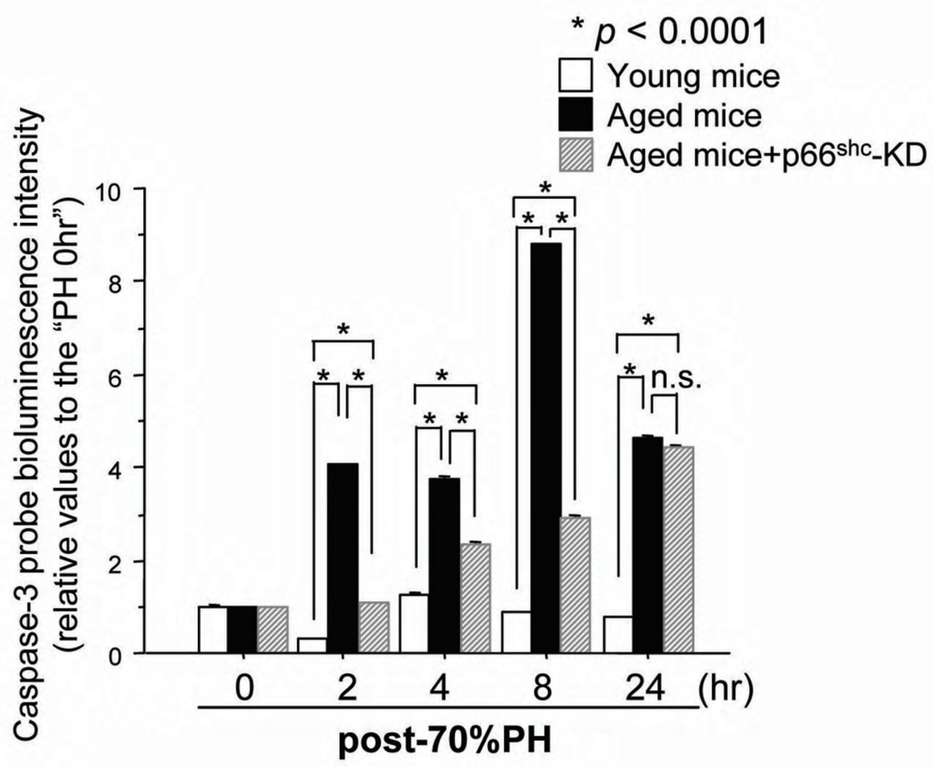
Figure 6

a


* p < 0.0001
** p < 0.05
Young mice
Aged mice
Aged mice p66Shc-KD
oxidative stress (relative values to the "PH 0hr")
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
1
2
4
(hr)
post-70%PH


post-70%PH (hr)
0
1
2
4
Young mouse
Aged mouse
Aged mouse p66Shc-KD
oxidized
reduced

b


* p < 0.0001
Young mice
Aged mice
Aged mice+p66shc-KD
Caspase-3 probe bioluminescence intensity (relative values to the "PH 0hr")
10
8
6
4
2
0
0
2
4
8
24
(hr)
n.s.
post-70%PH

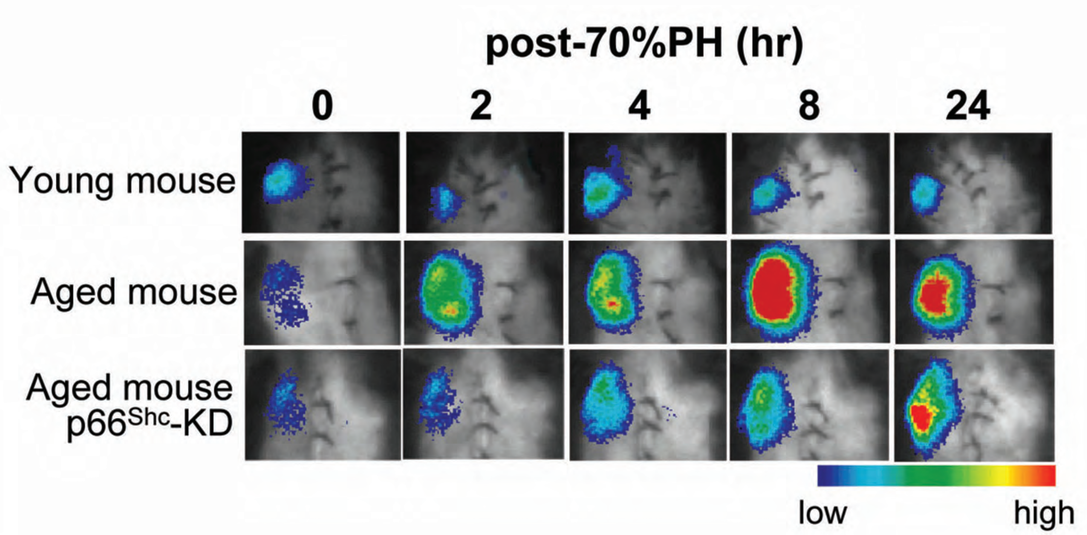
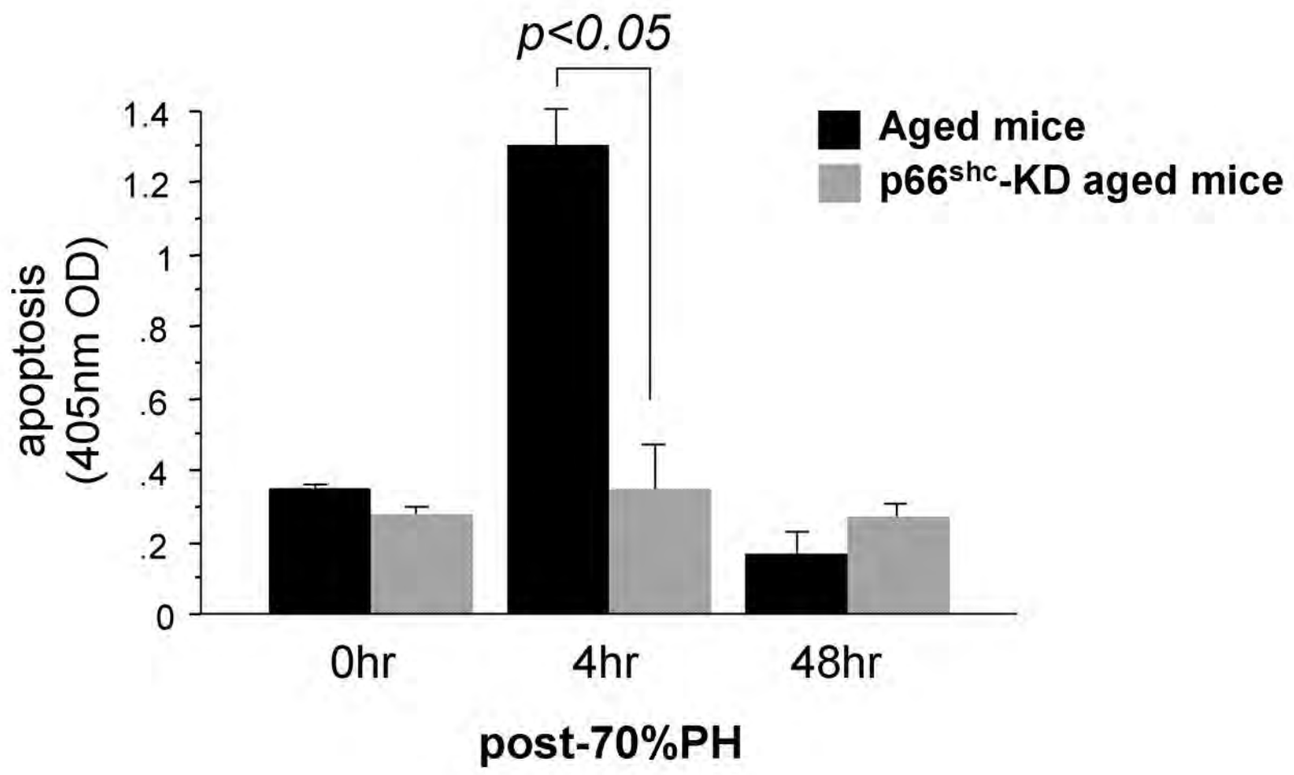

post-70%PH (hr)
0
2
4
8
24
Young mouse
Aged mouse
Aged mouse p66Shc-KD
low
high

Figure 6c


p<0.05
1.4
1.2
1
.8
.6
.4
.2
0
apoptosis
(405nm OD)
0hr
4hr
48hr
post-70%PH
Aged mice
p66shc-KD aged mice