

## Regulation of Expression of the Rat Orthologue Of Mouse Double Minute 2 (*Mdm2*) By $H_2O_2$ -Induced Oxidative Stress in Neonatal Rat Cardiac Myocytes\*

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The *Mdm2* ubiquitin ligase is an important regulator of p53 abundance and p53-dependent apoptosis. *Mdm2* expression is frequently regulated by a p53-*Mdm2* autoregulatory loop whereby p53 stimulates *Mdm2* expression and hence its own degradation. Though extensively studied in cell lines, relatively little is known about *Mdm2* expression in heart where oxidative stress (exacerbated during ischemia-reperfusion) is an important pro-apoptotic stimulus. We demonstrate that *Mdm2* transcript and protein expression is induced by oxidative stress (0.2 mM  $H_2O_2$ ) in neonatal rat cardiac myocytes. In other cells, constitutive *Mdm2* expression is regulated by the P1 promoter (5' to exon 1), with inducible expression regulated by the P2 promoter (in intron 1). In myocytes,  $H_2O_2$  increased *Mdm2* expression from the P2 promoter which contains two p53 response elements (REs), one AP-1 RE and two Ets REs.  $H_2O_2$  did not detectably increase expression of p53 mRNA or protein but did increase expression of several AP-1 transcription factors.  $H_2O_2$  increased binding of AP-1 proteins (c-Jun, JunB, JunD, c-Fos, FosB, Fra-1) to an *Mdm2* AP-1 oligodeoxynucleotide probe, and chromatin immunoprecipitation assays showed it increased binding of c-Jun or JunB to the P2 AP-1 RE. Finally, antisense oligonucleotide-mediated reduction of  $H_2O_2$ -induced *Mdm2* expression increased caspase 3 activation. Thus, increased *Mdm2* expression is associated with transactivation at the P2 AP-1 RE (rather than the p53 or Ets REs), and *Mdm2* induction potentially

represents a cardioprotective response to oxidative stress.

Exposure of cardiac myocytes to sufficiently-high levels of reactive oxygen species (ROS<sup>2</sup>) such as  $H_2O_2$  leads to their death (1-3) and this probably involves a continuum from apoptosis to necrosis, depending the severity of the oxidative stress (4). In aerobic tissues such as the heart, the mitochondria probably represent a significant source of ROS and increased ROS production by these organelles during hypoxia and ischemia-reperfusion injury may be particularly important in myocardial injury (5,6). However, at lower concentrations, ROS have been reported to promote either growth of the cardiac myocyte (7) or to induce 'preconditioning' (8), either of which potentially increases the ability of the cardiac myocyte to survive cytotoxic stresses.  $H_2O_2$ -induced oxidative stress simultaneously stimulates a number of potentially pro-apoptotic and cytoprotective signaling pathways in the whole heart or cardiac myocytes (9), and the final outcome (cell death or survival) could depend on which signaling pathway(s) predominates and endures.

As shown by our microarray studies,  $H_2O_2$  can positively and negatively regulate global gene expression in cardiac myocytes (3,10). One gene consistently upregulated by  $H_2O_2$  in rat cardiac myocytes at toxic and non-toxic concentrations is the orthologue of transformed mouse 3T3 cell double minute 2 (*Mdm2*) (3,10), a protooncogene (11,12), to which we will refer as *Rdm2*<sup>3</sup>. The human orthologue will be abbreviated to *HDM2*. The *Mdm2* protein binds to the pro-apoptotic p53

tumor suppressor transcription factor to inhibit its transactivating activity (13). Perhaps more importantly, Mdm2 is an E3-ubiquitin ligase which ubiquitinates p53 and other proteins (13), thus promoting their proteasomal degradation. Indeed, the stability of p53 protein appears to be of major importance in controlling its abundance (13). In addition, Mdm2 may autoubiquitinate to promote its own degradation (14,15).

Regulation of *Mdm2* expression is complex and involves two alternative promoters. The P1 promoter lies 5' to exon 1 and the P2 promoter lies within intron 1 (16). P1 primarily regulates constitutive expression of *Mdm2* with P2 contributing to a lesser extent. Inducible expression of *Mdm2* is regulated by P2 which contains two p53 response elements and, through these, p53 itself regulates stress-induced expression of *Mdm2* as part of a negative feedback loop (16). Transcripts from the P1 promoter may be translated more slowly than those from P2 because of the presence of short (but differing) upstream open reading frames (two in each) in exon 1 of both *HDM2* and *Mdm2* transcripts (17,18). However, P2 contains additional response elements (AP-1, Ets) that may allow induction of *Mdm2* expression in a p53-independent manner (19-21). The P1- and the P2-regulated transcripts can each give rise to two identical Mdm2 proteins with translation from the initiation codon in exon 3 encoding an Mdm2 species that migrates at about 90 kDa on SDS-PAGE. A truncated 76 kDa species can also be expressed from a second in-frame initiation codon in exon 4 either following removal of exon 3 by alternative splicing or by internal ribosomal entry (22,23). Expression of p76-Mdm2 protein is more favored with transcription from P1 than from P2, without there being any change in absolute p90-Mdm2 protein expression (23). p76-Mdm2 cannot bind to p53 or inhibit its transactivating activity, and it may in fact inhibit the actions of p90-Mdm2 (22). Here, we characterize the *Rdm2* gene and the expression of *Rdm2* mRNA and protein in response to exposure to ROS ( $H_2O_2$ ) in neonatal rat cardiac myocytes. We demonstrate that upregulation of *Rdm2* expression by ROS is largely independent of p53 but correlates instead with transcriptional activation at the AP-1 response element.

Furthermore, *Rdm2* is cytoprotective against ROS-induced apoptosis (caspase 3 cleavage) in cardiac myocytes.

## EXPERIMENTAL PROCEDURES

*Materials* -  $H_2O_2$  was standardized volumetrically before use. It was stable at 4°C for at least 6 months. Antibodies against *Rdm2* [sc-965, a mouse monoclonal antibody raised to residues 154-167 of HDM2 corresponding to residues 169-173 in *Rdm2* (Supplemental Material Fig. 1) in which region *Rdm2* and HDM2 are identical in primary sequence], c-Jun (sc-45X, for supershifting), JunB (sc-46X), JunD (sc-74X), phospho-Elk-1(Ser-383) (sc-7979X), Fli-1 (sc-356X), c-Fos (sc-52X), FosB (sc-48X), Fra-1 (sc-605X), Fra-2 (sc-171X) and ATF2 (sc-187X) were from Santa Cruz Biotechnology Inc. Antibodies against c-Jun (9162, used for immunoblotting) and 17 kDa caspase-3 (9661) were from Cell Signaling Technology. Sarcomeric  $\alpha$ -actin antibodies (A2172) were from Sigma Aldrich and appropriate horseradish peroxidase-linked secondary antibodies were from DAKO.

Six Santa Cruz Biotechnology Inc. anti-p53 antibodies were tested. These were 2B2.71 (sc-71819, a mouse monoclonal IgG<sub>2b</sub> raised against residues 370-378 of human p53), DO-1 (sc-126, a mouse monoclonal IgG<sub>2a</sub> raised against residues 11-25 of human p53), FL-393 (sc-6243, a rabbit polyclonal IgG raised against full-length human p53), Pab 240 (sc-99, a mouse monoclonal IgG<sub>1</sub> raised against residues 156-214 of mammalian p53), Pab 246 (sc-100, a mouse monoclonal IgG<sub>1</sub> raised against residues 88-93 of mouse p53), and R-19 (sc-1313, a goat polyclonal IgG raised against an epitope mapping to the C-terminus of rat p53). With the exception of DO-1 which is not explicitly specified by the supplier as being able to recognize rat p53, all other antibodies are supposed to recognize rat p53 on immunoblotting. As negative and positive controls, we used lysates from non-transfected 293T cells (sc-117752) and from 293T cells transfected with mouse *p53* (sc-125766), respectively, and extracts of daunorubicin-treated cardiac myocytes.

The p53 electrophoretic mobility shift assay (EMSA) oligodeoxynucleotide probe was from Santa Cruz Biotechnology Inc. (sc-

2579). Other probes were synthesized by Sigma Genosys (Sigma Aldrich). Phosphorothioate-protected ODNs and standard oligonucleotides were from MWG Biotech. Lipofectin was from Invitrogen. SMART RACE cDNA amplification kits were from Clontech/BD Bioscience.

*Primary culture of neonatal rat cardiac myocytes* - Myocytes (yield of 3.5 ± 4.5 million cells/heart) were dissociated from the ventricles of 1- to 3-day-old Sprague-Dawley rat hearts by an adaptation of the method of Iwaki *et al.* (24) as previously described (25). Unless stated otherwise, cells were plated in gelatin-coated Primaria culture dishes (BD Biosciences) at a density of  $2 \times 10^6$  cells/35 mm dish or  $4 \times 10^6$  cells/60 mm dish for 18 h in 15% (v/v) fetal calf serum. For most experiments, serum was withdrawn for the 24 h before experimentation and the cells were used 2 d after their isolation.

*Extraction of RNA, cDNA synthesis and semiquantitative or quantitative polymerase chain reaction (RT-sqPCR or RT-qPCR)* - RNA [for which quantity and purity was assessed from the  $A_{260}$  and the  $A_{260}/A_{280}$  ratio (1.8-2.0 deemed acceptable)] was isolated from cardiac myocytes with RNA-Bee (GE Healthcare) according to the manufacturer's instructions, cDNA synthesized with random hexamers and RT-sqPCR (see Table 1 for details of primers) measurements performed as described in detail previously (3,10). To ensure that there was no amplification of genomic DNA, primers were designed to cross exon boundaries where possible (Table 1) and controls in which the RT step was omitted were carried out. The resulting RT-sqPCR products were analysed by ethidium bromide-agarose gel electrophoresis and the bands captured under UV illumination. Sizes of PCR products were estimated by comparison with a  $\lambda$ X174 RF DNA HaeIII digest DNA ladder or a 100 bp DNA ladder (Invitrogen). Densitometric analysis was performed using ImageMaster 1D Prime, version 3.0 (GE Healthcare). Values were normalized to the housekeeping gene *Gapd*. PCR cycles used (Table 1) lay within the exponential phase of amplification (confirmed by construction of amplification curves from PCR over a range of cycle numbers). Sequences of PCR amplicons were determined using an ABI 3100 Genetic

Analyser by the Advanced Biotechnology Centre, Imperial College London).

For RT-qPCR, cDNA was prepared from 1 mg RNA using High Capacity Reverse Transcription Kits (Applied Biosystems). Primers for qPCR were designed with Primer Express v3.0 (<http://www.appliedbiosystems.com>) using deduced *Rdm2* sequences (Supplemental Material Fig. 2, Table 1). qPCR was performed using a 7500 Real-Time PCR System (Applied Biosystems). A master-mix containing (per reaction) 12.5 : 1 Sybr-Green Jump Start Taq Readymix (Sigma-Aldrich) and 5 : 1 oligonucleotides (200 mM forward and reverse primers) was dispensed into Optical 96-well reaction-plates (Applied Biosystems), and cDNA template added (7.5 : 1, 1/15 dilution in water). PCR conditions for all primer pairs were 50°C for 2 min, 95°C for 10 min, followed by 40 cycles of 95°C for 15 s and 60°C for 60 s. Following qPCR, dissociation curve analysis was performed to check for aberrant amplification products. An absolute quantification protocol was used. Values were normalized to *Gapd* expression.

*5'-RACE* - Poly(A)<sup>+</sup> RNA was purified from total RNA (150 : g) using oligo dT-cellulose (Sigma Aldrich). Briefly, total RNA (in 600 : 1 deionized water) was incubated for 5 min at 65°C followed by addition of 1 vol. of 2× binding buffer [20 mM Tris.HCl pH 7.5, 1 M NaCl, 2 mM EDTA, 0.1% (w/v) SDS]. Oligo dT-cellulose (5 mg in 100 : 1 binding buffer) was added followed by rotation at room temperature for 15 min. The oligo dT-cellulose was washed twice with binding buffer (1 ml) and twice with washing buffer [10 mM Tris.HCl pH 7.5, 0.2 M NaCl, 1 mM EDTA, 0.05 % (w/v) SDS]. Poly(A)<sup>+</sup> RNA was recovered in 250 : 1 of elution buffer [10 mM Tris.HCl pH 7.5, 1 mM EDTA, 0.05 % (w/v) SDS; two incubations of 5 min at 37°C]. The purification procedure was repeated and poly(A)<sup>+</sup> RNA was precipitated with 50 : 1 of 4 M NaCl and two volumes of ethanol followed by centrifugation (12,000 × g, 15 min, 4°C). After washing with 70 % (v/v) ethanol and centrifugation, poly(A)<sup>+</sup> RNA was dissolved in deionized water (8 : 1). Poly(A)<sup>+</sup> RNA was reverse-transcribed using a SMART RACE cDNA Amplification Kit (Clontech/BD Bioscience). Poly(A)<sup>+</sup> RNA

(0.9 : g) was mixed with oligo-dT primer (10 mM 5'-CDS primer A, 1 : 1), 10 mM SMART II A oligonucleotide (10 mM, 1 : 1) in a total volume of 5 : 1. This was heated at 72°C for 2 min and cooled on ice. Subsequently, 5× reaction buffer (2 : 1; 250 mM Tris.HCl pH 8.3, 30 mM MgCl<sub>2</sub>, 375 mM KCl), 10 mM dNTP (1 : 1), 20 mM DTT (1 : 1) and 1 : 1 PowerScript™ reverse transcriptase (1 : 1) were added and mixture was incubated at 42°C for 90 min. Reverse transcriptase was inactivated at 72°C for 7 min. The 5'-RACE cDNA reaction mixture (10 : 1) was diluted to 250 : 1 with 10 mM Tricine pH 8.5, 1 mM EDTA and stored at -80°C. Sequence corresponding to 5'-end of *Rdm2* mRNA was amplified using the SMART RACE cDNA Amplification Kit UPM (complementary for the extended 5'-end of the 5'-RACE cDNA) and a reverse primer to mRNA in exon 3 of *Rdm2* exon 3 (bases 269-302, Table 1). For each PCR reaction, 5'-RACE cDNA (2.5 : 1) was combined with 10× 'Advantage' Polymerase Buffer [10 : 1; 40 mM Tricine-KOH pH 9.2, 15 mM KOAc, 3.5 mM Mg(OAc)<sub>2</sub>], 5'-RACE 1 primer (1 : 1, 10 : M), 10× UPM (5 : 1), dNTP (10 mM) and Advantage 2 Polymerase Mix (1 : 1). The PCR programme was as follows: 94°C, 5 min; 5 cycles of 94°C, 30 s and 72°C, 2 min; 5 cycles of 94°C, 30 s, 70°C, 30 s and 72°C, 2 min; then 25 cycles of 94°C, 30 s, 68°C, 30 s and 72°C, 2 min, and finally 72°C, 4 min. PCR products were analysed on ethidium bromide-stained 2 % agarose gels and the bands were captured under UV illumination. Products were excised from the gel and then purified using QIAquick PCR purification columns for automated sequencing (Advanced Biotechnology Centre, Imperial College London).

#### *Soluble and nuclear protein extraction*

- For immunoblotting, myocytes were washed in ice-cold PBS (3×) and scraped into 100 : 1 (35 mm dishes), or (in the case of 60 mm dishes) into 80 : 1 (antisense experiments) or 150 : 1 (remaining experiments) of ice-cold Buffer A [20 mM β-glycerophosphate pH 7.5, 20 mM NaF, 2 mM EDTA, 0.2 mM Na<sub>3</sub>VO<sub>4</sub>, 10 mM benzamide, 5 mM DTT, 1 mM PMSF, 0.2 mM leupeptin, 2 : M microcystin LR, 10 : M E64, 1% (v/v) Triton X-100]. After centrifugation (10,000 × g, 5 min, 4°C),

supernatant protein concentrations were determined using the Bradford method (26), boiled with 0.33 vol SDS electrophoresis buffer [300 mM Tris-HCl pH 6.8, 10% (w/v) SDS, 13% (w/v) glycerol, 130 mM DTT, 0.2% (w/v) bromophenol blue] and stored at + 20°C.

For crude nuclear extracts, PBS-washed myocytes were scraped into 150 : 1 ice-cold Buffer B (10 mM HEPES pH 7.9, 10 mM KCl, 1.5 mM MgCl<sub>2</sub>, 0.3 mM Na<sub>3</sub>VO<sub>4</sub>, 0.2 mM leupeptin, 10 : M E64, 5 mM DTT, 0.3 mM PMSF, 2 : M microcystin LR). Extracts were centrifuged (10,000 g, 5 min, 4°C) and the pellets resuspended in 100 : 1 Buffer B containing 0.1% (v/v) Nonidet P40 (NP-40). Samples were centrifuged (10,000 g, 5 min, 4°C) and the pellets resuspended in 50 : 1 ice-cold Buffer C (20 mM HEPES pH 7.9, 420 mM NaCl, 1.5 mM MgCl<sub>2</sub>, 0.2 mM EDTA, 25% (v/v) glycerol, 0.3 mM Na<sub>3</sub>VO<sub>4</sub>, 0.2 mM leupeptin, 10 : M E64, 5 mM DTT, 0.3 mM PMSF, 2 : M microcystin LR). Suspensions were incubated on ice (1 h) with mixing every 15 min, and then centrifuged (10,000 g, 5 min, 4°C). Supernatants were retained and stored at + 80°C or were boiled with SDS electrophoresis buffer.

*Immunoblotting* - Proteins were separated by SDS-PAGE using between 8 to 12% (w/v) resolving gels as appropriate with 4 to 6% (w/v) stacking gels, and transferred to nitrocellulose membranes as described previously (27). Gels were standardized using 'rainbow' markers (GE Healthcare). Nonspecific binding sites were blocked (60 min, room temperature) with 5% (w/v) non-fat milk powder in TBST [20 mM Tris-HCl, pH 7.5, 137 mM NaCl, 0.1% (v/v) Tween 20]. Blots were incubated overnight with primary antibodies diluted in TBST containing 5% (w/v) bovine serum albumin. Membranes were washed in TBST (3 × 5 min, room temperature) and incubated (1 h, room temperature) with horseradish peroxidase-conjugated secondary antibodies in TBST containing 1% (w/v) non-fat milk powder. After washing in TBST (3 × 5 min, room temperature), bands were detected by the enhanced chemiluminescence method (reagents from Santa Cruz Biotechnology Inc.). In some cases the sensitivity of detection was increased by using unconjugated secondary antibodies in TBST/1% (w/v) non-

fat milk powder and, after washing with TSBT, blots were incubated with horseradish peroxidase-conjugated tertiary antibodies before detection by enhanced chemiluminescence.

*Antisense ODN transfection* - The 20-mer antisense phosphothioate-protected ODN, 5'-TGACATCTGCTCTCACTCGG-3', was directed against *Rdm2* mRNA exon 7 bases 602-621 (Supplemental Material Fig. 2). A mixed back-bone HDM2 antisense ODN (5'-UGACACCTGTTCTCACUCAC-3') against the corresponding region (*HDM2* mRNA bases 660-679, accession no. NM\_002392.2) has been used previously to inhibit *HDM2* expression in colon cancer cells (28). A random sequence (5'-TGGATCCGACATGTTCAGA-3') was used as a control. For transfection experiments, cells in 60 mm dishes were washed 3 times with antibiotic-free DMEM before exposure to DMEM containing 200 nM ODN and 20 : g/ml lipofectin (Invitrogen). Myocytes were incubated for 24 h at 37°C, then the medium was then replaced with lipofectin-free maintenance medium containing 200 nM ODN. Cells were pre-incubated for 1 h before exposure to 0.2 mM H<sub>2</sub>O<sub>2</sub> for 6 h and extracted into 80 : 1 Buffer A (see above).

*Electrophoretic mobility shift assays (EMSA)* - Double-stranded ODN EMSA probes (see Table 2) were prepared essentially as described previously (29). Briefly, ODNs were 5'-labelled with 15 : Ci [<sup>32</sup>P]ATP (GE Healthcare), 10 IU T4 polynucleotide kinase (Promega), and 1.2 : 1 of Promega 10 × kinase buffer. The reaction mixture was incubated (37°C, 30 min) and the reaction then terminated by addition of 1 : 1 EDTA (13 : M). Excess [<sup>32</sup>P]ATP was removed by centrifugation (700 g, 3 min, room temperature) through Chroma Spin columns (pore size 10) (Clontech/BD Biosciences) in 1× TE buffer (10 mM Tris-HCl pH 8.0, 1 mM EDTA) and the EMSA probes were diluted to 0.4 ng/1. Crude nuclear extracts (10 : g) were incubated (10 min, room temperature) with 4 : 1 binding buffer [50 mM Tris-HCl pH 7.5, 250 mM NaCl, 5 mM EDTA, 1 mM DTT, 25% (v/v) glycerol] and 1 : g poly dI-dC (GE Healthcare), in a total volume of 20 : 1. Radiolabelled EMSA probe (1 : 1, 0.4 ng) was added and the mixture incubated (20 min,

room temperature). Samples were subjected to electrophoresis (120 V, 3 h) on 5% (w/v) non-denaturing polyacrylamide gels formed in 1× TBE buffer (89 mM Tris, 89 mM boric acid, 2 mM EDTA, pH 8.3) with 0.5× TBE as running buffer. Gels were dried onto Whatman 3MM paper and exposed to X-ray film for 24 : 48 h at -80°C. Images were analysed semi-quantitatively by densitometry (ImageMaster 1D Prime, version 3.0, GE Healthcare). For competition experiments, crude nuclear extracts were incubated (10 min) with the required amount of unlabelled competing probe in binding buffer with poly dI-dC as in the standard assay, followed by addition of the radiolabeled wild type probe and continuation of the assay in the standard manner. For supershift assays, crude nuclear extracts (3 : g protein) were pre-incubated (1 h, 4°C) with 1 : 2 : g of antibody.

*ChIP assays* - Myocytes were exposed to H<sub>2</sub>O<sub>2</sub> (0.2 mM, 2 h) and formaldehyde [final concn. 1% (w/v)] was added to medium (10 min, room temperature). Cross-linking was terminated with 0.125 M glycine (5 min). Myocytes were rinsed twice in ice-cold PBS and scraped into 200 : 1 PBS containing 0.2 mM leupeptin, 10 : M E64, 5 mM DTT, 1 mM PMSF and 2 : M microcystin LR. Suspensions were centrifuged (4,000 g, 10 min, 4°C) and pellets resuspended in 0.8 ml ChIP lysis buffer [50 mM Tris-HCl pH 8.0, 85 mM KCl, 0.2 mM leupeptin, 10 : M E64, 5 mM DTT, 0.3 mM PMSF, 2 : M microcystin LR, 0.5% (v/v) NP-40]. Suspensions were incubated on ice (10 min), centrifuged (4,000 g, 10 min, 4°C) and the pellets resuspended in 0.8 ml sonication buffer [50 mM Tris-HCl pH 8.0, 10 mM EDTA, 1% (v/v) SDS, 0.2 mM leupeptin, 10 : M E64, 5 mM DTT, 1 mM PMSF and 2 : M microcystin LR]. Samples were sonicated [5 × 30 sec, 0°C, amplitude 30% (Sonics Vibra-Cell™ sonicator with a 2 mm probe) followed after each sonication by 2 min recovery in ice-water] to shear DNA into fragments of 200-800 bp. Sonicated samples were centrifuged (4,000 g, 10 min, 4°C) and the supernatants were retained. Samples (20 : 1) for total DNA input were taken at this stage. Sonicated extracts (750 : 1) were diluted with 3.65 ml ChIP buffer [20 mM Tris.HCl pH 8.0, 150 mM NaCl, 2 mM EDTA, 0.01% (w/v) SDS, 1% (v/v) Triton X100] and were pre-

cleared with 30 : 1 50% Protein A-Sepharose slurry containing 5 : g/ml sonicated salmon sperm DNA (rotation at 4°C for 30 min). Following centrifugation (200 g, 1 min, 4°C), anti-transcription factor antibodies (5 : g) were added followed by incubation (4°C, 16 h, with mixing by rotation). Antibody-protein-DNA complexes were recovered by incubation (1 h, 4°C, with mixing by rotation) with 50% Protein A-Sepharose slurry (80 : 1 containing 5 : g/ml sonicated salmon sperm DNA). Protein A-Sepharose-antibody-transcription factor complexes were recovered by centrifugation (200 g, 1 min, 4°C) and pellets were washed in low salt buffer [20 mM Tris.HCl pH 8.0, 150 mM NaCl, 2 mM EDTA, 0.1% (w/v) SDS, 1% (v/v) Triton X100, 1 ml], high salt buffer [20 mM Tris.HCl pH 8.0, 500 mM NaCl, 2 mM EDTA, 0.1% (w/v) SDS, 1% (v/v) Triton X100, 1 ml], LiCl buffer [10 mM Tris.HCl pH 8.0, 250 mM LiCl, 1 mM EDTA, 1% (w/v) deoxycholic acid, 1% (v/v) NP-40] and then twice in 10 mM Tris.HCl pH 8.0, 1 mM EDTA. Protein-DNA complexes were recovered by incubation (15 min, 65°C) with 0.1 M NaHCO<sub>3</sub>, 1% (w/v) SDS (250 : 1), samples were centrifuged (200 g, 1 min, 4°C) and supernatants retained. This elution step was repeated and supernatants combined. Cross-linking was reversed by incubation (16 h, 65°C) with 0.2 M NaCl. DNA was extracted by mixing equal volumes of samples with phenol:chloroform:isoamyl alcohol (25:24:1, pH 8.0) and with separation of the phases by centrifugation (15,000 g, 10 min, 4°C). The upper aqueous phases were retained and DNA was precipitated by adding 1 vol. isopropanol for 1 h on ice. Following recovery of DNA by centrifugation (21,000 g, 10 min, 4°C), DNA was washed [70% (v/v) ethanol] and resuspended in 20 : 1 Milli-Q water for subsequent PCR. PCR reactions were performed in 1× Buffer IV® (AB Gene, 25 : 1) containing Taq polymerase (1 U), dATP, dCTP, dGTP and dTTP (0.2 mM each) and 50 pmol primers. PCR settings were: 94°C, 4min; 35 × (94°C, 30s; 59°C, 30s; 72°C, 30s), followed by 72°C, 4 min. The resulting RT-PCR products were analysed by ethidium bromide-agarose gel electrophoresis and the bands captured under UV illumination.

*Statistical analysis* - Results are expressed as means ± SEM. Statistical

significance was determined by either Student's *t*-test or one-way analysis of variance (ANOVA) followed by Tukey's multiple comparison test, as appropriate. *P* values of <0.05 were considered significant.

## RESULTS

*Structure of the Rdm2 gene* - Mdm2 (NP\_034916.1, 489 residues) and HDM2 (NP\_002383.2, 497 residues) are encoded by established genes and are highly conserved, sharing precise identity in about 80% of residues (Supplemental Material Fig. 1). In contrast, *Rdm2* is a predicted gene on chromosome 7(q22) in the NCBI database (<http://www.ncbi.nlm.nih.gov>) whose provisional processed transcript NM\_001108099.1 (21 December 2008) encodes a protein that differs significantly from Mdm2 and HDM2. A BLAST search of the mouse *Mdm2* transcript NM\_010786.3 against the rat genome identified a 24233 bp sequence on the minus strand of contig NW\_047774 corresponding to a 2930 nucleotide transcript from 12 exons with high homology to the *Mdm2* transcript (Supplemental Material Fig. 2). The deduced 2930 nucleotide sequence of the full-length transcript is identical to 2855 nucleotide NM\_001108099.1 except that it contains an extra exon, the 75 nucleotide (protein-coding) exon 4. A BLAST search of this exon revealed 14 rat ESTs with a region of precise sequence identity within them, thus establishing that exon 4 is transcribed and is present in mature *Rdm2* mRNA. The structural relationship of the first four exons in *Rdm2* is shown in Fig. 1. The initiation codon for p90-Rdm2 lies in exon 3 whereas that for p76-Rdm2 lies in-frame in exon 4 (Fig. 1). Two short and overlapping upstream open reading frames are present in exon 1 of the deduced *Rdm2* mRNA sequence (Supplemental Material Fig. 2). The *HDM2* and *Mdm2* transcripts also each contain two (differing) upstream open reading frames (17,18). The deduced amino acid sequence of Rdm2 and the Mdm2 sequence are approximately 90% identical, though Mdm2 possesses a more extended Ser-rich region at residues 203-211 (Supplemental Material Fig. 1).

*Expression of Rdm2 mRNA and protein in response to H<sub>2</sub>O<sub>2</sub>* - We examined the effects of H<sub>2</sub>O<sub>2</sub> on *Rdm2* expression by RT-sqPCR and RT-qPCR. Up-regulation of *Rdm2* mRNA was rapid being detectable at 1 h (Fig. 2, A-C), maximal at 2 h and maintained for at least 6 - 24 h. The absolute extent of maximal upregulation depended on the technique used with sqPCR giving 3- to 4-fold (Fig. 2A) but with qPCR giving 20- to 30-fold (Fig. 2, B and C). This probably reflects differences in primer design and the semi-quantitative nature of densitometric analysis. At 1 h, *Rdm2* mRNA was detectably-induced with 0.1 mM H<sub>2</sub>O<sub>2</sub> and maximally-induced with 0.2-0.3 mM H<sub>2</sub>O<sub>2</sub> (Fig. 2, D and E). At higher concentrations of H<sub>2</sub>O<sub>2</sub>, *Rdm2* mRNA abundances remained at control values (Fig. 2, D and E). At 2 h of exposure, the maximal response was greater and was shifted to higher H<sub>2</sub>O<sub>2</sub> concentrations (Fig. 2E). These 'bell-shaped' concentration dependencies are typical of a number of responses of the cardiac myocyte to H<sub>2</sub>O<sub>2</sub>. The stimulation of *Rdm2* expression by H<sub>2</sub>O<sub>2</sub> at 1 h was prevented by CHX (Fig. 3, A and B), indicating that *Rdm2* is not an immediate early gene (i.e. the stimulation of its transcription by H<sub>2</sub>O<sub>2</sub> is dependent on preceding *de novo* protein synthesis).

Since H<sub>2</sub>O<sub>2</sub> can inhibit overall protein synthesis in cardiac myocytes (3), we investigated whether the increased abundance of *Rdm2* transcripts was reflected in their translation into protein (Fig. 2, F and G). *Rdm2* migrated at about 90 kDa on SDS-PAGE and protein abundance increased about 5-fold over 45 min -1.5 h (Fig. 2F). In some blots, multiple bands were observed (Fig. 2, F and G). Whilst one of these may represent p76-Rdm2, they may be degradation products or cross-reacting species. Abundance of *Rdm2* protein was maximal at 1 to 2 h and declined gradually thereafter (Fig. 2G), but remained elevated over control values (about 2- to 3-fold greater) for up to 8 h.

Abundance of any individual mRNA species is regulated by the rate of its transcription and the rate of its degradation. The 3' untranslated region of *Rdm2* mRNA contains an AU-rich instability element [probably a class I ARE consisting of overlapping or adjacent AUUUA pentamers (30), bases 2072-2085, Supplemental Material

Fig. 2] which is orthologous with a putative *Mdm2* mRNA ARE [see the Organism ARED (30) at <http://brp.kfshrc.edu.sa/ARED/> and Reference (23)], though the *Mdm2* ARE may be non-functional (23). We therefore examined the half-life of *Rdm2* transcripts when transcription was inhibited (by actinomycin D) in the absence or presence of 0.2 mM H<sub>2</sub>O<sub>2</sub> (Fig. 3C). The data sets ( $n = 4$  for each condition) were treated as monophasic exponential decays. *Rdm2* mRNA was degraded with a half-life of 1.16 h ( $k = 0.596 \pm 0.140 \text{ h}^{-1}$ ) in the absence of H<sub>2</sub>O<sub>2</sub>, whereas it was 1.82 h ( $k = 0.381 \pm 0.141 \text{ h}^{-1}$ ) in the presence of H<sub>2</sub>O<sub>2</sub>. There was thus no significant difference in the stability of the transcripts under the two conditions and thus upregulation of *Rdm2* expression results primarily from increased transcription.

*Alternative promoter usage in Rdm2 transcription* - Transcription of *Mdm2* and *HDM2* is regulated by two alternative promoters, P1 or P2, lying 5' to exon 1 or exon 2, respectively (16). To assess alternative promoter usage for *Rdm2*, we used forward primers in exon 1 (F1) or in exon 2 (F2) and a reverse primer in exon 4 (Fig. 1, Supplemental Material Fig. 2) to produce amplicons of 333 bp from P1 (long mRNA) or 220 bp from either P1- or P2 (long + short mRNAs). In unstimulated cardiac myocytes, mRNA was detectable at 333 bp (Fig. 4A) using primer F1 and this would contribute to the 220 bp band seen with primer F2 to an unassessable extent. Following exposure to H<sub>2</sub>O<sub>2</sub> (0.2 mM, 2 h), there were no changes in the amplicon abundances using primer F1, but primer F2 amplicon abundances increased about 4- to 5-fold. The sequences of the 220 and 333 bp PCR products were confirmed, indicating that H<sub>2</sub>O<sub>2</sub>-inducible transcription was regulated by the P2 promoter.

To confirm increased P2 promoter usage, we conducted 5'-RACE. The theoretical lengths of the amplicons were 332 bp for a transcript expressed from the P1 promoter and 162 bp for a transcript expressed from the P2 promoter (Fig. 1, Supplemental Material Fig. 2). Under control conditions, the major product (amplicon A) was 300 ! 400 bp in length with a weaker band (amplicon B) at 100 ! 200 bp (Fig. 4B). Following exposure to H<sub>2</sub>O<sub>2</sub> (0.2 mM, 2 h), the product corresponded

essentially completely to the shorter amplicon B. DNA sequencing confirmed that amplicon A corresponded to exons 1, 2 and 3 (up to the reverse primer site) whereas amplicon B corresponded to exons 2 and 3. These results confirm that transcripts originate from P1 with some expression from P2 in the control, whereas promoter usage shifts primarily to P2 following exposure to H<sub>2</sub>O<sub>2</sub>.

*Transcription factor-response elements in intron 1 of the Rdm2 gene* - We identified potential regulatory elements in *Rdm2* intron 1 by analogy with published data for intron 1 of the *Mdm2* and *HDM2* genes and by using TFSEARCH ([www.cbrc.jp/research/db/TFSEARCH.html](http://www.cbrc.jp/research/db/TFSEARCH.html)). A region in intron 1 of the *Mdm2* (402-523), *Rdm2* (374-494, Fig. 1) and *HDM2* (406-524) genes is highly conserved with ~75% identity (Supplemental Material Fig. 3). This contains the two p53-response elements (31,32) and a composite AP-1-Ets element [Ets<sup>(AP-1)</sup>] (33,34). An upstream Ets [Ets<sup>(upstream)</sup>] element in *Rdm2* and *Mdm2* lies outside the conserved region (Supplemental Material Fig. 3, Fig. 1). High-stringency searching also reveals an NF-E2-like site (35) in *Rdm2* which overlaps with the AP-1 site and which is conserved between *Mdm2* and *HDM2*. *Rdm2* and *Mdm2* also contain a sequence reminiscent of an MZF-1 element (36) that is not conserved in *HDM2*, though *HDM2* contains an alternative MZF-1 site (Supplemental Material Fig. 3). However, neither NF-E2 or MZF-1 are thought to be significantly expressed outside hematopoietic cells (35,37), and they were not studied further.

*p53* - Induction of *p53* is frequently a response to mutational or cytotoxic interventions and is of established importance in the regulation of inducible expression of *Mdm2* (16). We examined whether *p53* mRNA expression increased in response to H<sub>2</sub>O<sub>2</sub>. Though an amplicon of the appropriate size for *p53* was detectable by RT-sqPCR, exposure of myocytes to 0.2 mM H<sub>2</sub>O<sub>2</sub> for up to 24 h did not alter its expression (results not shown).

The matter of whether p53 protein is induced by ROS is contentious and doubts have been raised about the reliability of antibodies obtained from Santa Cruz Biotechnology Inc. (see Discussion). We characterized six different antibodies using

lysates of 293T cells with (positive control) or without (negative control) transfection with mouse *p53* (Fig. 2). Three of these reliably detected p53 by immunoblotting in our hands [FL-393 (Fig. 5A), Pab 240 (Fig. 5B) and 2B2.71 (Fig. 5C)]. In all cases, p53 migrated slightly more rapidly than a 52 kDa marker (GE Healthcare, RPN800E). With FL-393 (Fig. 5A) and 2B2.71 (Fig. 5C), cross-reacting proteins were detectable in whole cell extracts of 293T cells, one of which migrated slightly more slowly than p53 at ~52 kDa. We confirmed that p53 in crude nuclear extracts of rat cardiac myocytes which had been exposed to the anthracycline, daunorubicin, [anthracyclines induce p53 in these cells (38)] co-migrated with murine p53 in the positive-control 293T cells (Fig. 5D).

Following exposure of cardiac myocytes to 0.2 mM H<sub>2</sub>O<sub>2</sub>, *Rdm2* transcript abundances reach their maximum levels in crude nuclear extracts after about 2 h (Fig. 2, A-C). If *de novo* induction of transcription factor proteins is a prerequisite for this event, it should occur over within this period. We assessed whether p53 protein was induced over a period of up to 8 h in crude nuclear extracts of cardiac myocytes exposed to 0.2 mM H<sub>2</sub>O<sub>2</sub> using antibodies FL-393 (Fig. 6A), 2B2.71 (Fig. 6, B and C) and Pab 240 (Fig. 6D). We also assessed whether increasing the H<sub>2</sub>O<sub>2</sub> concentration to 0.5 mM had any additional effect (Fig. 6C). In all cases, a positive control for p53 protein induction was included using crude nuclear extracts of cardiac myocytes exposed to 0.5 : M daunorubicin for 6.5 - 7.5 h. In no instance could we detect induction of p53 by H<sub>2</sub>O<sub>2</sub> (Fig. 6, A-D) although p53 protein was reliably detected following treatment with daunorubicin (0.5 : M for 6.5-7.5h).

To confirm the immunoblotting results (Fig. 6, A-D), we assessed whether any p53 DNA binding activity could be detected in crude nuclear extracts of myocytes exposed to H<sub>2</sub>O<sub>2</sub> using EMSAs. Although daunorubicin increased protein binding to a p53 consensus response element consensus sequence, 0.2 mM H<sub>2</sub>O<sub>2</sub> did not induce any detectable binding (Fig. 6E). DO-1 antibodies to p53 produced a supershifted band on EMSAs with daunorubicin whereas FL-393 antibodies prevented binding to the probe (Fig. 6F), thus



confirming that the band detected on EMSAs with daunorubicin was indeed p53. An irrelevant antibody (to JunD) did not supershift the complex (Fig. 6F). Thus, using two independent methodologies and a variety of antibodies, we were unable to find evidence for p53 induction by H<sub>2</sub>O<sub>2</sub>. We conclude that it is unlikely that p53 is responsible for the increased *Rdm2* P2 promoter activity induced by H<sub>2</sub>O<sub>2</sub>.

*Ets* - We examined whether *Ets* proteins may regulate *Rdm2* expression. An EMSA probe corresponding exactly to the *Ets*<sup>(upstream)</sup> region (Table 2, Fig. 1) detected three complexes (1, 2 and 3) in crude nuclear extracts of myocytes exposed to 0.2 mM H<sub>2</sub>O<sub>2</sub> for zero or 30 min, with complex 2 showing evidence of inducibility (Fig. 7A). Unlabelled wild type probe competed effectively for binding to complexes 1 and 2 (but not to complex 3) even at an equimolar concentration, whereas an unlabelled probe with two mutated bases did not completely compete for binding even when in a 100-fold excess (Fig. 7A). Thus complex 3 represents non-specific binding. Binding of complex 1 was 'constitutive' and remained constant over 2 h (Fig. 7B). Nevertheless, complex 1 may still be important in regulation of the P2 promoter as its transactivating activity (as opposed to DNA binding activity) could be subject to regulation [e.g. phosphorylation (39)]. Complex 2 was transiently induced to a maximum of about 8-fold after 30 min (Fig. 7B). By 1 h, approximately 60% of the induction had been lost and abundances had returned to baseline by 2 h (Fig. 7B), i.e. its peak induction significantly preceded *Rdm2* induction. We also examined the *Ets*<sup>(AP-1)</sup> element using EMSAs with a probe corresponding exactly to the *Ets*<sup>(AP-1)</sup> region (Table 2, Fig. 1). Although a complex was detectable, its abundance was not altered by exposure of myocytes to 0.2 mM H<sub>2</sub>O<sub>2</sub> for up to 8 h (results not shown). Furthermore, unlabeled probe for the *Ets*<sup>(AP-1)</sup> region did not effectively compete until present at a 50- to 100-fold excess (results not shown). Overall, therefore, any binding of proteins to the *Ets* sequence EMSA probes is either not inducible, not specific, or does not follow a time course appropriate for induction of *Rdm2* expression.

*AP-1*- The AP-1 element is situated immediately 5' to the *Ets*<sup>(AP-1)</sup> element in the

*Rdm2* P2 promoter (Fig. 1). An EMSA probe corresponding exactly to this AP-1 sequence (Table 2, Fig. 1) detected a complex in crude nuclear extracts of myocytes that was competed by unlabeled wild type, but not mutant, probe (Fig. 7C). Levels of this complex were increased by H<sub>2</sub>O<sub>2</sub> to a maximum at 1! 2 h (Fig. 7D). Supershift EMSAs were used to identify the AP-1 proteins (the Jun and Fos family members) binding to the AP-1 probe. In the absence of stimulation, the complex was partially supershifted by antibodies to JunB or JunD, but not by antibodies to c-Jun (Fig. 8A). Following exposure to H<sub>2</sub>O<sub>2</sub> (0.2 mM 1.5 h), antibodies to JunB, JunD, and, additionally, c-Jun partially supershifted the complex (Fig. 8B). Antibodies to c-Fos, FosB, and Fra-1 also supershifted this complex but antibodies to Fra-2 or ATF2 were ineffective (Fig. 8C). When a mixture of all supershifting antibodies (c-Jun, JunB, JunD, c-Fos, FosB and Fra-1) was used, supershifting of the complex was essentially complete (Fig. 8D). For c-Jun and JunB, ChIP assays confirmed that binding to an *Rdm2* P2 sequence containing the AP-1 site (Fig. 1, Table 1) increased following exposure of cardiac myocytes to H<sub>2</sub>O<sub>2</sub> (0.2 mM, 1.5 h) (Fig. 8E). These results indicate that Fos and/or Jun family transcription factors bind to the *Rdm2* P2 AP-1 sequence and this is increased by H<sub>2</sub>O<sub>2</sub>.

*Expression of Jun and Fos family members* - We examined the time courses of expression of *c-Jun*, *JunB* and *JunD* transcripts and proteins in response to 0.2 mM H<sub>2</sub>O<sub>2</sub>. Transcripts for both *c-Jun* (Fig. 9A) and *JunB* (Fig. 9B) were increased maximally (about 8- and 4-fold for *c-Jun* and *JunB*, respectively) by H<sub>2</sub>O<sub>2</sub> after about 1 h, but had declined to control values by 4 h. Protein abundances followed time courses essentially similar to those for transcripts with *c-Jun* showing a 7- to 8-fold increase (Fig. 9, C and D), and *JunB* showing a 2.0- to 2.5-fold increase (Fig. 9, E and F). There were no changes detectable in *JunD* transcript or protein abundances (results not shown).

A similar pattern of mRNA expression was observed for the Fos family members implicated by EMSAs in the binding to the *Rdm2* P2 AP-1 sequence (Fig. 10, A-D). Transcript abundances increased by approximately 20-fold for c-Fos (Fig. 10A),

15-fold for FosB (Fig. 10B) and 10-fold for Fra-1 (Fig. 10C) over 1 to 2 h before subsequently declining. Abundances of Fra-2 did not change significantly (results not shown) in accord with the results of supershift EMSAs (Fig. 8C). For c-Fos protein, abundance increased by approximately 15-fold over the same time period before declining (Fig. 10D). Antibodies against FosB and Fra-1 were not satisfactory for unequivocal use in immunoblotting in our hands. These results suggest that one factor in the increase in binding of AP-1 proteins to the *Rdm2* P2 sequence is an increase in their abundances.

*Effects of Rdm2 on caspase 3 cleavage in H<sub>2</sub>O<sub>2</sub>-treated cardiac myocytes* - Mdm2 and its orthologues are generally considered to be antiapoptotic. We examined whether *Rdm2* expression delayed the pro-apoptotic effects of oxidative stress in cardiac myocytes using an antisense ODN to a region of *Rdm2* exon 7 (Supplemental Material Fig. 2). This reduced H<sub>2</sub>O<sub>2</sub>-stimulated expression of Rdm2 protein by approximately 75% (Fig. 11A, top panel and Fig 11B). Apoptosis was assessed by formation of the 17 kDa active (cleaved) form of caspase 3. H<sub>2</sub>O<sub>2</sub> increased the abundance of 17 kDa caspase 3 in the absence or presence of lipofectin by about 2.5- to 4-fold (Fig. 11A, middle panel, Fig. 11C), thus demonstrating that, under the conditions used, H<sub>2</sub>O<sub>2</sub> was pro-apoptotic. The *Rdm2* antisense ODN (but not a scrambled ODN) further increased the H<sub>2</sub>O<sub>2</sub>-mediated stimulation of 17 kDa caspase 3 formation by some 2- to 3.5-fold [depending on the value of 17 kDa caspase 3 formation (lipofectin, no H<sub>2</sub>O<sub>2</sub>, or nonsense oligodeoxynucleotide + H<sub>2</sub>O<sub>2</sub>) used as denominator] (Fig. 11A, middle panel, Fig. 11C). As judged by immunoblotting for  $\alpha$ -actin, the adherence of the myocytes to the culture dishes was unaffected by any treatment (Fig. 11A, bottom panel). These results suggest that one role of increased *Rdm2* expression in myocytes exposed to oxidative stress is to reduce or delay apoptosis.

## DISCUSSION

*The effects of H<sub>2</sub>O<sub>2</sub> on Mdm2 expression in the heart* - The effects of ROS generally and H<sub>2</sub>O<sub>2</sub> in particular on *Mdm2* expression in cardiac and non-cardiac cells have not been extensively examined

previously. In non-cardiac cells, H<sub>2</sub>O<sub>2</sub> upregulates *Mdm2* mRNA and protein expression in concert with upregulation of p53 and the assumption is that induction of p53 protein is responsible for upregulation of *Mdm2* (40-42). However, this may not be universal (43). Of relevance to cardiac myocytes, in the H9c2 rat ventricular myoblast line, H<sub>2</sub>O<sub>2</sub> (0.4 mM, 24 h) increases Rdm2 protein abundance (44) whereas, in contrast to our microarray data (3,10), *Rdm2* transcript abundance was reported to decrease in cardiac myocytes exposed to H<sub>2</sub>O<sub>2</sub> (0.1 mM, 1 h) (45). To study Rdm2 in more detail, we first needed to characterize the *Rdm2* gene and its transcript, and Rdm2 protein using bioinformatics approaches (Fig. 1, Supplemental Material Figs. 1-3). The current details for *Rdm2* mRNA in the NCBI database (<http://www.ncbi.nlm.nih.gov>) are misleading as the 75 bp exon 4 has been omitted. It could be argued that this shorter is specific to the rat and could arise, for example, by alternative splicing. However, in addition to identifying exon 4 in rat ESTs, the reverse primer (Table 1) used in the experiments described in Fig. 3A lies within exon 4 and products of the predicted sizes were generated, thus establishing that exon 4 is expressed in mature *Rdm2* mRNA.

We showed that Rdm2 transcripts and protein were rapidly induced (within 1 - 2 h) by H<sub>2</sub>O<sub>2</sub> and that this occurs over the 0.1 - 1 mM range (Fig. 2, A-E). At higher concentrations, expression declines (Fig. 2, D and E). *Rdm2* was not regulated as an immediate early gene (Fig. 3, A and B) and the upregulation of the transcript did not involve transcript stabilization (Fig. 3C). As in other cells (16), constitutive *Rdm2* expression involved the 5'-P1 promoter, whereas H<sub>2</sub>O<sub>2</sub>-inducible expression was largely regulated through the P2 promoter within intron 1 (Fig. 4, A and B). Intron 1 contains several potential transcription factor binding sites including sites for p53, AP-1 and Ets (Fig. 1), any or all of which may be important in inducible expression of *Rdm2*.

*Induction of p53 by H<sub>2</sub>O<sub>2</sub> in cardiac myocytes* - At least two studies report that H<sub>2</sub>O<sub>2</sub> induced expression of p53 transcripts and protein in neonatal rat cardiac myocytes in culture (2,45). Because our original data contradicted these studies, we have been

encouraged to go to great lengths in order to prove that our data are correct. In addition to the antibody (FL-393) we originally used, we used two further antibodies (Pab 240 and 2B2.71) for immunoblotting. We first confirmed the selectivity and specificity of these antibodies for p53 by immunoblotting commercially-available whole cell extracts of 293T cells transfected with mouse p53 (Fig. 5, A-C). All three antibodies detected p53 as a band that migrated slightly more rapidly than the 52 kDa marker (Fig. 5, A-C). This band was absent from the negative control cell line, though it should be noted that cross-reacting proteins of different apparent molecular masses could be detected with two of the antibodies including one which migrated with the 52 kDa marker (Fig. 5, A, C and D). Furthermore, rat p53 (induced by treatment of cardiac myocytes with daunorubicin) co-migrated with murine p53 in the positive control cell line (Fig. 5D). None of the three antibodies detected any increase in p53 expression in cardiac myocytes following exposure to H<sub>2</sub>O<sub>2</sub>, despite a clear induction with daunorubicin (Fig. 6, A-D). Furthermore, we could not detect any induction of p53 by H<sub>2</sub>O<sub>2</sub> using EMSAs despite the clear induction by daunorubicin of a band which could be supershifted with p53 antibodies (Fig. 6, E and F). Thus, we are confident that 0.2 mM H<sub>2</sub>O<sub>2</sub> does not induce expression of p53 in cardiac myocytes and this probably excludes any role for p53 in H<sub>2</sub>O<sub>2</sub>-induced *Rdm2* expression.

It is not entirely clear why others have detected p53 induction by H<sub>2</sub>O<sub>2</sub> (2,45), but there are at least four potential areas of concern: (i) the antibody used, (ii) the cell extracts used, (iii) the conditions used, and (iv) the absence of positive controls for p53. First, both von Harsdorf *et al.* (2) and Long *et al.* (45) used a monoclonal antibody from Calbiochem of which there are currently six listed (http://www.emdbiosciences.com or http://www.merckbiosciences.co.uk). Not surprisingly given the time elapsed, none of the three authors of Reference (2) could recall which antibody was used, and indeed the choice may have been limited or nomenclature not specified by the supplier at this stage. In the report by Long *et al.* (45), Dr. José Marín-García informed us that they had used the Calbiochem Ab-4 antibody (cat. no. OP32)

from the Pab 246 clone, but he now purchases this from Santa Cruz Biotechnology Inc. (cat no. sc-100). We found that Pab 246 cross-reacted with several proteins in the 52 kDa region in 293T whole cell extracts (results not shown) and we did not use this antibody. Secondly, in both reports, whole cell extracts of cardiac myocytes were used rather than crude nuclear extracts. Generally, we find that whole cell extracts are unsatisfactory for detection of nuclear transcription factors by immunoblotting, mainly because of cross-reaction with other proteins. Indeed, two of the three antibodies showed cross-reactivity with a band at 52 kDa in 293T whole cell extracts (Fig. 5, A, C and D) which was not detectable in nuclear extracts from rat cardiac myocytes (Fig. 5D and Fig. 6, A-D) but which, in the absence of a positive control, could be mistaken for p53. Thirdly, although the conditions used by Long *et al.* (45) (0.1 mM H<sub>2</sub>O<sub>2</sub> for 30 min, 1 h or 24 h) resembled our own, von Harsdorf *et al.* (2) used a potentially more severe oxidative stress (0.1 mM H<sub>2</sub>O<sub>2</sub>/0.1 mM Fe<sup>2+</sup> for 1 h, followed by further culture in H<sub>2</sub>O<sub>2</sub>/Fe<sup>2+</sup>-free medium for up to 23 h). The combination of H<sub>2</sub>O<sub>2</sub> and Fe<sup>2+</sup> leads to a catalytic disproportionation of H<sub>2</sub>O<sub>2</sub> into the highly-reactive hydroxyl radical (which is toxic and induces a severe oxidative stress), and a peroxide radical, and is commonly known as the Fenton reaction (Fe<sup>2+</sup> + H<sub>2</sub>O<sub>2</sub> → Fe<sup>3+</sup> + OH<sup>•</sup> + OH<sup>-</sup>; Fe<sup>3+</sup> + H<sub>2</sub>O<sub>2</sub> → Fe<sup>2+</sup> + OOH<sup>•</sup> + H<sup>+</sup>). Fourthly, for both of the published studies (2,45), there were no positive controls for p53, nor were the positions of molecular mass markers included.

*Regulation of inducible Mdm2 by p53-independent mechanisms* - Expression of the *Mdm2* gene can also be regulated by p53-independent mechanisms (19-21). Thus, point mutations in any one of the AP-1, Ets<sup>(AP-1)</sup> or Ets<sup>(upstream)</sup> elements reduce induction of *Mdm2* expression by oncogenic Ras or Raf in NIH-3T3 cells (19). Furthermore, elevated *HDM2* expression in a breast cancer cell line is partly dependent on the composite AP-1/Ets<sup>(AP-1)</sup> element (20). In contrast, up-regulation of *Mdm2* in certain mouse erythroleukaemia lines is partly attributable to increased expression of Fli-1 (an Ets family transcription factor) and may involve the Ets<sup>(upstream)</sup> element (21).

Ets family transcription factors number >20 members (39) that require a core GGA motif for response element recognition with slightly varying preferences in the flanking sequences (34). In cardiac myocytes exposed to H<sub>2</sub>O<sub>2</sub>, constitutive (complex 1) and transiently-inducible (complex 2) protein binding to the Ets<sup>(upstream)</sup> element was detected by EMSAs (Fig. 7, A and B). We attempted to supershift the Ets<sup>(upstream)</sup> complexes with antibodies to the biologically activated form of Elk-1 [phospho-Elk-1(Ser-383)] (the orthologous residue in rat Elk-1 is in fact Ser-382) and to Fli-1 but were unsuccessful (results not shown). We consider it unlikely that the Ets<sup>(upstream)</sup> element is significant in *Rdm2* upregulation because (i) the level of complex 1 does not change and (ii) levels of complex 2 were returning to zero-time values before any significant induction of *Rdm2* transcripts or *Rdm2* protein was detectable (Fig. 2, A-C, and F, Fig. 7B). Equally, we could not obtain any convincing evidence that the Ets<sup>(AP-1)</sup> element might be involved. The EMSA band with the Ets<sup>(AP-1)</sup> probe was not inducible, and was not competed by unlabeled probe.

We turned our attention to the AP-1 site. AP-1 is a heterodimer of Fos and Jun family members or possibly a homodimer of Jun family members, and it controls the transcription of numerous genes (46). The AP-1 complex can either activate or inhibit gene expression and its two subunits do not necessarily act in concert. Thus, whereas c-Fos and FosB act in concert with c-Jun (the most powerful transcriptional regulator), c-Jun may be antagonized by JunB, and by Fra-1 and Fra-2 which do not contain transactivation domains. Furthermore, the transactivating activities of AP-1 proteins can be influenced by post-translational modification (e.g. phosphorylation). As with Ets transcription factors, there is evidence that AP-1 may participate in regulation of *Mdm2* expression (19). In our study, EMSAs showed specific binding of proteins to the *Rdm2* AP-1 element (Fig. 7C) with a time-course consistent with induction of *Rdm2* expression (Fig. 2, A-C, and Fig. 6D). c-Jun and JunD bound to the probe in unstimulated cells (Fig. 8A). In cells exposed to H<sub>2</sub>O<sub>2</sub>, JunB (Fig. 8B) and Fos family members (c-Fos, FosB, Fra-1, but not Fra-2) were also bound (Fig. 8C). The binding of Fra-1 is a little surprising given that

expression of *Rdm2* is increased but Fra-1 is supposed to reduce AP-1-dependent stimulation of gene expression (46), and we do not have any explanation for this at present. A cocktail of antibodies to c-Jun, JunB, JunD, c-Fos, FosB and Fra-1 resulted in essentially a complete supershift of the complex (Fig. 8D). Of the Jun and Fos members mentioned but with the exceptions of JunD and Fra-2, transcripts (and usually proteins) were induced by H<sub>2</sub>O<sub>2</sub> (Figs. 9 and 10) within the time-period chosen for supershifting (1.5 h). Using ChIP assays, we demonstrated increased binding of c-Jun and JunB to an *Rdm2* P2 promoter region encompassing the AP-1 site (Fig. 8E). ChIP assays using antibodies to the remaining Fos/Jun proteins were less successful, presumably because of their inadequacy in immunoprecipitation protocols. These results strongly suggest that the *Rdm2* AP-1 element is of significance in the upregulation of *Rdm2* expression by H<sub>2</sub>O<sub>2</sub>, and that increased abundances of AP-1 transcription factors [several of which have been confirmed as immediate early genes in cardiac myocytes in the context of endothelin stimulation (47)] participate in *Rdm2* mRNA upregulation.

H<sub>2</sub>O<sub>2</sub> and ROS are established regulators of AP-1 (48). All of the three major MAPK cascades (JNK, ERK1/2, p38-MAPK) are activated by H<sub>2</sub>O<sub>2</sub> in cardiac myocytes (49) and may influence AP-1 expression and activity. JNKs phosphorylate c-Jun in its transactivation domain and increase its transactivating activity (46). In addition, *c-Jun* mRNA and protein is upregulated by a combination of activation of ERK1/2 (to increase transcription of *c-Jun*) and JNKs (to increase protein stability) (50). Thus, H<sub>2</sub>O<sub>2</sub>-mediated stimulation of MAPK cascades might be a factor in the upregulation of AP-1 transcription factor levels and activities in our study.

*Cardioprotective effects of Mdm2* - p90-Mdm2 is present in whole murine heart in greater abundance than p76-Mdm2 (though both at much lower abundances than in other tissues such as testis) (23). Cardioselective deletion of *Mdm2* is embryonically-lethal and this lethality can be rescued by deletion of *p53* (51), thus emphasizing the importance of *Mdm2* in limiting *p53* expression during cardiac development. In the developed heart,

the role of Mdm2 in cardioprotection is implicit from a number of studies. Increasing Mdm2 abundance by overexpression of the transcriptional coactivator p300 protects against apoptosis induced by the cardiotoxic anthracycline doxorubicin in mice *in vivo* (52). Cardiospecific overexpression of insulin-like growth factor 1 increases the association between p53 and Mdm2 thus reducing the binding of p53 to the promoter of the proapoptotic *bax* gene (53). The growth factor also reduces mechanical strain-induced apoptosis in isolated cardiac myocytes, one possible mechanism involving an Rdm2-mediated reduction in p53 abundance (54). Overexpression of Mdm2 also protects against the pro-apoptotic effects of hypoxia and inhibition of the p53-Rdm2 interaction increases the sensitivity to hypoxia (55). Furthermore, reduced expression of *Mdm2* increases the susceptibility of the isolated heart to injury induced by ischemia and reperfusion (55).

In general agreement with these earlier studies, our studies here suggest that the

induction of *Rdm2* expression by H<sub>2</sub>O<sub>2</sub> represents a cytoprotective defence against oxidative stress in the cardiac myocyte (Fig. 11). Thus, diminished H<sub>2</sub>O<sub>2</sub>-mediated induction of *Rdm2* using an antisense ODN to *Rdm2* promoted caspase 3 activation (Fig. 11, A and C). It is pertinent to ask how Rdm2 can decrease apoptosis, given that H<sub>2</sub>O<sub>2</sub> did not induce p53 expression (Fig. 6). One explanation may be that other pro-apoptotic proteins expressed in myocytes are inhibited or downregulated by Rdm2. Precedents for this exist. For example, treatment of p53-null neuroblastoma cells with the HDM2-protein interaction inhibitor, nutlin-3, stimulates apoptosis by inhibiting the interaction with the p53-related protein, p73 (56). It should perhaps also be noted that inhibition of HDM2 is currently under intensive investigation as a chemotherapeutic intervention (57). From the results of our own and other studies, such therapies may decrease cardiac myocyte survival, particularly under conditions of oxidative stress which probably occur during myocardial ischemia and heart failure.

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## ABBREVIATIONS

<sup>2</sup> 5'-RACE, 5'-rapid amplification of cDNA ends; ARE, AU-rich instability region; ChIP, chromatin immunoprecipitation; CHX, cycloheximide; DCM, dilated cardiomyopathy; DTT, dithiothreitol; E64, trans-epoxy-succinyl-l-leucylamido-(4-guanidino)-butane; EMSA, electrophoretic mobility shift assay; ERK, extracellular signal-regulated kinase; Gapd, glyceraldehyde 3-phosphate dehydrogenase; JNK, c-Jun N-terminal kinase; MAPK, mitogen-activated protein kinase; Mdm2, mouse double minute 2 (HDM2 and Rdm2, *Homo sapiens* and rat orthologues of Mdm2, respectively); MZF-1, myeloid zinc finger protein-1; ODN, oligodeoxynucleotide; PBS, phosphate-buffered saline; PMSF, phenyl methyl sulfonyl fluoride; ROS, reactive oxygen species; RT-qPCR and RT-sqPCR, reverse transcriptase-quantitative polymerase chain reaction and semiquantitative PCR; SDS-PAGE, sodium dodecyl sulfate - polyacrylamide gel electrophoresis; TBE, Tris-borate-EDTA; TBST, Tris-buffered saline with Tween 20; UPM, universal primer A mix.

<sup>3</sup>Rdm2 and HDM2 refer specifically to rat and *Homo sapiens*, respectively, whereas Mdm2 will refer specifically to the mouse or to the three orthologues generally.

## CONFLICT OF INTERESTS

There are no conflicts of interest to report.

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## FIGURE LEGENDS

**FIG. 1. The deduced structure of the 5' region of the *Rdm2* gene.** Further details are provided in the Results section. The complete deduced sequence of mature *Rdm2* mRNA is shown in Supplemental Material Fig. 2. The numbering refers to the positions of the nucleotides in the gene sequence. The positions of the primers used to determine P1/P2 promoter usage in exons 1, 2 (forward primers F1 and F2, respectively) and in exon 4 are indicated, as are the two alternative translational initiation codons [ATG(1) for p90-*Rdm2*, ATG(2) for p76-*Rdm2*]. The consensus sequences for the transcription factor response elements are: MZF-1, AGTGGGGA or the more-extended CGGGNGAGGGGAA (36); Ets, C(A/C)GGA(A/T)G(C/T) (34); AP-1, TGA(C/G)TCA (33); NF-E2, (C/T)TGCTGA(C/G)TCA(C/T) (35); p53, two (A/G)(A/G)(A/G)C(A/T)(A/T)G(C/T)(C/T)(C/T) elements separated by 0 to 13 nucleotides (31). The positions of the response elements and the 5' to 3' directions applicable are marked by arrows. The

positions of the primers used in the chromatin immunoprecipitation studies of the AP-1 response element are indicated by underlying asterisks (see also Table 1).

**FIG. 2. Expression of *Rdm2* transcripts and protein in cardiac myocytes exposed to H<sub>2</sub>O<sub>2</sub>.** RNA or protein was extracted and *Rdm2* mRNA or protein abundances were determined by RT-sqPCR, RT-qPCR or immunoblotting as described under 'Experimental Procedures'. (A,B,C) Myocytes were exposed to 0.2 mM (A,B) or 1 mM (C) H<sub>2</sub>O<sub>2</sub> for the times indicated and *Rdm2* transcripts measured by RT-sqPCR (A) or RT-qPCR (B,C). (D,E) Dependence of *Rdm2* mRNA expression at 2 h [(D), RT-sqPCR; (E), RT-qPCR] or 1 h (E, RT-qPCR) on H<sub>2</sub>O<sub>2</sub> concentration. No RT: as a control for genomic contamination, the RT step was omitted. (F,G) *Rdm2* protein abundances were determined by immunoblotting of whole cells extracts at the times indicated. Primary antibody dilution: both at 1/750. Representative primary data are shown and the quantified results are expressed as means ± SEM for at least 3 independent observations on separate preparations of myocytes.

**FIG. 3. *Rdm2* is not an immediate early gene, nor is *Rdm2* mRNA stabilized by H<sub>2</sub>O<sub>2</sub>.** (A,B) Cardiac myocytes were pretreated with cycloheximide (CHX, 20 : M) for 30 min, then exposed additionally to 0.2 mM H<sub>2</sub>O<sub>2</sub> for 2 h (A, RT-sqPCR) or 1h (B, RT-qPCR). (C) H<sub>2</sub>O<sub>2</sub> (0.2 mM) exposure does not affect *Rdm2* transcript stability. Myocytes were exposed (●) or not exposed (•) to 0.2 mM H<sub>2</sub>O<sub>2</sub> for 2 h, then to 4 : M actinomycin D for the times indicated, followed by RT-sqPCR. Results were fitted to monophasic exponential decay curves. Representative primary data are shown and the quantified results are expressed as means ± SEM for 3-4 independent observations on separate preparations of myocytes. Statistical significance: \*, *P*<0.001 by one-way ANOVA with Tukey's multiple comparison test.

**FIG. 4. Promoter usage for *Rdm2* expression.** (A) Cardiac myocytes were exposed to or not treated with 0.2 mM H<sub>2</sub>O<sub>2</sub> for 2 h. RNA was extracted and RT-sqPCR was used with a reverse primer in exon 4 and forward primers lying in exon 1 (primer F1) to assess P1 promoter usage (long product, 333 bp) or exon 2 (primer F2) to assess combined P1 and P2 promoter usage (short product, 220 bp) (Fig. 1 and Table 1). Representative primary data are shown and the quantified results are expressed as means ± SEM for 6 independent observations on separate preparations of myocytes. Statistical significance versus control: \*, *P*<0.01 by one-way ANOVA with Tukey's multiple comparison test. (B) 5' RACE for *Rdm2* transcripts in myocytes exposed or not exposed to 0.2 mM H<sub>2</sub>O<sub>2</sub> for 2 h. The theoretical lengths of amplicon A (from P1 promoter use) and amplicon B (from P2 promoter use) are 332 and 162 bp, respectively.

**FIG. 5. Characterization of p53 antibodies.** Extracts of 293T cells that had either been transfected with mouse *p53* (positive control) or not transfected (negative control) were examined by SDS-PAGE and immunoblotting with (A) FL-393 antibody, (B) Pab 240 antibody, or (C and D) 2B2.71 antibody, all at 1/1000 dilution. In (D), a crude nuclear extract from cardiac myocytes exposed to 0.5 : M daunomycin for 6.5 h was included. The position of the 52 kDa molecular mass marker is indicated.

**FIG. 6. H<sub>2</sub>O<sub>2</sub> does not induce expression of p53 in cardiac myocytes.** Myocytes were exposed to 0.2 mM (A-F) or 0.5 mM (C) H<sub>2</sub>O<sub>2</sub> for the times indicated or to daunorubicin. (A-D) Immunoblots of crude nuclear extracts from myocytes. Blots were probed with the p53(FL-393) antibody (A) at a dilution of 1/1200, with the 2B2.71 antibody (B,C) at a dilution of 1/1000, or with the Pab 240 antibody (D) at a dilution of 1/1000. For 2B2.71 and Pab 240, an amplification step with an rabbit anti-mouse antibody and a goat anti-rabbit horseradish peroxidase-conjugated tertiary antibody was used. (E) EMSAs of crude nuclear extracts were carried out with a p53 consensus binding sequence probe. (F) Myocytes were exposed to 0.5 : M daunorubicin for 7.5 h and supershift EMSAs were carried out with the antibodies indicated. Representative primary data are shown for 3 independent observations on separate preparations of myocytes.



**FIG. 7. Binding of proteins to the Ets<sup>(upstream)</sup> and AP-1 response elements in the *Rdm2* P2 promoter as assessed by EMSAs.** Cardiac myocytes were exposed to 0.2 mM H<sub>2</sub>O<sub>2</sub> as indicated and crude nuclear extracts prepared. Sequences of probes are given in Table 2. (A,C) EMSAs using the Ets<sup>(upstream)</sup> probe (A) or the AP-1 probe (C). Binding specificities were assessed using unlabelled probe. Two specific complexes (1 and 2) were detected with the Ets<sup>(upstream)</sup> probe (A) and one was detected for the AP-1 probe (C). (B,D) Time courses of binding to the Ets<sup>(upstream)</sup> probe (B) or the AP-1 probe (D). Representative primary data are shown and the quantified results are expressed as means ± SEM for 3-5 independent observations on separate preparations of myocytes.

**FIG. 8. Binding of AP-1 proteins to the AP-1 response element in the *Rdm2* P2 promoter as assessed by supershift EMSAs or ChIP assays.** Cardiac myocytes were exposed to 0.2 mM H<sub>2</sub>O<sub>2</sub> as indicated and crude nuclear extracts prepared. (A-D) Supershift EMSAs were performed using the antibodies indicated. SS: supershifted complex. (E) ChIP assays using c-Jun or JunB antibodies, as indicated. Representative primary data are shown and the quantified results are expressed as means ± SEM for 3 independent observations on separate preparations of myocytes. Statistical significance versus control: \*, *P*<0.05 by an unpaired two-way Student's *t* test.

**FIG. 9. Expression of c-Jun and JunB transcripts and proteins.** Cardiac myocytes were exposed to 0.2 mM H<sub>2</sub>O<sub>2</sub> as indicated. mRNA abundance was determined by RT-sqPCR, and protein abundance in crude nuclear extracts was assessed by immunoblotting. (A,B) Expression of *c-Jun* (A) and *JunB* (B) transcripts. No RT: no reverse transcriptase step. (C-F) Expression of c-Jun (C,D) and JunB (E,F) proteins. Antibody dilutions: c-Jun, 1/750; JunB, 1/5000. Representative primary data are shown and the quantified results are expressed as means ± SEM for 3-4 independent observations on separate preparations of myocytes.

**FIG. 10. Expression of *c-Fos*, *Fos-B* and *Fra-1* transcripts and c-Fos protein.** Cardiac myocytes were exposed to 0.2 mM H<sub>2</sub>O<sub>2</sub> as indicated. mRNA abundance was determined by RT-sqPCR, and protein abundance in crude nuclear extracts was assessed by immunoblotting. (A-C) Expression of *c-Fos* (A), *FosB* (B) and (C) *Fra-1* transcripts assessed by RT-sqPCR. No RT: no reverse transcriptase step. (D) Expression of c-Fos protein. Antibody dilution for c-Fos: 1/20,000. Representative primary data are shown and the quantified results are expressed as means ± SEM for 3-4 independent observations on separate preparations of myocytes.

**FIG. 11. 'Knock-down' of *Rdm2* protein in cardiac myocytes with an antisense ODN to the *Rdm2* transcript increases H<sub>2</sub>O<sub>2</sub>-induced activation of caspase 3.** AS, antisense ODN; NS, scrambled ODN. (A) Abundances of *Rdm2* (top panel), active caspase 3 (middle panel) and sarcomeric  $\alpha$ -actin (bottom panel) in whole cell extracts were assessed by immunoblotting. (B,C) Quantification of (B) *Rdm2* or (C) active caspase 3 abundances. Antibody dilutions: *Rdm2*, 1/500; caspase 3, 1/1000;  $\alpha$ -actin, 1/2000. Representative primary data are shown and the quantified results are expressed as means ± SEM for 4 independent observations on separate preparations of myocytes. Statistical significance versus control: \*, *P*<0.05; \*\*, *P*<0.001 by one-way ANOVA with Tukey's multiple comparison test

**TABLE 1.** Details of RT-sqPCR/qPCR primers used. For the *Rdm2* transcript, the numbering used refers to the deduced sequence shown in Supplemental Material Fig. 2. For *Rdm2*, primers for *Rdm2*(A) were used for sqPCR analysis of general *Rdm2* expression, primers for *Rdm2*(B) were used for qPCR analysis of general *Rdm2* expression, primers for *Rdm2*(C) and *Rdm2*(D) were used to investigate P1/P2 promoter usage (sqPCR), primers for *Rdm2*(E) were used for 5' RACE (sqPCR), and primers for *Rdm2*(F) were used for CHIP analysis (sqPCR). The sequence of *Rdm2* intron 1, in which the primers used for chromatin immunoprecipitation lie, is shown in Fig. 1. The predicted rat *FosB* transcript sequence (NM\_001013146.1) is truncated at its 3' end. The rat *FosB* gene is located on chromosome 1 at 78668523..78673784 (RGSC genome assembly v3.4). The RT-sqPCR product corresponds to 78667636..78667773, sequence:

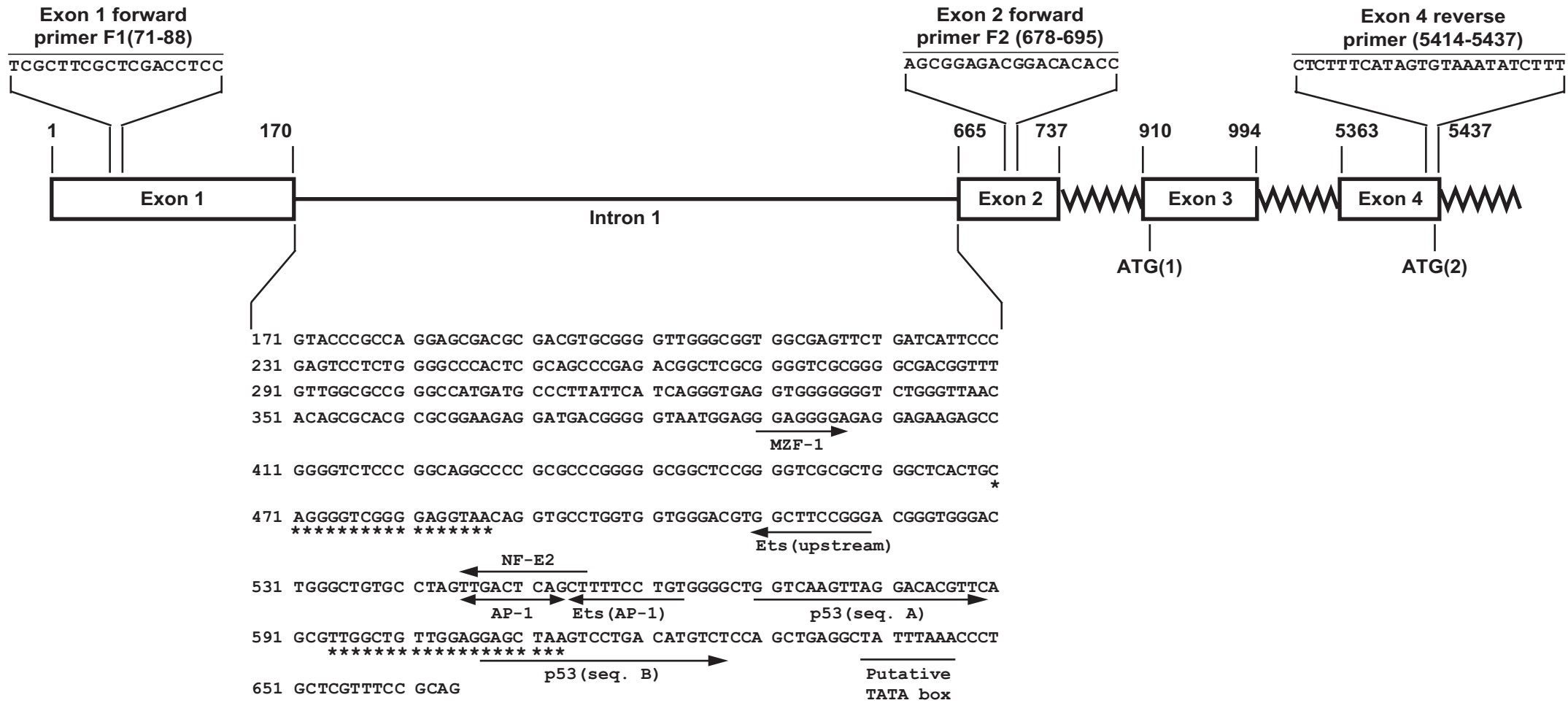
**ACCCCTGTGCAGTATTATGC**CATGTCCCTCTCACCCCCACGGGCAACCCAGGCGCCCTTGGCCGTCCTCGTTGGGCCTTTCTGGT  
TTTGGGCAGCAGGGGGCGCTGCGACGCCCGTCT**TGCTGGAGCGCTTTATACTG** (primers underlined and emboldened). In contrast, the mouse *FosB* mRNA sequence (NM\_008036.2) is more extended and contains the PCR sequence described. The PCR sequence identifies two rat ESTs (C06882.1, CB747983.1) and these lie 3' to the predicted rat *FosB* transcript. In addition, the two rat ESTs correspond to the 3' untranslated region of the mouse *FosB* mRNA.

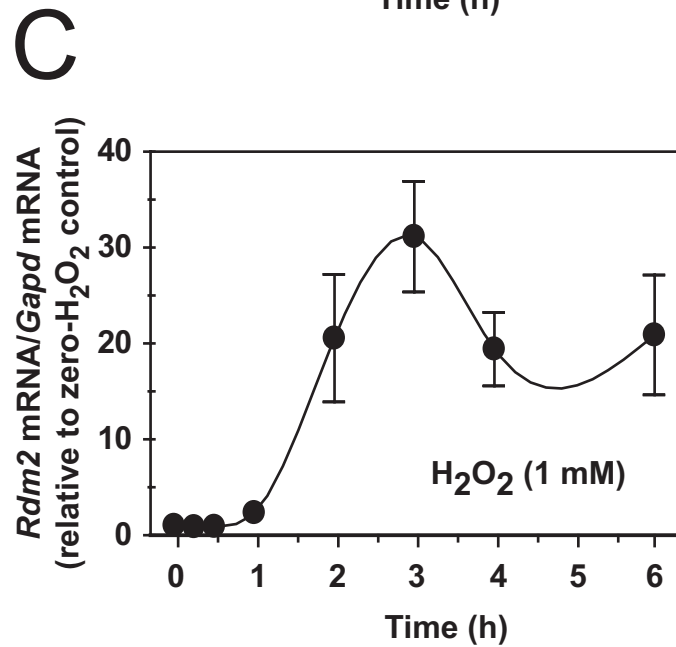
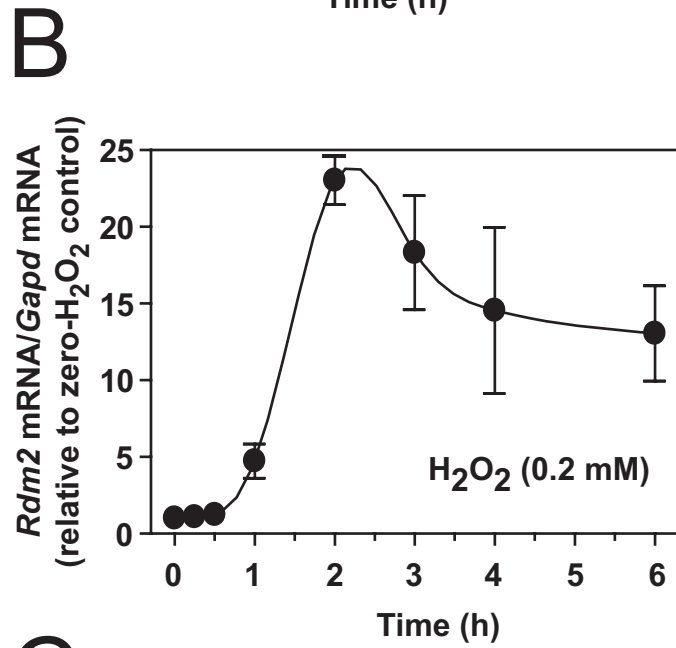
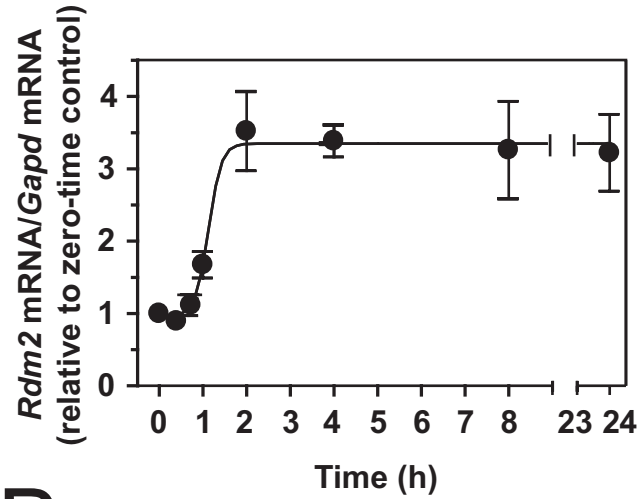
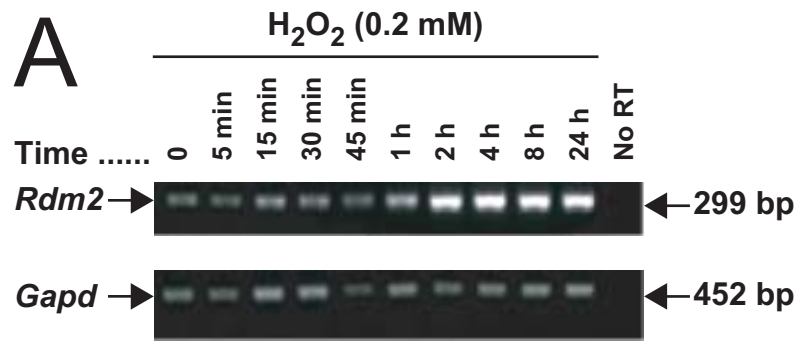
Transcript for	Forward primer (5'→3')	Exon	Reverse primer (5'→3')	Exon	Amplicon identity or transcript accession no.	Position of primers in mRNA	Product length (bp)	No. of cycles used
<i>Rdm2</i> (A)	ATCCAGCTTCTCTCTGAACG	12	AGACTAAGACAATGCTCCGG	12	Supplemental Material Fig. 1	1504-1802	299	27
<i>Rdm2</i> (B)	TCCGACCACCGTGCTTCT	2	TCGGTAGACACAGACATGTTGGTA	3	Supplemental Material Fig. 1	211-279	69	---
<i>Rdm2</i> (C)	TCGCTTCGCTCGACCTCC	1	CTCTTTCATAGTGTAATATCTTT	4	Fig. 1	71-403	333	27
<i>Rdm2</i> (D)	AGCGGAGACGGACACACC	2	CTCTTTCATAGTGTAATATCTTT	4	Fig. 1	184-403	220	27
<i>Rdm2</i> (E)	AAGCAGTGGTATCAACGCAGA GTACGCGGG	N/A	TCTGTGAGGTGCCTGCAGCACCTCG GTAGACAC	3	5' RACE tag	N/A-302	332 (P1) 162 (P2)	35
<i>Rdm2</i> (F)	CAGGGGTCGGGGAGGTAA	Intron 1	TTAGCTCCTCCAACAGCCAA	Intron 1	Fig. 1	Intron 1	144	35
<i>Gapd</i>	ACCACAGTCCATGCCATCAC	6	TCCACCACCTGTTGCTGTA	8	NM_17008.2 NM_17008.3	1369-1820 596-1047	452	20
<i>p53</i>	TTGAGGTTCTGTGTTTGTGCC	7	CACGGGCATCCTTTAATTCC	9	NM_030989.3	934-1188	255	
<i>c-Jun</i>	ATGACTGCAAAGATGGAAACG	N/A	TATTCTGGCTATGCAGTTCAG	N/A*	NM_021835	859-1234	376	24
<i>JunB</i>	ATCACGACGACTCATACGCA	N/A	TGGAGGCTAGCTTCAGAGAT	N/A*	NM_021836	299-523	225	25
<i>JunD</i>	ATGGAAACGCCCTTCTATGG	N/A	CTTCTTCAGCATGCTGCTC	N/A*	NM_138875	264-420	157	28
<i>c-Fos</i>	AGTGGTGAAGACCATGTCAG	2	AATGTTCTTGACCGGCTCCA	4	NM_22197.1 NM_22197.2	464-911 482-929	448	25
<i>FosB</i>	ACCCCTGTGCAGTATTATGC		CAGTATAAAGCGCTCCAGCA	See Table 1 Legend			138	27
<i>Fra-1</i>	AATTGCAGTGGATGGTGCAG	2	ACTTAGCAGCTGCTAGCTTG	3	NM_012953	377-595	219	26
<i>Fra-2</i>	AATCAACGCCATCACCACCA	2	GGTGGTACCAATGGTCTTGA	2	NM_012954	150-330	181	26

**TABLE 2.** Sequences of EMSA probes. See Fig. 1 for details of position in the *Rdm2* gene and its intron 1. p53 EMSAs, a consensus p53 probe was used.

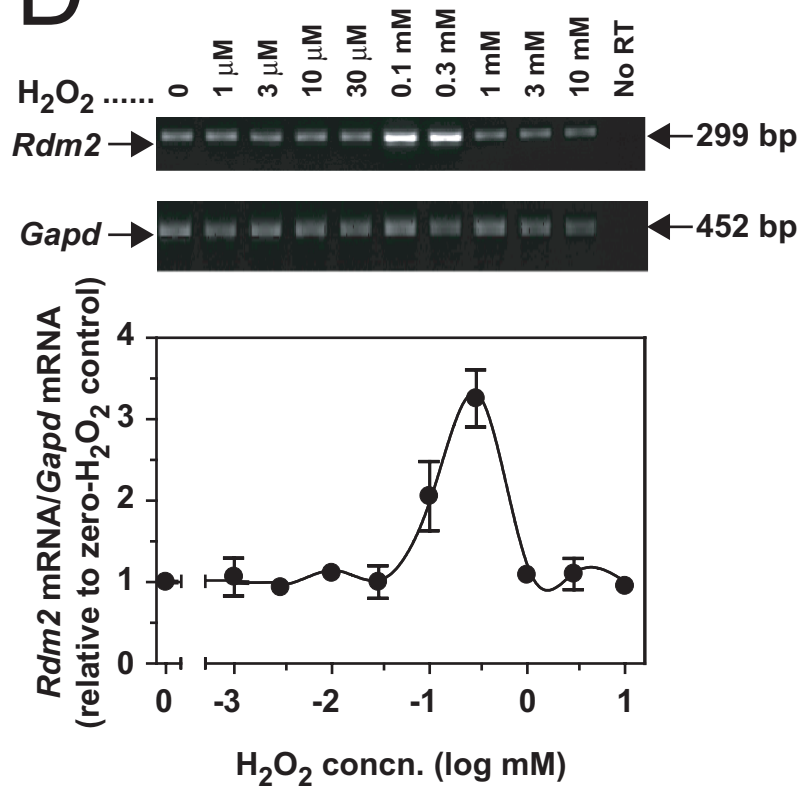
EMSA Probe for	EMSA Probe (5'→3')	Position in gene	Position in intron 1	Mutant EMSA Probe (5'→3')
<i>Rdm2</i> AP-1	GCCTAGTTGACTCAGCTTTTC	539-559	369-389	GCCTAGTTGACT <u>TGG</u> CTTTTC
<i>Rdm2</i> Ets <sup>(upstream)</sup>	GGACGTGGCTTCCGGGACGGGT	504-525	334-355	GGACGTGG <u>A</u> TTCC <u>A</u> GGACGGGT
<i>Rdm2</i> Ets <sup>(AP-1)</sup>	GACTCAGCTTTTCCTGTGGGGCTGG	547-571	277-301	GACTCAGCTTTTC <u>CGG</u> GGGGCTGG
<i>Rdm2</i> MZF-1	ATGGAGGGAGGGGAGAGGAG	384-403	214-233	ATGGAGGG <u>A</u> GG <u>T</u> AGAGGAG
p53 response element	TACAGAACATGTCTAAGCATGCTGGGGACT	N/A	N/A	N/A

Pikkarainen et al. Figure 1

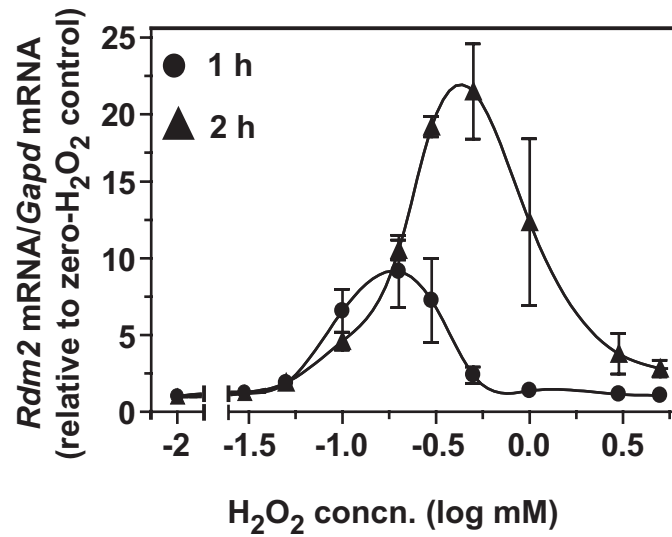


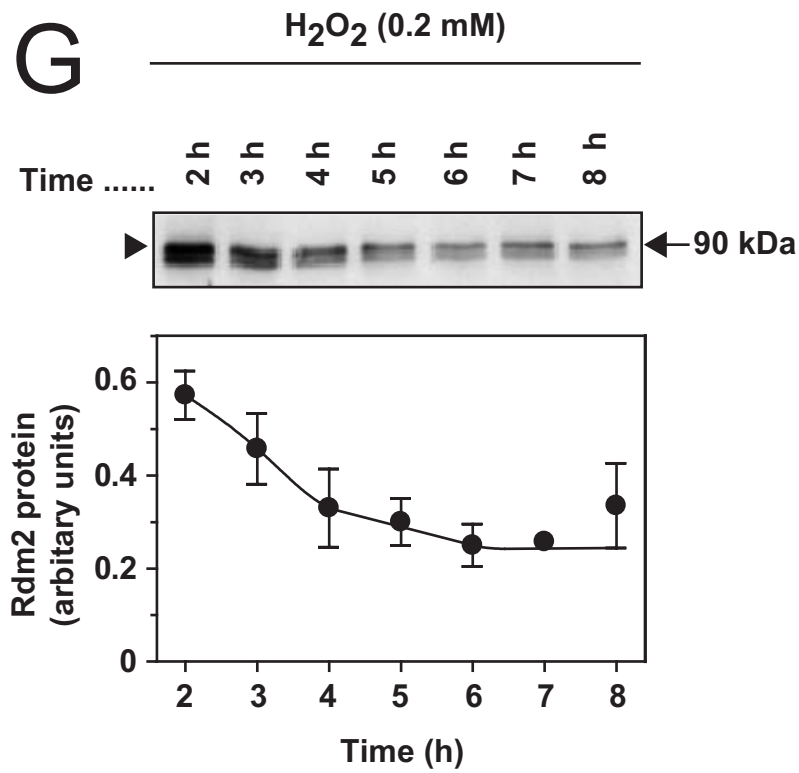
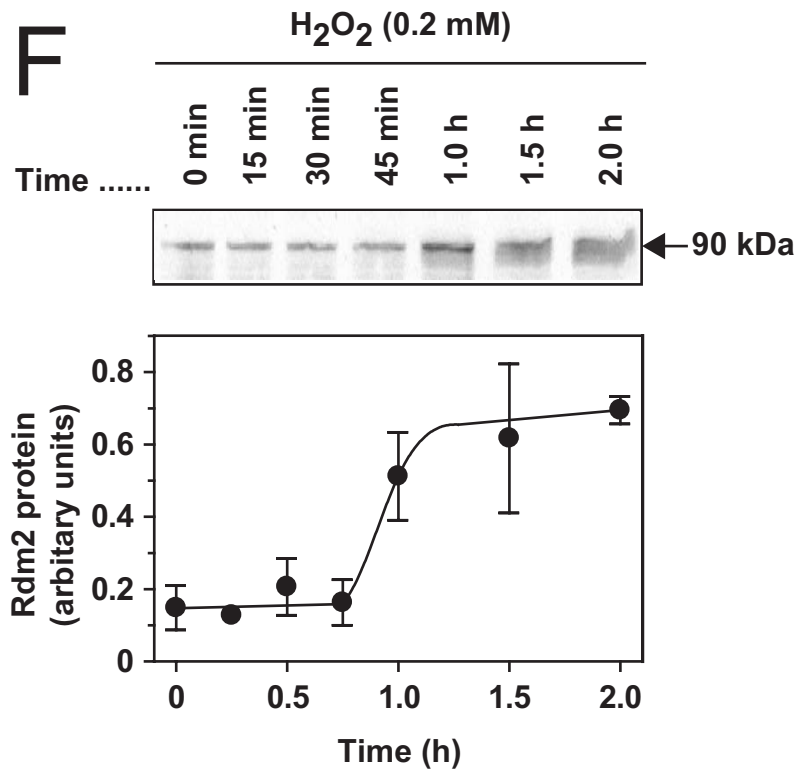


**D**

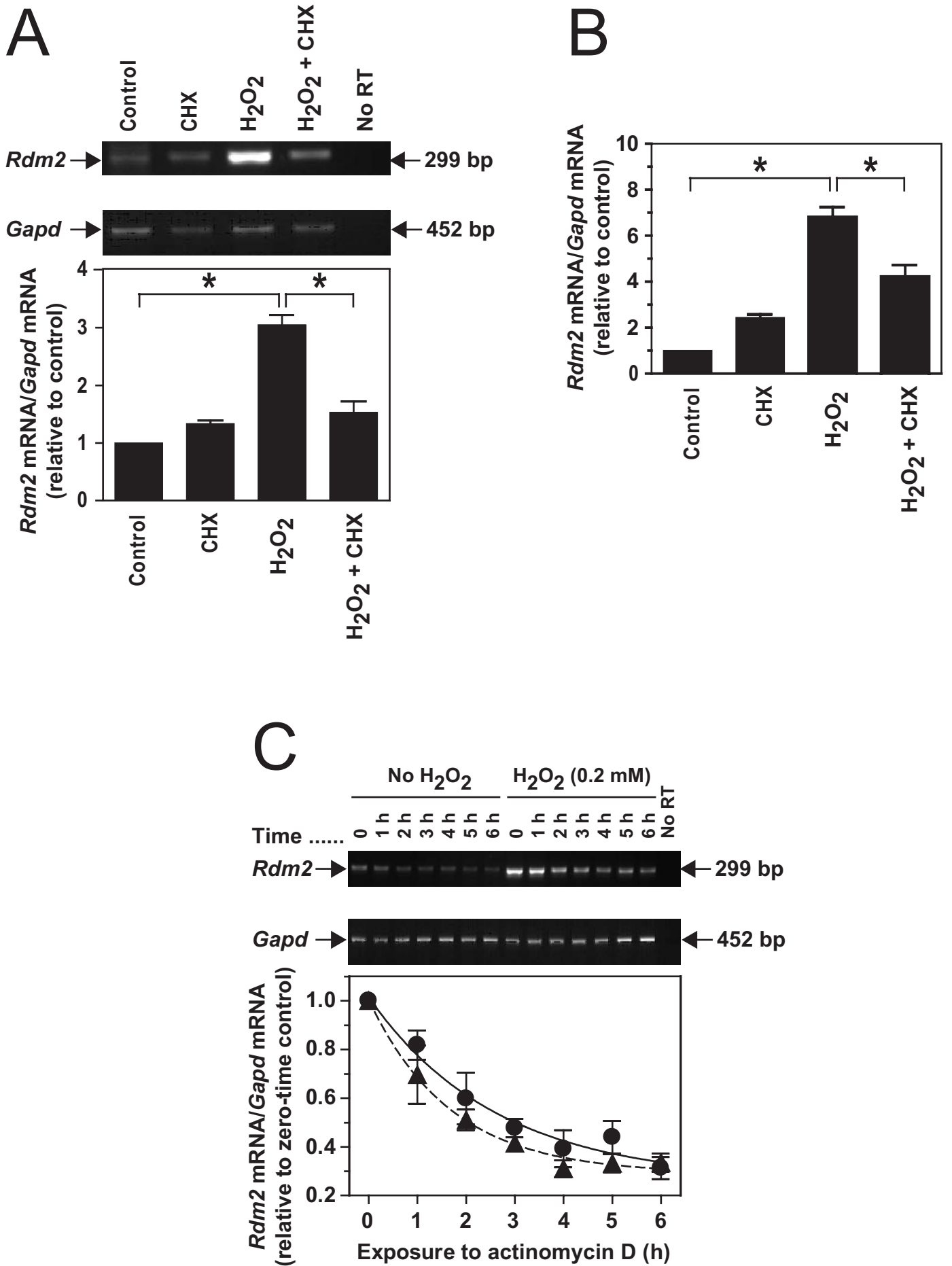


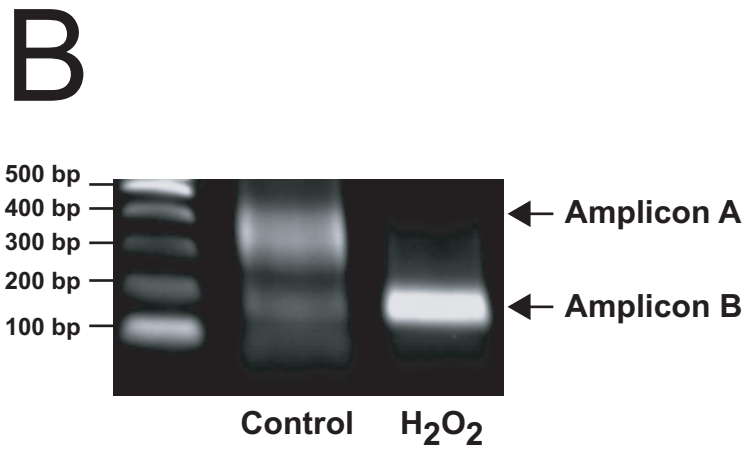
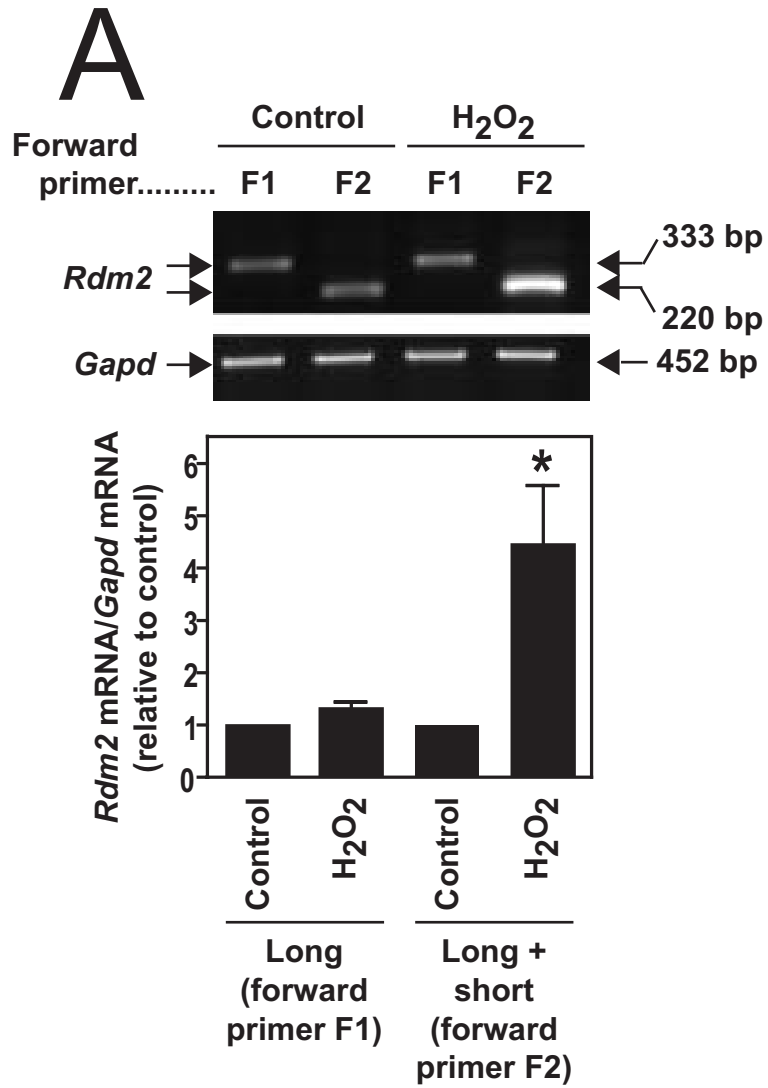
**E**



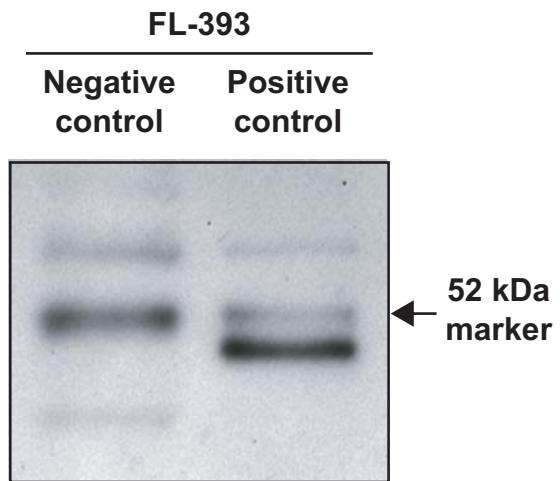




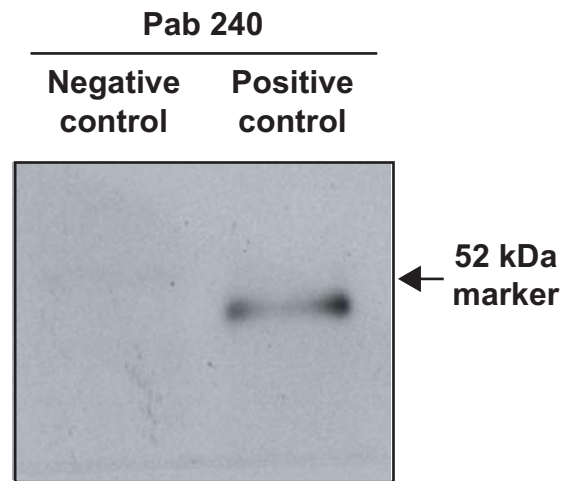




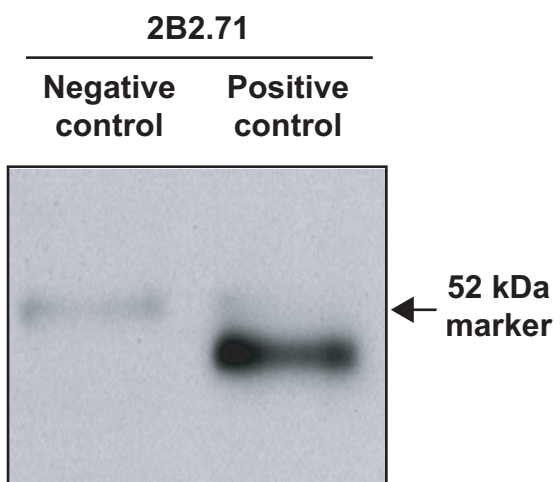
**A**



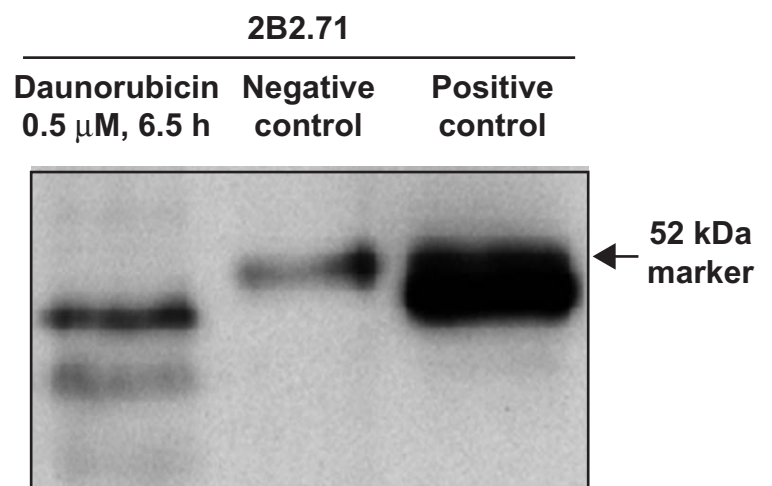
**B**

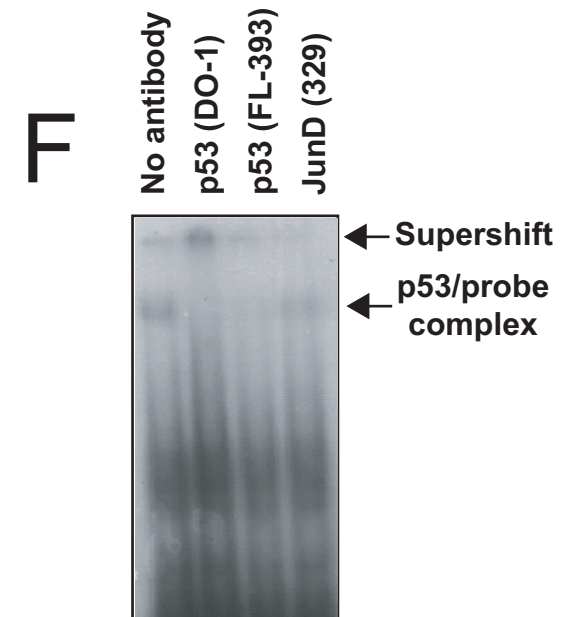
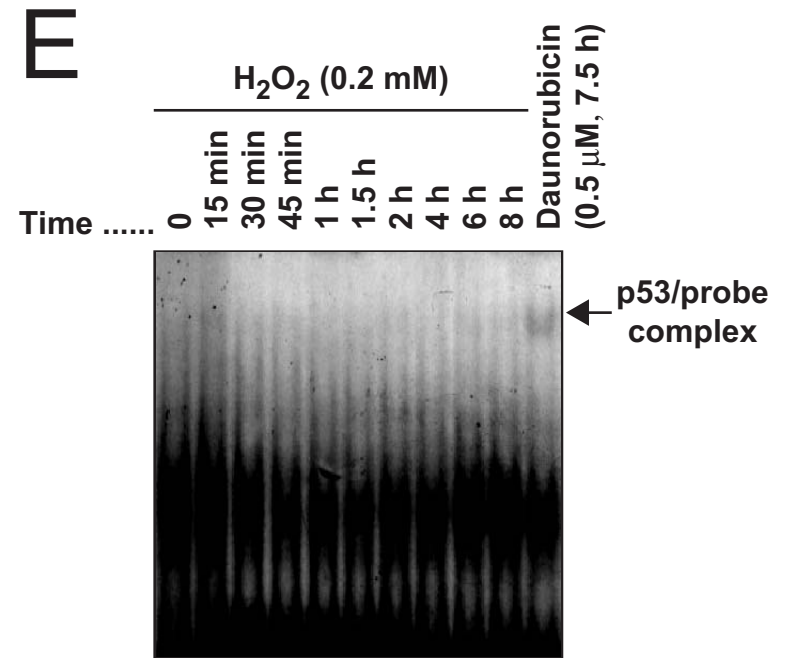
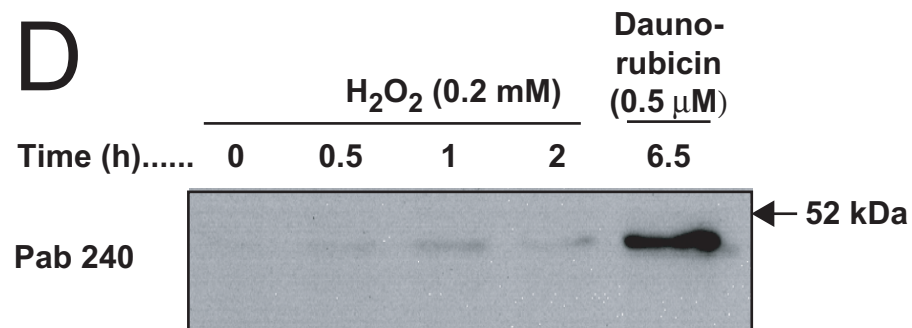
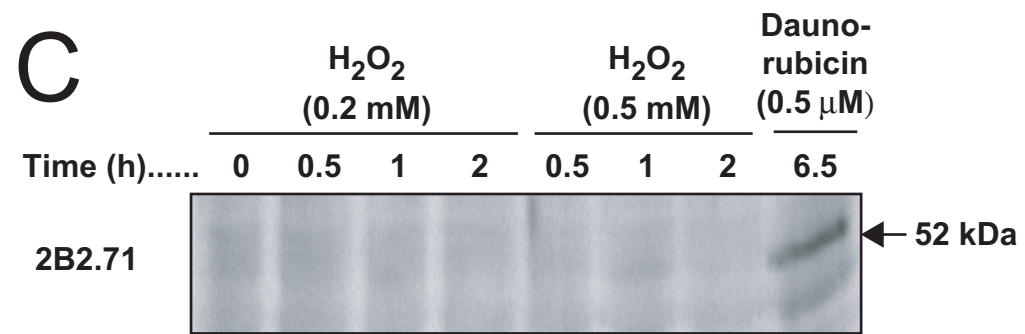
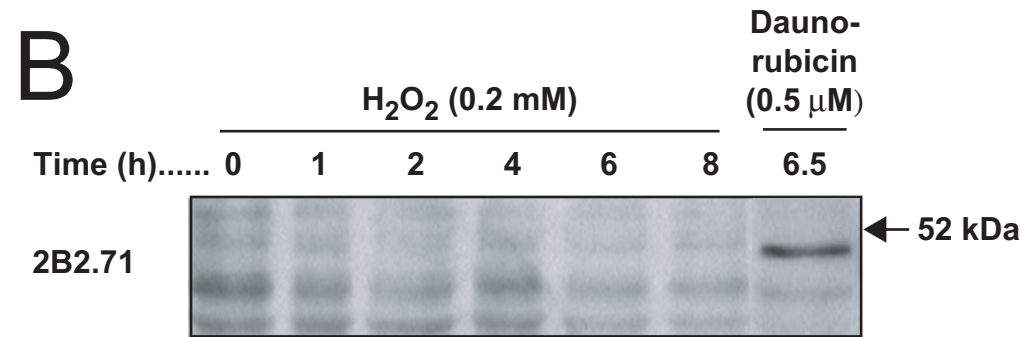
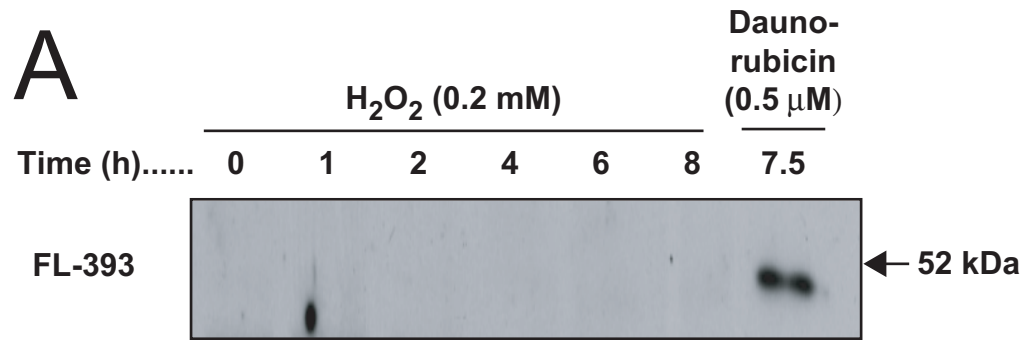


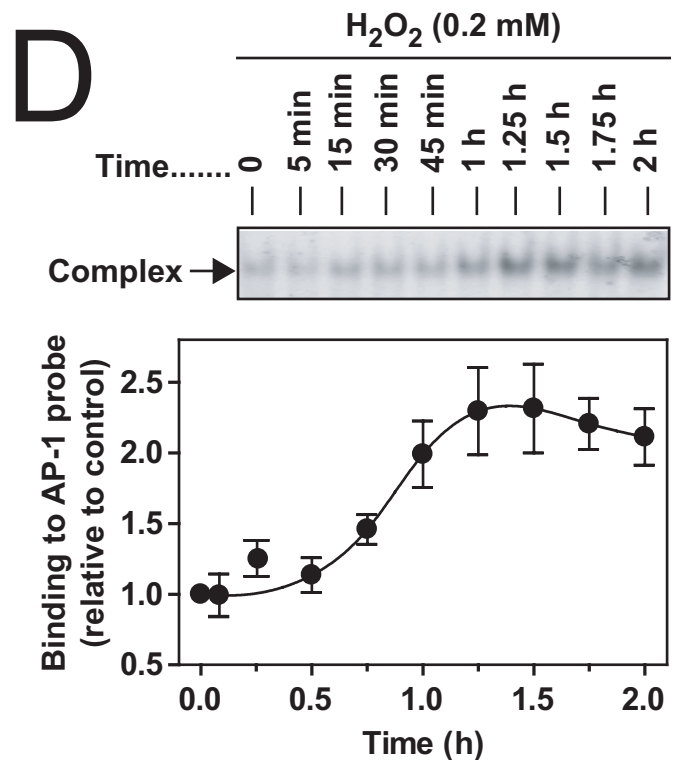
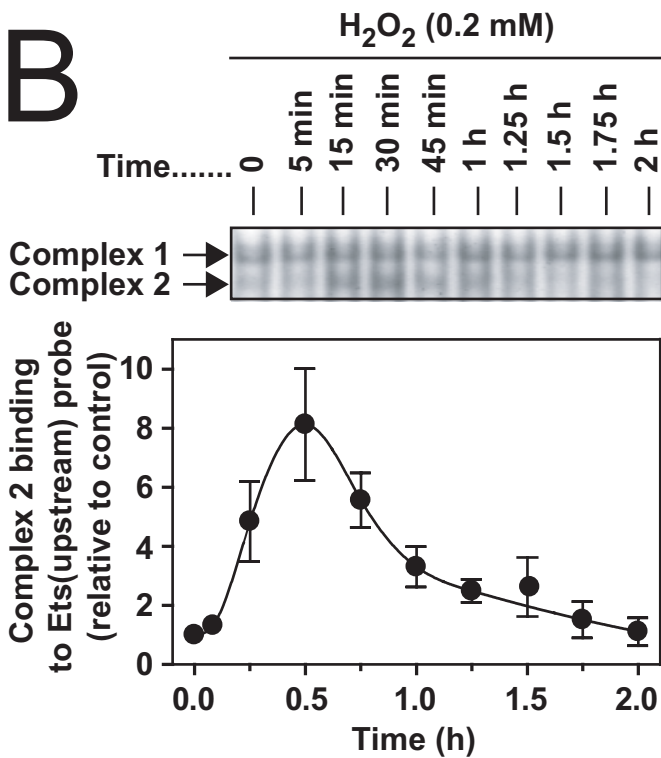
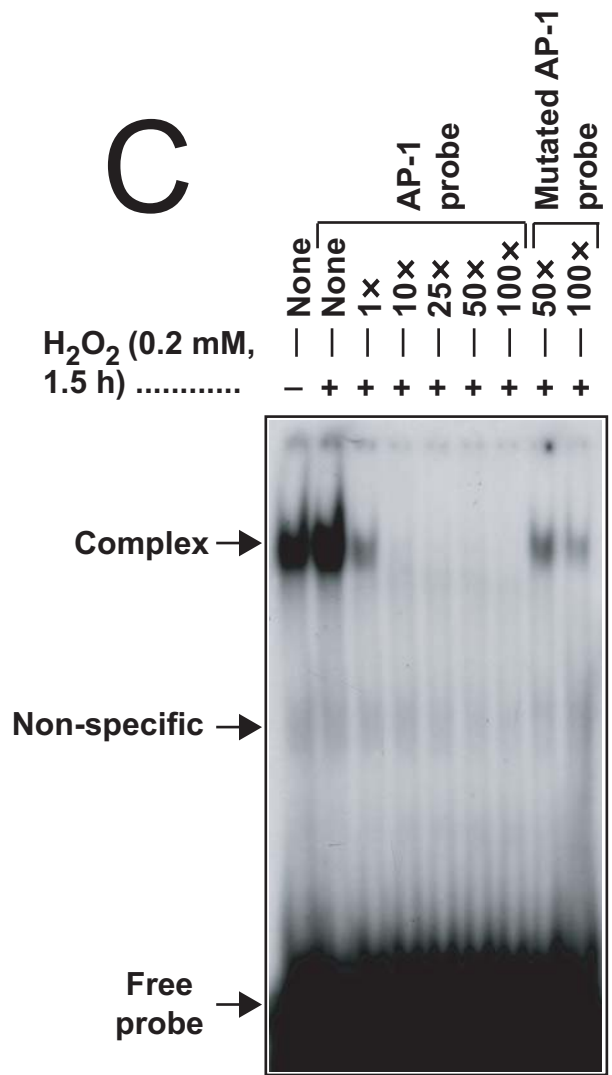
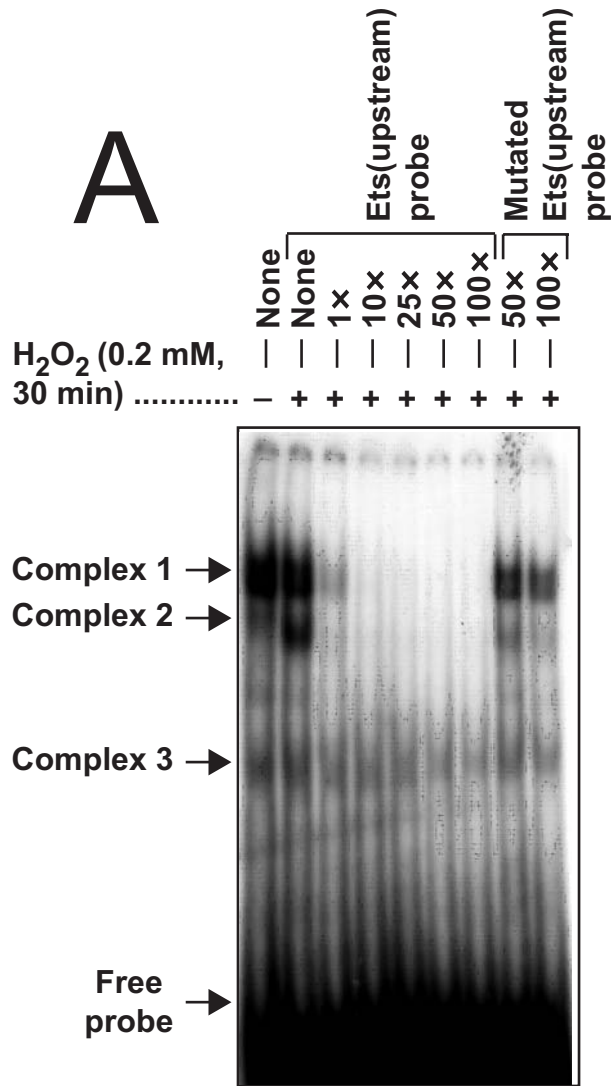
**C**



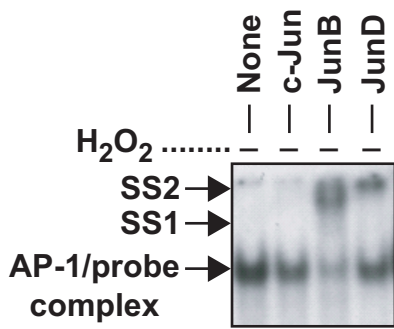
**D**



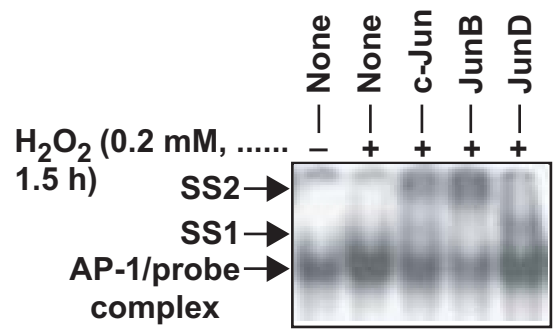




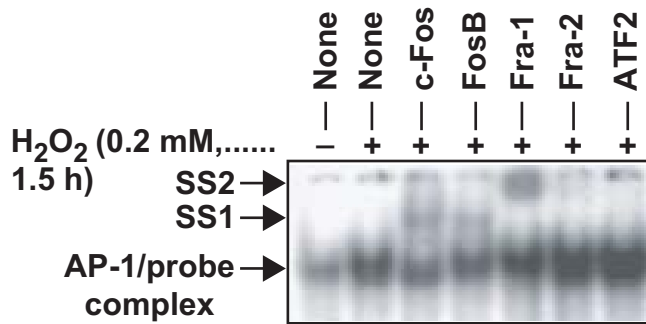
**A**



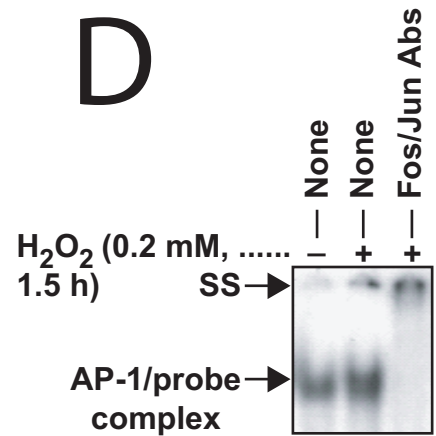
**B**



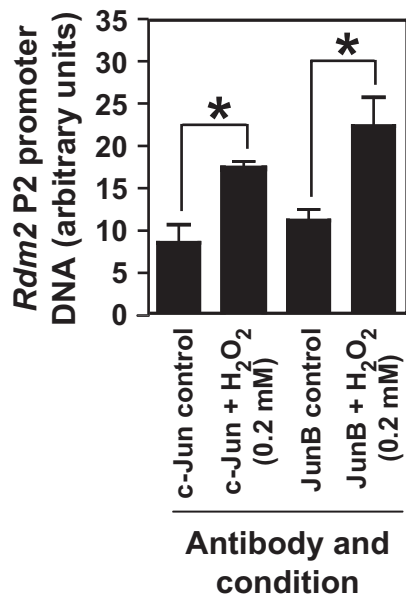
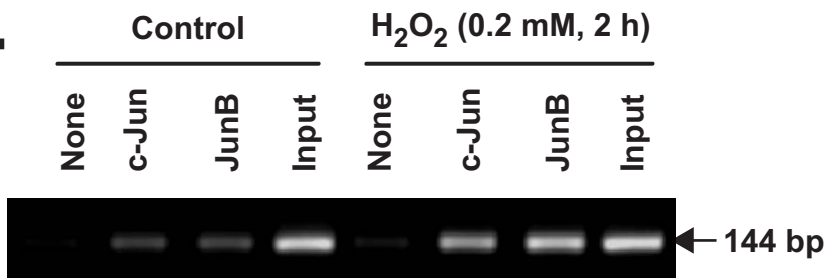
**C**

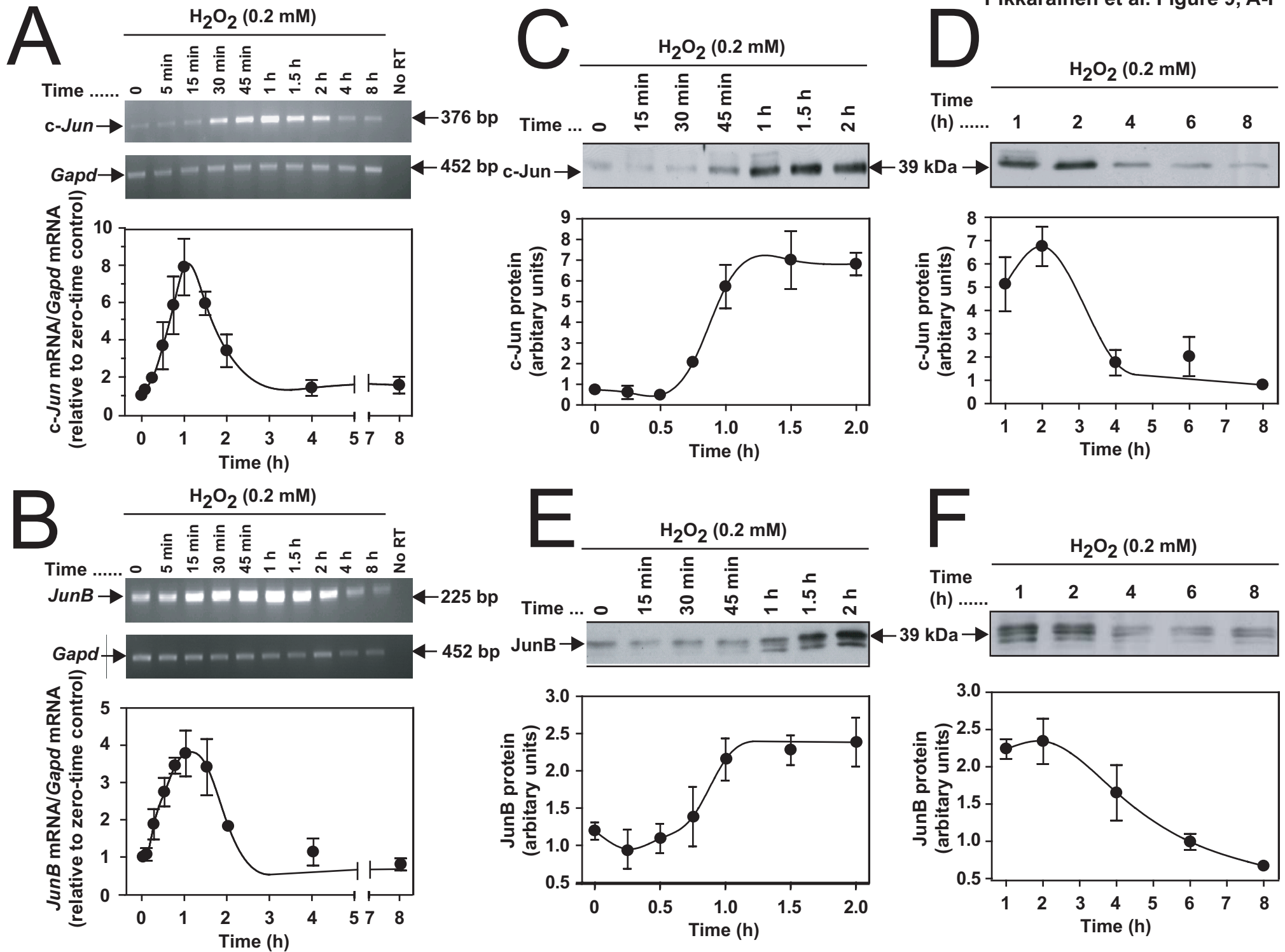


**D**

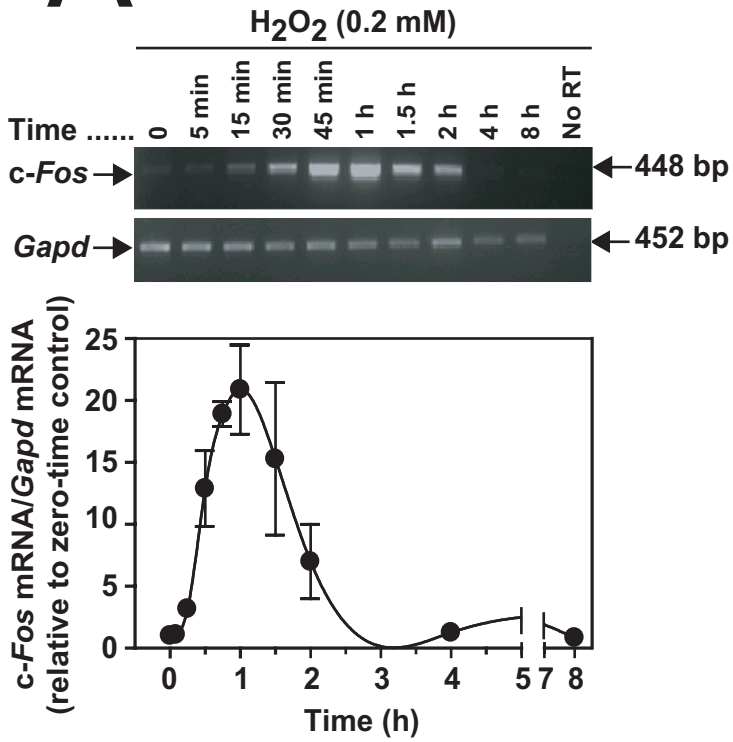


**E**

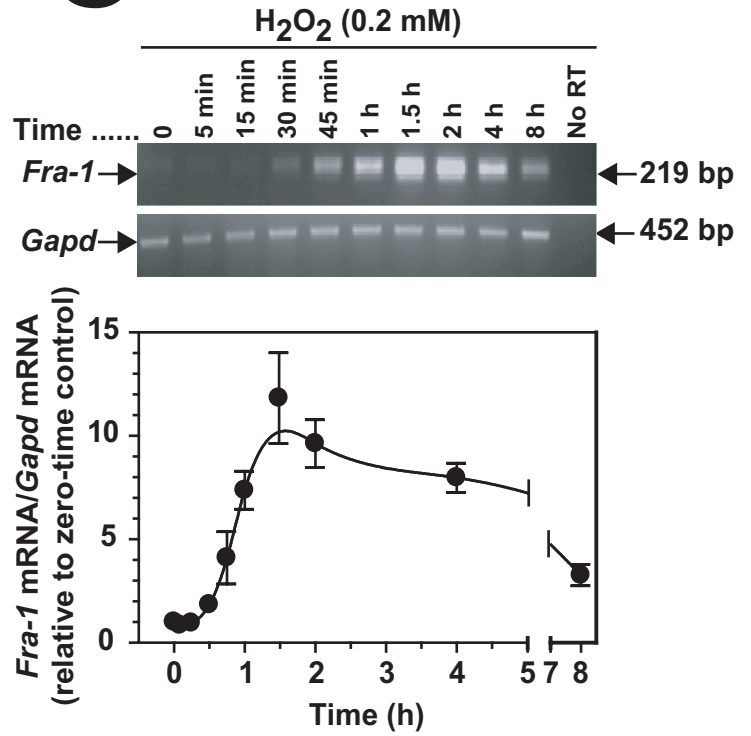




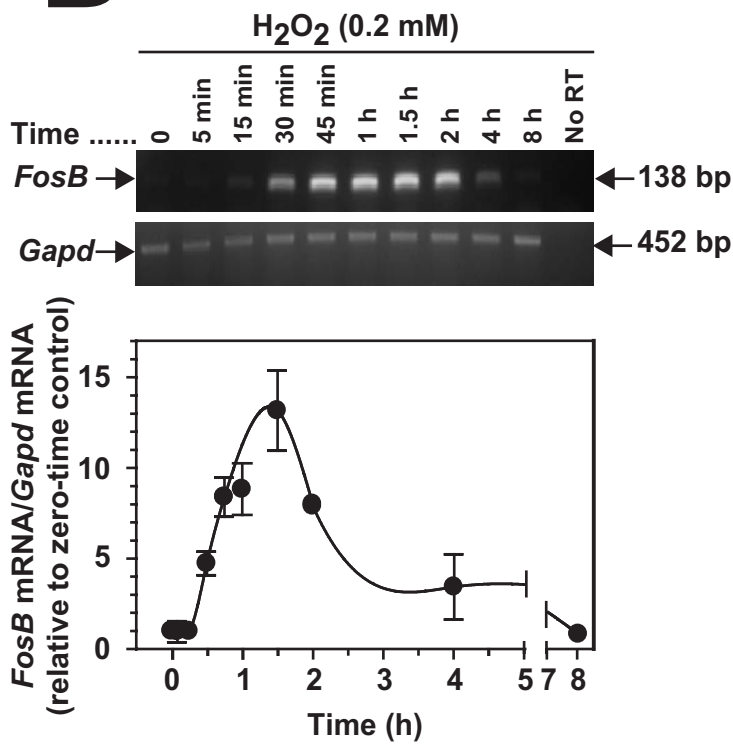
**A**



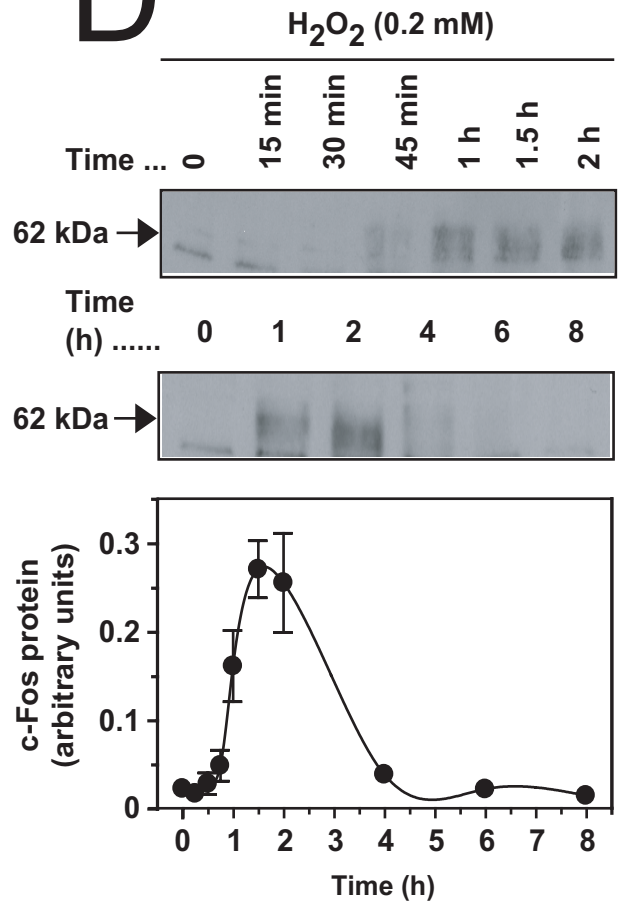
**C**



**B**

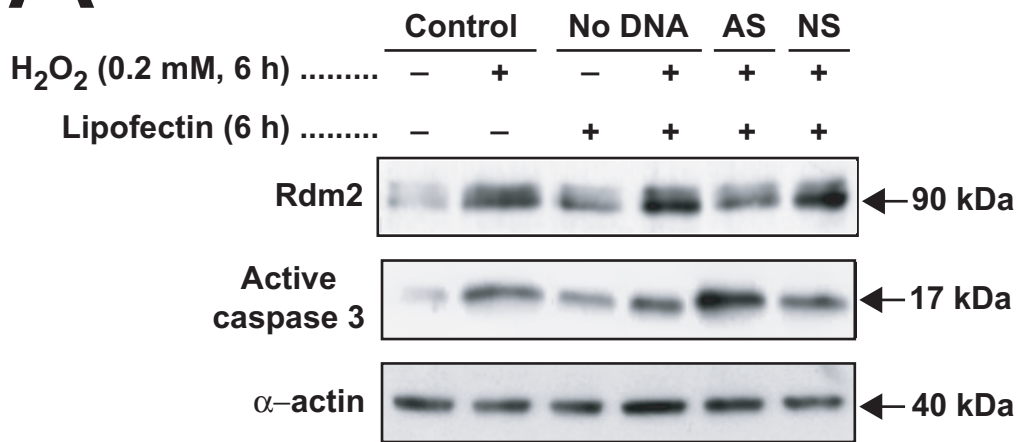


**D**

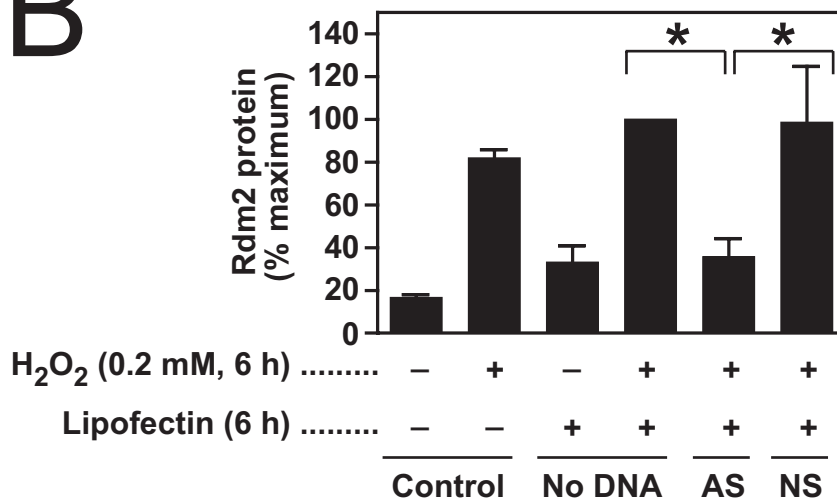




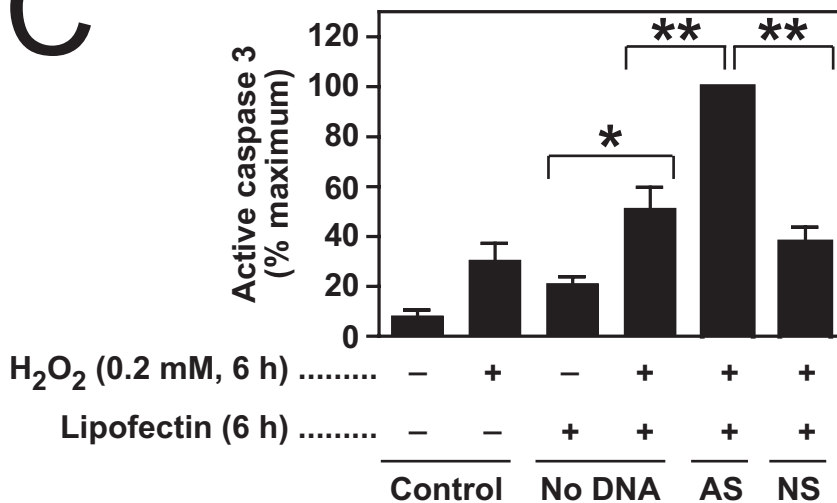
**A**



**B**



**C**



## SUPPLEMENTAL MATERIAL

**Supplemental Material FIG. 1. Alignment (ClustalW2) of the amino acid sequences of Mdm2 (NP\_034916.1) and its human orthologue HDM2 (NP\_002383.2) and the deduced amino acid sequence of the rat orthologue of Mdm2 (Rdm2) obtained from the predicted nucleotide sequence of the Rdm2 transcript (see Supplemental Material Fig. 2).** The non-conserved N-terminal hexapeptide extension in HDM2, which is often ignored for the purposes of numbering HDM2 residues, is underlined.

**Supplemental Material FIG. 2. Alignment (ClustalW2) of the *Mdm2* transcript NM\_010786.3 and the deduced sequence of the 2930 nucleotide *Rdm2* transcript.** The genomic sequence (T in place of U) is shown. The transcript is encoded by 12 exons as follows: exon1, nucleotides 1-170; exon 2, nucleotides 171-243; exon 3, nucleotides 244-328; exon 4, nucleotides 329-403; exon 5, nucleotides 404-537; exon 6, nucleotides 538-587; exon 7, nucleotides 588-646; exon 8, nucleotides 647-743; exon 9; nucleotides 744-892; exon 10, nucleotides 893-1048; exon 11, nucleotides 1049-1126; exon 12, nucleotides 1127-2930. Exon boundaries are indicated by highlighting in light blue (start) and yellow (end). Primer sequences are annotated as given in Table 1. Other features are highlighted and annotated. The translational initial codon for p90-Rdm2 open reading frame (ORF) is at nucleotides 248-250 (in exon 3) and that for the p76-Rdm2 is at nucleotides 395-397 (in exon 4). In addition, there are two short upstream ORFs (uORFs) in exon 1. These are out-of-phase with the initiation codon of uORF2 overlapping with the termination codon of uORF1 in an ATGA sequence at nucleotides 138 to 141. The *Rdm2* termination codon is at nucleotides 1697-1699. There is a putative AU-rich instability signal at nucleotides 2072-2085 and a putative polyadenylation signal at nucleotides 2906-2911. ODN, oligodeoxynucleotide.

**Supplemental Material FIG. 3. Alignment of intron 1 sequences from *Mdm2*, *Rdm2* and *HDM2*.** Features are highlighted and annotated. The four response elements highly conserved in intron 1 of the *Rdm2*, *Mdm2* and *HDM2* genes (the two p53 response elements and the composite AP-1/Ets sequence) are encompassed by boxes. The features of the intron 1 regions are described in more detail in the full text. In addition to these, the *HDM2* intron 1 contains five non-conserved GGGGC repeats at bases 112-144 immediately upstream of an E-box (ACGTG) which are important in constitutive expression from the P2 promoter under some circumstances (1). RE, response element.

### Reference

1. Phelps, M., Darley, M., Primrose, J. N., and Blaydes, J. P. (2003) *Cancer Res.* **63**, 2616-2623.

# Supplemental Material Figure 1

Rdm2 -----MCNTNMSVSTEGAAGTSQIPASEQETLVRPKPLLLKLLKSVGAQKDIYTMKEII 54  
Mdm2 -----MCNTNMSVSTEGAASTSQIPASEQETLVRPKPLLLKLLKSVGAQNNTYTMKEII 54  
HDM2 MVRSRQMCNTNMSVPTDGAVTTSQIPASEQETLVRPKPLLLKLLKSVGAQKDTYTMKEVL 60  
\*\*\*\*\* .\*:\*\* . \*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*

Rdm2 FYIGQYIMTKRLYDEKQQHIVYCSNDLLGDVFGVPSFSVKEHRKIYAMIYRNLVVVSQQ- 113  
Mdm2 FYIGQYIMTKRLYDEKQQHIVYCSNDLLGDVFGVPSFSVKEHRKIYAMIYRNLVAVSQQ- 113  
HDM2 FYLGQYIMTKRLYDEKQQHIVYCSNDLLGDLFGVPSFSVKEHRKIYTMIIYRNLVVVNQQE 120  
\*\*:\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*.\*.\*

Rdm2 --DSGTSPSESRQPEGGSDLKDPVQASQEEKPSSSDVSRPSTSSRRRAISETTEENTDE 171  
Mdm2 --DSGTSLSERSRQPEGGSDLKDPLQAPPEEKPSSSDLI SRLSTSSRRRSISETTEENTDE 171  
HDM2 SSSDGTSVSENRCHLEGGSDQKDLVQELQEEKPSSSHLVS RPSTSSRRRAISETTEENSDE 180  
\*\*\*\*\* \*\*.\* : \*\*\*\*\* \*\* :\* \*\*\*\*\* .:;\* \*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*

Rdm2 LPPERQKRHRHRA----LSFDESLGLCVLREICCE----RSSSSEATDTPSHQDLDDGVS 222  
Mdm2 LPPERHRKRRRS----LSFDPSLGLCELREMCSSGSSSSSSSSSESTETPSHQDLDDGVS 227  
HDM2 LSGERQKRHKSDSISLSFDESLALCVIREICCE----RSSSSESTGTSPSNPDLGAGVS 235  
\*.\*:\*\*\*:\*\*\*:~: \*\*\*\*\* \*\*.\* :\*\*:\* . \*\*\*\*\*:\* \*\*\*: \*\*\* \*\*\*

Rdm2 DHSADCLDQDSVSDQFSVEFEVESLSEEDYSLSEDEGHESLSEDEDEVYRVTVYQAGESDAD 282  
Mdm2 EHSADCLDQDSVSDQFSVEFEVESLSEEDYSLSEDEGHESLSEDEDEVYRVTVYQAGESDAD 287  
HDM2 EHSADCLDQDSVSDQFSVEFEVESLSEEDYSLSEEGQELSEDEDEVYRVTVYQAGESDAD 295  
:\*\*\*.\* \*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*

Rdm2 SFEGDPEISLADYWKCTSCNEMNPPLPSHCNRCWTLRENWLPDDKGKDKVEISEKAKLES 342  
Mdm2 SFEGDPEISLADYWKCTSCNEMNPPLPSHCNRCWTLRENWLPDDKGKDKVEISEKAKLEN 347  
HDM2 SFEGDPEISLADYWKCTSCNEMNPPLPSHCNRCWALRENWLPEDKGKDKGEISEKAKLEN 355  
\*\*\* \*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\* \*\*\*\*\*

Rdm2 SDQAEGLDVPDGKKVTEDDAKESSAE-DSEKVAQMLLSQESDDYSQPSTSSSIVYSSQ 401  
Mdm2 SAQAEGLDVPDGKKLTENDAKEPCAEDSEKAEQTPLSQESDDYSQPSTSSSIVYSSQ 407  
HDM2 STQAEGLDVPDCKKTIVNDSRESCVE-ENDDKITQASQSESEDYSQPSTSSSIIYSSQ 414  
\* \*\*\*\*\*:\*\*\*\*\* \*\* :\*:\*.\*. . \* :.::\* \* \*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*

Rdm2 ESGKELK-EDTQDKEESMESSFSLNAIEPCVICQGRPKNGCIVHGKTGHLMSCFTCAKKL 460  
Mdm2 ESVKELK-EETQDKDESVESSFSLNAIEPCVICQGRPKNGCIVHGKTGHLMSCFTCAKKL 466  
HDM2 EDVKEFEREETQDKEESVSSLPLNAIEPCVICQGRPKNGCIVHGKTGHLMACFTCAKKL 474  
\* . \*\*\*:~: \*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*:\*\*\*\*\*

Rdm2 KKRNKPCPVCQRQPIQMIVLTYFN 483  
Mdm2 KKRNKPCPVCQRQPIQMIVLTYFN 489  
HDM2 KKRNKPCPVCQRQPIQMIVLTYFP 497  
\*\*\*\*\*

## Supplemental Material Figure 2

**1**  
*Rdm2* TGCTTTGTTAACGGGGCCTCCGAAGCCGGGGTAGCCTAGGAGCGGCCGCTTCTACGTCA 60  
*Mdm2* -GCTTTGTTAACGGGGCCTCCGGGGCCAGCGTAGCCTAGGAGCGGCCG-GTGAGGAGCC- 57  
 \*\*\*\*\*  
 Forward primer *Rdm2*(C) uORF1  
*Rdm2* GGAGCCGCTG**TCGCTTCGCTCGACCTCC**CGAGCGAA-**ATGGTCTCTCAAGTCCCGCCAC** 119  
*Mdm2* ---GCCGCCTTCTCGTCGCTCGAGCTCTGGAGCGACCATGGTTCGCTCAGGCCCGGCCG 114  
 \*\*\*\*\*

uORF2 **12**  
*Rdm2* **CGGGCCTCCGCGCTCCCCATGAAGGGTCCGAGGCCGCGCGGGGAGTAG**CAG**CC**GGTCTGC- 178  
*Mdm2* GGGGCCTCCGCGCTCCCCGTGAAGGGTCCGAAGATGCGCGGGAAGTAGCAGCCGTCTGCT 174  
 \*\*\*\*\*

Forward primer *Rdm2*(D) Forward primer *Rdm2*(B)  
*Rdm2* AGGCG**AGCGGAGA**-----**CGGACACACC**GGGGA--CCTC**TCCGACCACCGTGCTTCT**G 229  
*Mdm2* GGGCGAGCGGGAGACCGACCGACACCCCTGGGGACCTCTCGGATCACC GCGCTTCTC 234  
 \*\*\*\*\*

**23** p90-*Rdm2* ORF Reverse primer *Rdm2*(E)  
*Rdm2* CTGCGCGCCTCCAG**CCAAATGTGCAATACCAACATGTCTGTGCTACCGAGGGTGCTGCA** 289  
**TACCAACATGTCTGTGCTACCGA**  
 Reverse primer *Rdm2*(B)

*Mdm2* CTGCGGGCCTCCAGCCAAATGTGCAATACCAACATGTCTGTGCTACCGAGGGTGCTGCA 294  
 \*\*\*\*\*

**34**  
*Rdm2* **GGCACCTCACAGA**TTCCAGCGTCGGAACAAGAGACTCT**GG**TTAGACCAAACCATTGCTT 349  
*Mdm2* AGCACCTCACAGATTCCAGCTTCGGAACAAGAGACTCTGGTTAGACCAAACCATTGCTT 354  
 \*\*\*\*\*

p76-*Rdm2* ORF  
 Reverse primer *Rdm2*(C) / *Rdm2*(D) **45**  
*Rdm2* TTGAAGTTGTTAAAGTCTGTTGGAGCACAA**AAAGATATTACACTATGAAAGAG**ATTATA 409  
*Mdm2* TTGAAGTTGTTAAAGTCCGTTGGAGCGCAAACGACACTTACACTATGAAAGAGATTATA 414  
 \*\*\*\*\*

*Rdm2* TTTTATATTGGACAGTATATTATGACTAAAAGATTATATGATGAGAAGCAGCAGCACATT 469  
*Mdm2* TTTTATATTGGCCAGTATATTATGACTAAGAGTTATATGACGAGAAGCAGCAGCACATT 474  
 \*\*\*\*\*

*Rdm2* GTGTATTGCTCAAATGATCTCCTAGGAGATGTGTTCCGAGTCCCAAGTTTCTCTGTGAAG 529  
*Mdm2* GTGTATTGTTCAAATGATCTCCTAGGAGATGTGTTCCGAGTCCCGAGTTTCTCTGTGAAG 534  
 \*\*\*\*\*

**56** **67**  
*Rdm2* GAGCACAG**G**AAAATATATGCAATGATCTACAGAACTTAGTGGTTGTAAGTCAACAAG**AG**C 589  
*Mdm2* GAGCACAGGAAAATATATGCAATGATCTACAGAAATTTAGTGGCTGTAAGTCAACAAGAC 594  
 \*\*\*\*\*

Antisense ODN target **78**  
*Rdm2* TCTGGAACATCG**CCGAGTGAGAGCAGATGTCA**GCCTGAAGGTGGGAGTGACCTGAAG**GC** 649  
*Mdm2* TCTGGCACATCGCTGAGTGAGAGCAGACGTCAGCCTGAAGGTGGGAGTGATCTGAAGGAT 654  
 \*\*\*\*\*

*Rdm2* CCGTGCAAGCATCACAAGAAGAGAAACCTTCATCTTCTGATGTAGTTTCTAGACCATCT 709  
*Mdm2* CCTTTGCAAGCGCCACCAGAAGAGAAACCTTCATCTTCTGATTTAATTTCTAGACTGTCT 714  
 \*\* \*\*\*\*\* \*\* \*\*\*\*\* \*\* \*\*\*\*\* \*\* \*\*\*\*\* \*\*

*Rdm2* ACCTCATCTAGAAGGAGAGCAATTAGTGAAACA**GA**AAGAGAACACAGATGAACTACCTGGG 769  
*Mdm2* ACCTCATCTAGAAGGAGATCCATTAGTGAGACAGAAGAGAACACAGATGAGCTACCTGGG 774  
 \*\*\*\*\* \* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\*

*Rdm2* GAACGACAGAGGAAGCGCCACAGAGCCCTGTCCTTTGATGAGAGCCTGGGTCTGTGTGTG 829  
*Mdm2* GAGCGGCACCGGAAGCGCCGAGGTCCTGTCCTTTGATCCGAGCCTGGGTCTGTGTGAG 834  
 \*\* \* \* \*\*\*\*\* \*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*

*Rdm2* CTCAGGGAGATATGCTGTGAA-----AGAACGAGCAGCAGCGAGGCCACA 874  
*Mdm2* CTGAGGGAGATGTGCAGCGCGGCAGCAGCAGCAGTAGCAGCAGCAGCAGCGAGTCCACA 894  
 \*\* \*\*\*\*\* \*\* \* \* \*\*\*\*\* \*\*\*\*\*

*Rdm2* GACACCCCTCACATCAG**GG**ATCTTGATGATGGCGTAAGTGACCATTCTGCTGATTGCCTG 934  
*Mdm2* GAGACGCCCTCGCATCAGGATCTTGACGATGGCGTAAGTGAGCATTCTGGTGATTGCCTG 954  
 \*\* \* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\*

*Rdm2* GATCAGGATTCAGTTTCTGATCAATTCAGTGTAGAATTTGAAGTTGAGTCTCTTGACTCA 994  
*Mdm2* GATCAGGATTCAGTTTCTGATCAGTTTAGCGTGAATTTGAAGTTGAGTCTCTGGACTCG 1014  
 \*\*\*\*\* \*\*\*\*\* \*\* \* \* \*\*\*\*\* \*\*\*\*\*

*Rdm2* GAAGATTACAGCCTGAGTGATGAAGGGCATGAGCTCTCAGATGAGGATGATGAG**GG**TCTAT 1054  
*Mdm2* GAAGATTACAGCCTGAGTGACGAAGGGCACGAGCTCTCAGATGAGGATGATGAGGTCTAT 1074  
 \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\*

*Rdm2* CGGGTCACAGTCTATCAGGCAGGAGAAAGCGATGCAGACTCTTTTGAGGGAGATCCTGAA 1114  
*Mdm2* CGGGTCACAGTCTATCAGACAGGAGAAAGCGATACAGACTCTTTTGAAGGAGATCCTGAG 1134  
 \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\*

*Rdm2* ATTTCCCTTAGCT**IG**ACTATTGGAAATGCACCTCGTGCAATGAAATGAATCCTCCCCTTCCA 1174  
*Mdm2* ATTTCCCTTAGCTGACTATTGGAAAGTGTACCTCATGCAATGAAATGAATCCTCCCCTTCCA 1194  
 \*\*\*\*\* \*\*\*\*\* \* \*\*\*\*\* \*\*\*\*\*

*Rdm2* TCACACTGCAACAGATGTTGGACCCTTCGTGAGAACTGGCTTCCAGACGATAAGGGGAAA 1234  
*Mdm2* TCACACTGCAAAAGATGCTGGACCCTTCGTGAGAACTGGCTTCCAGACGATAAGGGGAAA 1254  
 \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\*

*Rdm2* GATAAAGTGGAATTTCTGAAAAAGCCAAACTGGAAAGCTCAGATCAGGCAGAAGAAGGC 1294  
*Mdm2* GATAAAGTGGAATCTCTGAAAAAGCCAAACTGGAAAGCTCAGCTCAGGCAGAAGAAGGC 1314  
 \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\*

*Rdm2* TTAGATGTGCCTGATGGCAAAAAGTGACAGAGGATGATGCTAAGGAGTCATCTGCTGAG 1354  
*Mdm2* TTGGATGTGCCTGATGGCAAAAAGCTGACAGAGAATGATGCTAAAGAGCCATGTGCTGAG 1374  
 \*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\* \* \* \*\*\*\*\*

*Rdm2* GA---TAGCGAGGAAAAAGTGGCCAGATGCTCCTGTCACAGGAGAGTGACGACTATTCC 1411  
*Mdm2* GAGGACAGCGAGGAGAAGGCCGAACAGACGCCCTGTCCAGGAGAGTGACGACTATTCC 1434  
 \*\* \*\*\*\*\* \*\* \* \* \*\*\*\*\* \*\* \*\*\*\*\* \*\*\*\*\*

*Rdm2* CAGCCGTCGACTTCCAGTAGCATTGTTTACAGCAGCCAAGAAAGTGGCAAAGAGTTGAAG 1471  
*Mdm2* CAACCATCGACTTCCAGCAGCATTGTTTATAGCAGCCAAGAAAGCGTGAAAGAGTTGAAG 1494  
 \*\* \*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \* \*\*\*\*\*

**Forward primer *Rdm2*(A)**

*Rdm2* GAGGACACACAAGACAAAGAGGAAAGTATGGA**ATCCAGCTTCTCTCTGAACG**CCATCGAG 1531  
*Mdm2* GAGGAAACGCAGGACAAAGACGAGAGTGTGGAATCTAGCTTCTCCCTGAATGCCATCGAA 1554  
 \*\*\*\*\* \*\* \*\* \*\*\*\*\* \*\* \*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\*

*Rdm2* CCATGTGTGATTTGCCAGGGGCGGCCTAAAAATGGTTGCATTGTTACGGCAAACCGGA 1591  
*Mdm2* CCATGTGTGATCTGCCAGGGGCGGCCTAAAAATGGCTGCATTGTTACGGCAAGACTGGA 1614  
 \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\* \*\*

*Rdm2* CACCTGATGTCATGTTTCACGTGTGCAAAGAAGCTAAAGAAGAGGAATAAGCCCTGCCCC 1651  
*Mdm2* CACCTCATGTCATGTTTCACGTGTGCAAAGAAGCTAAAAAAAAGAAACAAGCCCTGCCCA 1674  
 \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\* \*\* \* \*\*\*\*\*

**Termination codon**

*Rdm2* GTGTGCAGACAGCCGATCCAAATGATTGTGCTCACGTACTTCAAC**TAG**ACGGCGGGC--- 1708  
*Mdm2* GTGTGCAGACAGCCAATCCAAATGATTGTGCTAACTTACTTCAACTAGCTGACCTGCTCA 1734  
 \*\*\*\*\* \*\*\*\*\* \*\* \*\*\*\*\* \* \* \*\*

*Rdm2* -AGACGCAGACCTTTACACTTCTAA-TGTATGACCCCAAATTAGACAACATGGGTATTA 1766  
*Mdm2* CAAAAATAGAATTTTATATTTCTAACTATATGACCCCAAATTAGACAACATGGGTATTA 1794  
 \* \* \*\* \* \*\*\*\*\* \* \*\*\*\*\*

**Reverse primer *Rdm2*(A)**

*Rdm2* TTTTCATACATTAAG**CCGGAGCATTGTCTTAGTCT**TACATAAAGTTCATTTGTAATTTAT 1826  
*Mdm2* TTTTATACATTAAGCCAGAAAAGTGTCTTAGTCCACATAAAATTCATTATAATTTAT 1854  
 \*\*\*\* \*\*\*\*\* \*\* \* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\* \*\*\*\*\*

*Rdm2* CCTCGAGAGTAAGAATAGTAACTGTTTTCTTCCTTTT-AGGAAAATTTTCAGTTGATTATT 1885  
*Mdm2* CCTGGAGAGTAAATATGGTGAATATTTTCTTCCTTTTTAGGGAAATTTCACTTGTATTATT 1914  
 \*\* \*\*\*\*\* \*\* \*\* \* \* \*\*\*\*\* \*\* \*\*\*\*\* \*\* \*\*\*\*\*

*Rdm2* TTATATTTGTGTTTTAACGTAATTTGCATTAGCTCTTTTCATTTTCCTTACGTTTTAAGT 1945  
*Mdm2* TTATATTTGTGTTTTAA-GTAATTTGCATTGGCTGTTTATATTTTCCTTATATTTTAAAT 1973  
 \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\* \*\* \*\*\*\*\* \*\*\*\*\* \*

*Rdm2* AATCTCCACTTGGAAGGACTTTTGAAGTATACTTTATACAGTGAGAAGTCCTCTCCATC 2005  
*Mdm2* AATCTCCGCTTGGAAGGACTTT-GGAAGTGTAT-----GTGAGAAGTCCTTCCATC 2024  
 \*\*\*\*\* \*\*\*\*\* \* \*\*\*\*\* \*\* \*\*\*\*\* \*\*\*\*\*

*Rdm2* TCTGTCTCTTGGAGATA-----ATGATAGGCTATCGAATTGTGCTTGATTTCTT 2055  
*Mdm2* TCCTGCAGATGATGGTGGACCTTCCATCAAGGGCTACAGAA--GTACTTGATTTCTGT 2082  
 \*\* \* \*\* \* \* \*\* \* \*\*\*\*\* \*\* \*\* \*\*\*\*\* \*

**AU-rich instability element**

*Rdm2* TTTTTTCCTTGTTAAT-----**ATTTAATTTATTTA**GTATCTTTCATGTAAAGAGTTAAA 2109  
*Mdm2* TTTTTTGTTAATAATAAGAACATTTAATTTATTAGTGTCTTTCATGTAAAGAGTTAAA 2142  
 \*\*\*\*\* \*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\*

<i>Rdm2</i>	GACTATGTGAAGGATTGAGTGTATATTTAAGTTATTGAAATTCTGAACCTCCTTAGTTCT	2169
<i>Mdm2</i>	GACTATGTGAAGGAT---TGTATATTTAAGTTATTGAAATTCTGAAACTGTAGTAATCT	2198
	*****	
<i>Rdm2</i>	CTTAAGTGGGGTGTGGGCTGCAGAGAAGAGTCAGCCGGTAAAGGCGCCCACTGTGTAT	2229
<i>Mdm2</i>	AAAATGTGTGAGTTGTGGGCTGCAGAGAAGACTCAGCCAGTAAAGGCACCTGCTGTGTAC	2258
	* ** * *****	
<i>Rdm2</i>	GCCTAATGACACACATTTGATCCTTGCAACGCCAGAAAGAGAGAACCAGTTCCACAAAG	2289
<i>Mdm2</i>	ACCCACTGACACACATTTGATCCTTGGAACCCCCAGGAAGAGTGAACCAGTTCCACAAAG	2318
	** * *****	
<i>Rdm2</i>	TAGTTCTCGGATCTCCAAATGGATTCAT-----ATACACACTTTTTTTTTT-----	2334
<i>Mdm2</i>	TTGTTCCCTGATCTTCAAATGGATGCACGCATGCACGCACACACACGCGCGCTGCGCAC	2378
	* **** * ***** ** * ***** *	
<i>Rdm2</i>	-----TTTTTAAGGT	2344
<i>Mdm2</i>	ACAGTTTTAAAGGC	2438
	**** **	
<i>Rdm2</i>	CTGAGTTGCATCTGGTGATAcataaagtGAAAACACACACCTTGTTTTCCAGC-----	2396
<i>Mdm2</i>	ATGAATTGCATCTGGTGATGTAAGTAAAACACACGCCTTATTTCCAGCATTTTCAG	2498
	*** ***** ** ***** *****	
<i>Rdm2</i>	-TTTTTGTcATATGGGGTGTGGCACGAGTgTTCAGTCTGTCCCAGGTTGAAAAAGTCTG	2455
<i>Mdm2</i>	CTTTTTGTcATA-GGGGTGTGGCACAAGTgTTCAGTTTTGTCCCAGGTTGAAAA-GCCTG	2556
	***** ***** ***** ***** ***** * **	
<i>Rdm2</i>	TGGCCCTTCGAAGCACCTTCATGGCCC-GCTCCATGGTTCCTGATGGCTGTTGAAGTTTC	2514
<i>Mdm2</i>	AGGCTGGTAGAAGCGCCTTTTTGCCTCAGCTCCGTGGTTCCTGGTGGTGCCTATGTTTC	2616
	*** * ***** ** * * ***** ***** ** * *****	
<i>Rdm2</i>	AGGCCTGTACTTAGTCTAGGTT-AGAAACCAGTCCATTcAGAAAGACTAAATCAGAGCAT	2573
<i>Mdm2</i>	AGGCCTGTACTTAGGCTAGGTTTAGAAACCAGCCATTcAGAAAGACTGAATCAGAACAT	2676
	***** ***** ***** ***** ***** *	
<i>Rdm2</i>	GGATGAAGTGGATCC-----TCCAACCGTGTAGATGAGTCTCTTGATTC	2617
<i>Mdm2</i>	GGATAAAGTGAACtCATtCTAAGATGACTCGTCTATCCATGTAGATTAATCTCCTGGTTC	2736
	**** ***** * * ** * ** ***** * **** * **	
<i>Rdm2</i>	ATAATAAGAATCTTCCATTTTAATTGAAGGGTCATGCCTAAGTGTAGAAAACAAGTTCCC	2677
<i>Mdm2</i>	ATAATAGGCCTCTTCC-CTTTGATTGAAGGGTCACGTCTAAGTATAGAAAACATAAAACT	2795
	***** * ***** ** ***** ***** ***** *	
<i>Rdm2</i>	TAACTGTATGGAGTAACCAAAGGATAGTTCTGTATTGAAGTTGACTTAAAGTATCAAAGA	2737
<i>Mdm2</i>	GTAAGGTA--GAGGAAGCGAAGGATAGCTTTGTATTAAATGTTGCGTTAAAGCTTCAGAGA	2853
	* ** * ** * ***** * ***** * ***** ***** ** **	



*Rdm2* T-----CACTCCCCACATGATTTAGCAGTTAAGTCGGAGGCAGCGCCTCAGCCT 2786  
*Mdm2* CAAGAACAAGAACAACACTCCTCCCACGTGACAGCATTGAAATAGGAGGCGGTG-----GGTG 2908  
 \*\*\*\*\* \* \* \* \* \* \*\*\*\*\* \* \* \* \*

*Rdm2* GGCATCCTAACTCTGGACTTTGATTCCCCATTTACAATGTAATACTGAGGTTATATCCT 2846  
*Mdm2* CGGCAGCCTGG----GCAGCTTCAGTCCCGATTTACAATAAAGTACC----TTGT----- 2955  
 \*\*\*\*\* \* \* \* \* \* \*\*\*\*\* \* \* \* \* \* \*\*\*\*\* \* \* \*

*Rdm2* AGTATTACTAGTTCTTAAATGTTTATTTAGGTGTGGTAGACATACATTATTTATTTGCAA 2906  
*Mdm2* -GTGTTATTAGTTCTTAAATGTTTATTTAGAAATGGCATTGATG--TTATTTATTTGCAA 3012  
 \*\* \*\*\* \*\*\*\*\* \*\*\*\*\* \*\*\*\*\* \* \* \* \* \* \*\*\*\*\* \*\*\*\*\*

**Polyadenylation signal** 12  
*Rdm2* **ATAAA**TGGTTTATTGAATTGTTTC 2930  
*Mdm2* ATAAATGGTTTATTG----- 3027  
 \*\*\*\*\*

### Supplemental Material Figure 3

*Mdm2* GTACCCGC-----TCCGTGGGCGGCGGAGAGTCCCGATCATTCCC--TCTTTTCC 48  
*Rdm2* GTACCCGCCAGGAGCGACGCGACGTGCGGGGTTGGGCGGTGGCGAGTTCTGATCATTCCC 60  
*HDM2* GTACTGGCCCGG-----CAGCGAGCGTCACTTTTGGGTCTGGGCT-CTGACGGT 49  
 \*\*\*\* \* \* \* \* \* \* \* \*

**MZF-1 RE**

*Mdm2* GCGCCCTCCGGGGCCTACTCGTAACCCGGGCGGCTCGTGGGGTC-GCGGGGCACGAGGC 107  
*Rdm2* GAGTCCTCTGGGGCCCACTCGCAGCCCGAGACGGCTCGCGGGGTC-GCGGGGC----- 112  
*HDM2* **GTCCCCTC**TATCGCTGGTTCCAGCCTCTGCCCGTTCGCAGCCTTTGTGCGGTTCTGTGGC 109  
 \* \*\*\*\* \*\* \* \* \* \* \* \* \* \* \* \* \* \* \* \* \*

**GGGGC repeats**

**E-box**

*Mdm2* TGGGCGACCGTTTGCCTCGCGC-TGGGCCCTGATGTCATTCTGCGGCCGGGGGTGTGCGTG 166  
*Rdm2* -----GACGGTTTGTGGCGC-CGGGCCATGATGCCCTTATTTCATCAGGGTG----- 158  
*HDM2* **TGGGGCTCGGGGCGCGGGGCGCGGGGCATGG-GGCACGTG**GCTTTGCGGAGGTTTGT 168  
 \* \* \* \* \* \* \* \* \* \* \* \* \* \* \*

*Mdm2* TGGGTGGGAGTGGGGGTGG--GGTGGGAGATGGCGCGG--TTAGCACGGCGCATGCGC 221  
*Rdm2* -AGGTGGG--GGGGTCTGG--GTTAACACAGCGCACGC--GCGGAA--GAGGATG-AC 206  
*HDM2* GGACTGGGGCTAGGCAGTCGCCGCCAGGGAGGAGGGCGGGATTTTCGGACGGCTCTCGCGG 228  
 \*\*\*\* \*\* \* \* \* \* \* \* \* \* \* \* \* \* \*

**MZF-1 RE**

**MZF-1 RE**

*Mdm2* **GGAGGGGA**CGGAG**GGAGGGGA**AGGAGGGAAGAGCGGGGTCTCCCA-GCAGGCCCCGCG 280  
*Rdm2* GGG-GGTAATGGAG**GGAGGGG-A**AGAGGAGAAGAGCCGGGGTCTCCCG-GCAGGCCCCGCG 263  
*HDM2* CGGTGGGGGTGGGGGTGGTTC--GGAGGTCTCCGCGGGAGTTCAGGGTAAAGGTCACGGG 286  
 \*\* \* \* \* \* \* \* \* \* \* \* \* \* \* \* \*

**Ets RE**

*Mdm2* CGCGGGGGGCCCGCTCCGGGGTTCGCGCTGGGCTCGTTGCTGGGGTCCAGGAGGTGACAGG 340  
*Rdm2* CCCGGGGG--CGGCTCCGGGGTTCGCGCTGGGCTCACTGCAGGGTTCGGGAGGTAACAGG 321  
*HDM2* GGCCGGGG--GCTGCGGGGCCGCTTCGG--CGCGG--**GAGGTCCGGATGATC**GCAGG 337  
 \* \*\*\*\* \*\* \* \* \* \* \* \* \* \* \* \* \* \* \* \* \*

**Ets RE**

*Mdm2* TGCCTGGTCCCGGACTCGCCGGGATGC**GGCTTCCGGG**ACGGGTGGGACTGGGCTGG---- 396  
*Rdm2* TGCCTGGT-----GGTGGGACGT**GGCTTCCGGG**ACGGGTGGGACTGGGCTGT---- 368  
*HDM2* TGCCTGTCGGGTCACTAGTGTGAACGCTGCGCGTAGTCTGGGCGGGATTGGGCCGGTTCA 397  
 \*\*\*\*\* \* \* \* \* \* \* \* \* \* \* \* \* \* \* \*

**AP-1 RE**

**Ets RE**

**p53 RE**

<i>Mdm2</i>	---GCCGAG	<b><u>TTGACTCAG</u></b>	<b><u>CTCTTCCTGTGG</u></b>	GGCT	<b><u>GGTCAAGTTGGGACACGTCC</u></b>	GGCGTC	453
<i>Rdm2</i>	---GCCTAG	<b><u>TTGACTCAG</u></b>	<b><u>CTTTTCCTGTGG</u></b>	GGCT	<b><u>GGTCAAGTTAGGACACGTTC</u></b>	AGCGTT	425
<i>HDM2</i>	GTGGGCAGG	<b><u>TTGACTCAG</u></b>	<b><u>CTTTTCCTCTTG</u></b>	AGCT	<b><u>GGTCAAGTTCAGACACGTTC</u></b>	CGAAAC	457

\* \*

**p53 RE**

```
Mdm2 GGCTGTCGGAGG AGCTAAGTCCTGACATGTCT CCAGCTGGGGTTATTTAAACGCTGCCCC 513
Rdm2 GGCTGTTGGAGG AGCTAAGTCCTGACATGTCT CCAGCTGAGGCTATTTAAACCCTGCTC- 484
HDM2 TGCAGTAAAAGG AGTTAAGTCCTGACTTGTCT CCAGCTGGGGCTATTTAAACCATGCATT 517
** **      ***** ***** ***** ***** ** ***** **
```

```
Mdm2 GTTTCGCAG----- 523
Rdm2 GTTTCGCAG----- 494
HDM2 --TTCC-CAGCTGTGTTTCAGTGGCGATTGGAGGGTAGACCTGTGGGCACGGACGCACGCC 574
**** **
```

```
Mdm2 -----
Rdm2 -----
HDM2 ACTTTTTCTCTGCTGATCCAGGTAAGCACCGACTTGCTTGTAGCTTTAGTTTTAACTGTT 634
```

```
Mdm2 -----
Rdm2 -----
HDM2 GTTTATGTTCTTTATATATGATGTATTTCCACAGATGTTTCATGATTTCCAGTTTTCAT 694
```

```
Mdm2 -----
Rdm2 -----
HDM2 CGTGTCTTTTTTTTTCCTTGTAG 716
```