Cell-cycle-dependent transcriptional and translational DNA-damage response of 2 ribonucleotide reductase genes in S. cerevisiae

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Cell-cycle-dependent transcriptional and translational DNA-damage response of ribonucleotide reductase genes in *S. cerevisiae*

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ABSTRACT

The ribonucleotide reductase (RNR) enzyme catalyzes an essential step in the production of deoxyribonucleotide triphosphates (dNTPs) in cells. Bulk biochemical measurements in synchronized S. cerevisiae cells suggest that RNR mRNA production is maximal in late G1 and S-phase; however, damaged DNA induces RNR transcription throughout the cell cycle. But such en masse measurements reveal neither cell-to-cell heterogeneity in responses, nor direct correlations between transcript and protein expression or localization in single cells which may be central to function. We overcame these limitations by simultaneous detection of single RNR transcripts and also Rnr proteins in the same individual asynchronous S. cerevisiae cells, with and without DNA-damage by methyl methanesulfonate (MMS). Surprisingly, RNR subunit mRNA levels were comparably low in both damaged and undamaged G1 cells, and highly induced in damaged S/G2 cells. Transcript numbers became correlated with both protein level and localization only upon DNA-damage in a cell-cycle dependent manner. Further we showed that the differential RNR response to DNA-damage correlated with variable Mec1 kinase activity in the cell-cycle in single cells. The transcription of RNR genes was found to be noisy and non-Poissonian in nature. Our results provide vital insight into cell-cycle-dependent RNR regulation under conditions of genotoxic stress.

INTRODUCTION

Unrepaired DNA-damage can result in cell growth arrest, apoptosis, premature aging, neurodegeneration and cancer (16, 18). Because most DNA repair pathways require de novo synthesis of DNA, damaged DNA signals the increased production and activation of the RNR enzyme (25, 36, 40). In almost all eukaryotes the functional RNR enzyme consists of a large and a small subunit (25). The S. cerevisiae genes RNR1 and RNR3 code for the large subunit proteins, while RNR2 and RNR4 code for of the small subunit proteins (Figure 1). The active form of the small subunit is a Rnr2-Rnr4 heterodimer (9, 26), and it relocalizes to the cytoplasm from the nucleus upon DNA damage (2, 36) to make the functional holoenzyme with the large subunit. Additionally, upon DNA damage the transcription of all RNR genes are induced by the Mec1-Rad53 pathway (20, 35), which also controls the subcellular localization of the Rnr2-Rnr4 heterodimer (23) and the activation of the RNR enzyme (39, 41). Much of our understanding of the response of RNR to DNA damage as a function of cell-cycle stage comes from bulk
biochemical studies involving the model eukaryote *S. cerevisiae* (Figure 1) (14, 15, 19). However, the synchronization methods employed in these studies may alter normal cell behavior. Further, mean-values probed in bulk population studies mask information on cell-to-cell variability in response, which is clearly resolvable with single-cell level imaging (1, 6, 29, 32). Moreover, mRNA and protein levels and localization are usually measured in separate experiments, and few studies have explored the measurement of both gene products in the same cells.

As a consequence, it remains unclear whether *RNR* genes are induced uniformly across cells by DNA damage via a homogeneous amplification of the normal cell-cycle transcript distributions, or whether cell-cycle-stage-specific amplification of transcripts occurs. Additionally, correlated variation in protein and mRNA levels in individual cells in distinct stages of the cell cycle with and without genotoxic stress remains unexplored. For example, mRNA and protein levels were recently found to become correlated for a number of genes under conditions of osmotic stress using bulk mass spectrometry (22), whereas little-to-no correlation between mRNA and protein has been observed in several bulk and single-cell studies in unperturbed cells (12, 17, 32). This discrepancy is likely to be because of the longer half-lives of most proteins that results in slower fluctuations in their numbers with respect to mRNAs that typically degrade rapidly in a programmed manner (5, 32, 34).

To overcome these limitations and reveal the possible cell-cycle-dependence of *Rnr* mRNA and protein to DNA damage, we assayed the transcriptional response of the *RNR* subunit genes by imaging single transcripts with fluorescence in situ hybridization (FISH) (28, 31, 37, 38), and subsequently combined this technique with immunofluorescence detection of *Rnr* proteins to simultaneously investigate their translational responses in the same individual cells as a function of the cell-cycle.

**MATERIALS AND METHODS**

**Cell growth and mRNA FISH.** All chemicals were from Sigma-Aldrich (St. Louis, MO), Invitrogen (Carlsbad, CA) or Ambion (Applied Biosystems, Austin, TX), unless otherwise noted. BY4741 cells were typically grown in YPD medium at 30°C with shaking. For experiments with RC634 cells YPDA (YPD with 0.003% Adenine hemisulfate) medium was used to avoid fluorescent purine precursors accumulating in the vacuoles. FISH was performed following
earlier studies in yeast (28, 31, 37, 38). Cells were diluted to an optical density (at 600 nm, \( \text{OD}_{600} \)) of 0.15 in the appropriate medium from an overnight saturated culture, and allowed to grow to an \( \text{OD}_{600} \) of 0.5 in a 10 ml volume for each experiment. At this point the culture was divided into two halves and cells were diluted in an equal volume of either control or MMS containing medium and allowed to grow for another hour. At this time point both broad cell-cycle categories are still represented in the population. The final MMS concentration was 0.02% like in previous works (36). For FISH experiments, cells were fixed for 45 minutes by direct addition of formaldehyde to a final concentration of 4%. Cells were then washed twice in Buffer B (1.2 M sorbitol, 100 mM potassium phosphate in nuclease-free water), spheroplasted in Buffer B with 100 mU/\( \mu \)l Lyticase, 0.06 mg/ml phenylmethylsulfonyl fluoride (PMSF), 28 mM \( \beta \)-Mercaptoethanol, 10 mM Vanadyl Ribonucleoside Complex (VRC, New England Biolabs (Ipswich, MA)) at 30°C, and washed twice again in Buffer B. The cells were then resuspended in 70% Ethanol and left overnight at 4°C. The cells were then resuspended for 5 minutes in wash buffer (2X SSC, 25% Formamide in nuclease free water) and resuspended in hybridization buffer (10 mM VRC, 1mg/ml BSA, 20X SSC, 0.5 mg/ml \textit{E.coli} tRNA, 0.5mg/ml ssDNA, 100mg/ml Dextran sulfate, 25% Formamide, 2X SSC, in nuclease-free water) with Alexa-568 labeled probes against the target mRNA. mRNA probes were obtained from Biosearch Technologies (Novato, CA). Hybridization was allowed proceed overnight at 30°C. The cells were then washed with wash buffer and stained for 30 minutes with 1\( \mu \)g/ml DAPI to stain the DNA. The cells were then washed and resuspended in 2X SSC and mounted in ProLong Gold Antifade reagent on cover-slides.

**mRNA probe design.** Each \textit{RNR} gene was targeted by 40 of 20-nucleotide long DNA oligo probes each with a 3’ Alexa 568 fluorophore. When designing probes we used bioinformatics to eliminate any probe which can potential cross-hybridize between genes like \textit{RNR1} and \textit{RNR3} which show large similarities (13) in nucleotide sequence (Supplementary Figure S1). The efficacy of this approach is apparent in the fact that control untreated asynchronous cells expectedly do not show any \textit{RNR3} expression, while a subpopulation of the same cells clearly stain for high numbers of \textit{RNR1} in keeping with the known large fluctuations of \textit{RNR1} expression in course of the normal cell cycle (15) (Figure 2B; Supplementary Figure S7). This indicates that \textit{RNR3} probes do not cross-hybridize with the ubiquitous \textit{RNR1} mRNA.

**Simultaneous detection of mRNA and protein.** mRNA FISH was performed as before, followed by immunofluorescence for proteins. All reagents were specifically made from nuclease-free materials, to avoid degradation of transcripts. We verified that largely same mRNA numbers were obtained when FISH was performed alone and when FISH was
performed with immunofluorescence (Supplementary Figure S2). Following mRNA FISH, subsequent steps were performed in the blocking solution made from nuclease-free materials. Cells were blocked in 1% BSA in PBS for 1 hour. Cells were stained with the primary antibodies at 1:1000 dilution for 3 hours, and then with the Alex-647-tagged secondary antibodies at 1:200 dilution for 1.5 hours following an earlier work (36). Cells were washed in 2X SSC and mounted in ProLong Gold Antifade reagent on cover-slides. The H2A-S129p antibody was obtained from Upstate (Millipore, Billerica, MA). All the Rnr antibodies used have been used in a previous study that demonstrated the translocation of Rnr2 and Rnr4 from the nucleus to the cytoplasm upon DNA damage (36). Rnr3 staining is not expected in WT cells in the absence of DNA-damage. The weak basal staining we see in WT cells is comparable to that in a Δrnr3 strain (Supplementary Figure S3). However, with DNA-damage there is a clear induction of Rnr3 expression in WT cells. The Rnr4 antibody worked well in assays where the cells are processed for flow cytometry, and showed proper nuclear localization in the absence of damage. A detergent permeabilization is used in this case. However, in FISH experiments the permeabilization is in 70% ethanol, which can potentially affect the recognition of a protein by its antibody. In our experiments the nuclear to cytoplasmic contrast of Rnr4 was poor when we attempted the simultaneous detection of RNR4 mRNA and Rnr4 protein. An induction of the signal could still be detected. But because of the lack of proper nuclear localization of Rnr4 in untreated cells, we have left this result out.

Antibody stains for flow cytometry. Cells were grown and spheroplasted as before (except without VRC), permeabilized in 0.2% Tween-20 in Buffer B for 10 minutes, and blocked with 1% BSA in PBS for 1 hr. Antibody stains were then performed as above. Flow cytometry was performed on an Accuri C6 Flow Cytometer.

Image and Statistical analyses. Images were acquired on an Observer Z1 microscope (Carl Zeiss, Jena, Germany) with a Hamamatsu Orca-ER camera (Hamamatsu, Hamamatsu City, Japan). Z-stack images in all channels were obtained. For mRNA spot counting we used an algorithm developed in a previous work (28). This has been used to count mRNA numbers in yeast (37), and we too verified that this works in our case (Supplementary Figure S4). mRNA numbers were reproducible among different experiments, and the variation of the means did not reflect the large variation within the population (Supplementary Figure S5). For evaluating total protein intensity, the edge-detection was performed on the phase image to extract the cell contours, and the antibody stain intensity was evaluated within this mask. The cells have
intrinsic autofluorescence, though this is low in the far-red wavelengths used. The mounting medium also introduces a certain amount of background fluorescence. The effects of these two factors are subtracted out by estimating the mean fluorescence levels in similarly mounted effectively unstained samples treated with just the secondary antibody. This mean intensity is subtracted from the measured intensities. Effort was made to use isolated single cells in all cases. Representative images were processed with ImageJ while all image analysis was performed in Matlab (Mathworks, Natick, MA). Statistical tests and graph plots were performed with Matlab and OriginPro 8.5 (OriginLab, Northampton, MA).

RESULTS

We first used single mRNA molecule FISH to measure RNR transcripts in a cell-cycle specific manner. Cell-cycle stage was deduced from nucleus and cell images (Figure 2 and Supplementary Figure S6). In control undamaged cells we found a stark absence of RNR1 mRNA in nearly all budded cells, i.e. cells in S or G2, and only a subset of control unbudded G1 cells had large amounts of RNR1 mRNA (Figure 2, Supplementary Figure S7). These results are consistent with previous bulk northern blot studies showing large fluctuations of RNR1 mRNA in the course of the normal cell-cycle with transcript levels peaking in the late G1/early S phases(15), but the near total absence of RNR1 mRNA in budded cells was surprising. This indicates that RNR1 mRNA numbers drop precipitously as cells initiate DNA synthesis. Also consistent with bulk studies (13, 15, 19), RNR3 mRNA was entirely absent throughout the cell-cycle in undamaged log-phase cells and the cell-cycle dependent differences RNR2 and RNR4 transcript numbers were relatively small, though significant for RNR4 (Figure 2B).

In contrast, cells damaged with the alkylating agent MMS for 1 hour exhibited clear induction of all four RNR mRNAs. RNR1 mRNA was highly induced from near absence in S/G2 cells, and for all RNR genes cell-cycle-dependent differences in mRNA numbers that were negligible in control cells became pronounced upon damage (Figure 2B). Thus, overall RNR transcriptional inductions observed upon DNA-damage in bulk studies are not mere amplifications of relative distributions of mRNA numbers across the cell-cycle in control untreated cells. Remarkably, G1 mRNA numbers were largely comparable between control and damaged cells for all three normal cell-cycle RNR genes (RNR1, RNR2, RNR4), whereas S/G2 numbers were significantly different (Figure 2C). This was unexpected as in previous work, under conditions of DNA damage, cells exhibited induction of RNR1, RNR2 and RNR3 mRNA in α-factor arrested G1
cells with northern blot measurements (14, 15), leading to the conclusion that $RNR$ gene induction is independent of the cell-cycle. And while a clear induction was seen, it should be noted that even in these studies the induction of $RNR2$ and $RNR3$ was lower in $\alpha$-factor arrested cells compared to asynchronous cells. We investigated this discrepancy by using the same $S.\ cer\textit{evisiae}$ strain and conditions used in the previous studies, and found that the perceived induction was likely due to a small subpopulation of budded S/G2 cells that escape arrest; this subpopulation had an overwhelming $RNR$ response to DNA-damage greatly biasing the mean (Supplementary Figure S8). Importantly 'shmooed' G1 cells showed no significant $RNR2$ induction. Also it is possible that $\alpha$-factor arrested cells activate DNA-damage checkpoints differently from G1 cells in asynchronous cultures. This underscores the importance of studying cells in a normal asynchronous cycling population versus under $\alpha$-factor arrest, and also the importance of single-cell response studies as opposed to bulk cell responses. Cell-cycle dependent responses in the previous studies were performed with alklylation damage by MMS, though other forms of genotoxic stress were also shown to induce $RNR$ expression. It can be expected that the $RNR$ response in the cell-cycle would be different for other forms of lesions like double-strand breaks (DSBs) or those caused by ultraviolet (UV) radiation. We tested this possibility for damage by the UV-mimetic agent 4-NQO and the radio-mimetic DSB causing agent bleomycin in terms of the transcriptional responses of the large-subunit (R1) gene $RNR1$ and the small-subunit (R2) gene $RNR2$. For both these agents we found that the transcriptional induction response was much larger in S/G2 cells than G1 cells. The induction of $RNR2$ in G1 was significant, but still much smaller than that in S/G2 cells (Supplementary Figure S9). Thus the cell-cycle dependent induction of $RNR$ genes seems to be a general feature of at least three different forms of genotoxic stress. $RNR$ induction when present is severely abrogated in G1 cells in asynchronous cultures.

Next, we determined whether the protein induction correlates with transcript induction, and how transcript induction relates to protein localization. We detected endogenous $RNR$ mRNA and Rnr protein in the same cells by FISH and antibody staining respectively. Rnr protein levels showed significant induction in S/G2 cells upon damage (Figure 3A). By staining mRNA in the same cells we were able to correlate $RNR1$, $RNR2$ and $RNR3$ gene products on a cell-by-cell basis (Figure 3B). Fluctuations in mRNA in the normal cell-cycle may not reflect in protein levels. But under conditions of stress, cell-cycle dependent induction of both transcript and protein were observed. Whereas levels were heterogeneous across individual cells, clear induction of mean-levels over cells was seen for both mRNA and protein. Unfortunately the
Rnr4 antibody did not work in the assay for simultaneous detection of mRNA and protein, and this is discussed in the Materials and Methods section.

In addition to R1 (Rnr1 and Rnr3) levels, active RNR enzyme numbers are regulated by the nuclear to cytoplasmic translocation of the R2 proteins (Rnr2 and Rnr4) upon DNA-damage (19, 36) (Figure 1) and Sml1-mediated inhibition of the RNR enzyme (39, 41). There was no obvious relation between Nuclear to Cytoplasmic Ratio (NCR) of Rnr2 and the number of RNR2 transcripts in control cells. But after one-hour of DNA-damage we observed that the cells that still had nuclear Rnr2 were typically in G1, and that these cells had low RNR2 transcripts. In contrast S/G2 cells exhibited clearly homogeneous or cytosolic Rnr2 and high numbers of RNR2 transcripts (Figure 4). While it is known that the Mec1-Rad53 pathway controls both the transcriptional induction of the RNR genes (20, 35) and the subcellular relocalization of Rnr2-Rnr4 (23), we show here that both of these responses are cell-cycle-dependent in asynchronous cell populations. In previous studies no nuclear to cytoplasmic translocation of Rnr2 or Rnr4 was observed in α-factor arrested G1 cells, and this was attributed to a possible lower activation of the Mec1-Rad53 pathway in these cells (36). However, recent research has demonstrated that the Mec1 kinase can be activated throughout the cell-cycle by two independent mechanisms dependent on the 9-1-1 complex and DNA polymerase ε (27). This study used the DNA-damage-dependent phosphorylation of the yeast histone H2A at Serine 129 (H2A-S129p) as a direct readout of Mec1 kinase activity (27). Hence we next adapted our approach of simultaneous detection of protein and mRNA to determine whether Mec1 kinase activity varies in the cell-cycle in a manner similar to the RNR transcriptional response.

Both asynchronous and α-factor arrested cells showed similar relative inductions H2A-S129p upon DNA-damage in terms of the mean response (Supplementary Figure S10). When we performed simultaneous detection of RNR2 mRNA and H2A-S129p in the same cells in an asynchronous population, we found an expected correlation between Mec1 kinase activity and RNR2 induction upon DNA-damage (Figure 5). However, both responses were cell-cycle dependent, and S/G2 cells clearly separated from G1 cells upon damage. The means show similar trends for both RNR2 and H2A-S129p induction, the few G1 cells that showed high H2A-S129p staining also generally had higher RNR2 mRNA. Thus, in response to MMS-damage G1 cells display much lower Mec1 kinase activity compared to S/G2 cells. While lower RNR2 expression in G1 cells was expected, the corresponding lower Mec1 kinase activity was somewhat surprising because a previous study has shown that Mec1 can be activated
throughout the cell-cycle (27), and we too detected Mec1 activity in α-factor arrested cells (Supplementary Figure S10). Future work will explore if this is a peculiarity of the damage caused by MMS, or if the 9-1-1 dependent pathway operating in G1 is less efficient at activating Mec1 than the Pol ε dependent pathway which operates in the S-phase in conjunction to 9-1-1 (27).

Finally, a core strength of investigating single-cell responses is that forms of the underlying distributions across cell populations can be assessed in addition to the means. The RNR2 mRNA distributions appeared bi-modal when cell cycle stage was ignored, but the two peaks resolved into two overlapping uni-modal distributions when cells were classified according to cell cycle. The two peaks were not as well-resolved in the RNR4 data. Single-cell level variability or ‘noise’ in RNR mRNA expression generally increased upon DNA damage, with the large subunits exhibiting greater variability in comparison with the small subunits (Figure 6) when resolved according to the cell-cycle stage. Fano factors (\(\sigma^2/\mu\) - variance by mean of the distributions) quantify this noise, and a Poissonian distribution has a Fano factor of 1 as expected for mRNA production with constant probability in time (29, 32). ‘Transcriptional bursting’ can however result in larger variability within the population and consequently higher Fano factors (29). Control, untreated mRNA distributions for all RNRs exhibited Fano factors greater than 1, indicative of noisy, non-Poissonian transcriptional processes (29, 32). While expression noise generally increased upon induction by DNA damage for most of the RNRs when parsed according to the cell-cycle, the assumption of a steady-state that is required to mechanistically interpret these distributions is not satisfied due to the transient nature of the DNA-damage response. Similar Fano factors cannot be calculated for the protein distributions as absolute numbers are not measured (29), but these exhibit different forms from the mRNA distributions (Supplementary Figure S11).

DISCUSSION

The principal conclusion of this work is that the RNR response to DNA damage does not operate similarly across the cell cycle at either the transcript or the protein level. We also show that these responses correlate even at the single-cell level with each other and with Mec1 kinase activity across the cell-cycle. Control of Rnr protein level and localization in turn regulates RNR enzyme numbers and implies that the dNTP synthesis potential of cell subpopulations varies according to cell-cycle stage under conditions of genotoxic stress. Such
fine-tuning of dNTP levels may possibly minimize spontaneous mutations within the population. Our results concur with a previous study showing that dNTP levels are low in G1 and high in S phase, and that constitutively high dNTP levels transiently arrest cells in late G1 and inhibit the DNA-damage checkpoint (11). It is not well understood why dNTP levels should necessarily be low in G1. Lesion bypass by DNA polymerases has been shown to be dependent on dNTP concentrations (30). In an in vitro assay, the replicative DNA polymerase ε could not bypass 4-NQO induced 8-oxoG lesions at normal S-phase concentrations of dNTP, but could bypass it when the concentrations were comparable to the DNA-damage induced state (30). Another independent line of evidence has demonstrated abundant incorporation of ribonucleotides into DNA by yeast replicative polymerases that if left unrepaired can block Pol ε (24). This in turn may activate the Mec1-Rad53 pathway (27) and the downstream RNR transcriptional response (20, 35). Given the large molar excess of rNTPs over dNTPs in cells (24), upregulating dNTP production may reduce rNTP misincorporation into DNA. However, it is well known that while dNTPs are essential for responding to genotoxic stress, high dNTP levels are mutagenic and the RNR enzyme is subject to dATP feedback inhibition (10). The Mec1-Rad53-Dun1 target SmI1 too regulates the activity of the RNR enzyme (39, 41). Thus cells have evolved a number of mechanisms for regulating dNTP concentrations by controlling the levels, localization and activation state of the RNR enzyme components. Our work shows that the observed low dNTP levels in G1 can, at least in part, be due to low absolute numbers of the active enzyme in this cell-cycle stage.

Expressions of RNR2, RNR3 and RNR4 genes are controlled by the transcriptional repressor Crt1, while RNR1 is under the regulation of the activator Ixr1 through a Dun1 independent branch of the Mec1-Rad53 pathway (20, 35). The resultant highly heterogeneous mRNA distributions are consistent with models of transcriptional bursting of the RNR genes (29). Unlike mammalian cells, only a small subset of yeast genes are thought to undergo bursting, and promoter regions in these genes are enriched in TATA elements (38). Only 20% of yeast genes have TATA boxes in their promoters, and these are also enriched in stress related genes (3, 4), which have been shown to exhibit particularly noisy expression (3). The RNR genes also have TATA regulatory elements in their promoters (4, 33), supporting the observed non-Poissonian nature of RNR transcription under control conditions. Functional consequences of this variability in expression may be important to ensure survival of subpopulations of cells under challenging environmental conditions (1, 29). Future work will explore how the heterogeneity in RNR expression promotes cell survival.
In the broader context of gene expression, a previous study that explored simultaneous
detection of YFP-tagged *E. coli* proteins and the transcripts that encoded them, found little
correlation between the levels of these two gene products (32). However, fluorescent protein
signals are severely attenuated in most fixation procedures and both mRNA numbers and
protein levels can be affected by the addition of tags. Further, mRNA-protein correlations under
conditions of stress have not been explored at the single cell level, as reported here in the
model eukaryote *S. cerevisiae*. The methods developed here for monitoring endogenous mRNA
and protein levels simultaneously offers important insight into RNR enzyme regulation in
eukaryotes, showing clear cell-cycle-dependent partitioning of the RNR response both in terms
of the mRNA and protein induction, and the subcellular trafficking of Rnr subunits. RNR genes
are overexpressed in many cancers (7, 8, 21). This work establishes an experimental platform
for subsequent studies on the effects of DNA damage in metazoan cells that may serve to
investigate the development and progression of cancer, which requires understanding the
misregulation of expression patterns at the single-cell level that result in disease phenotype.

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Figure 1. *S. cerevisiae* RNR enzyme response to damage. (A) The functional RNR holoenzyme consists of a large and a small subunit, in almost all eukaryotes from yeast to humans. The form of the enzyme can be more complex than $\alpha_2\beta_2$. Levels of all Rnr proteins go up, and Rnr2-Rnr4 translocate to the cytoplasm upon DNA-damage in *S. cerevisiae*. (B) The cytosolic Rnr1 and Rnr3 proteins constitute the large subunit, R1 and the Rnr2 and Rnr4 proteins constitute the small subunit (R2). The active form of the small subunit is an Rnr2-Rnr4 heterodimer ($\beta\beta'$), which normally resides in the nucleus but relocalizes to the cytoplasm upon DNA-damage. Rnr3 is not expressed in the absence of DNA-damage.
Figure 2. RNR mRNA induction depends on cell-cycle stage. (A) A typical single-molecule mRNA FISH experiment is shown. RNR4 mRNA transcripts are targeted with Alexa 568-labeled DNA oligo probes. DAPI stained DNA and phase-contrast images are also acquired to judge cell-cycle stage. The scale-bar shown is 2 μm. Z-projected images for the mRNA and DNA are shown. (B) Mean-numbers computed from mRNA distribution histograms for approximately 90-120 such cells are plotted for RNR1, RNR2, RNR3 and RNR4 mRNA for control cells and under conditions of DNA-damage by treatment with 0.02% MMS for 1 hour. Blue bars indicate unbudded G1 cells while red bars denote budded S/G2 cells. While absolute numbers of RNR1 mRNA is lower than RNR2 and RNR4 in untreated cells, the relative fluctuation is greatest for RNR1 due to the near-complete absence in budded cells (see also Figure 6 for RNR1 mRNA distributions). The relative distributions shift unexpectedly upon DNA-damage. (C) The same data as (B) parsed according to the cell-cycle stage to compare mRNA numbers in one cell-cycle stage between control and damaged cells. Light-hatched bars denote control cells while dense-hatched bars denote damaged cells. In all cases the error-bars are standard errors. ** indicates p<10^-3 in a Kolmogorov-Smirnov test (a non-parametric test is preferable given the non-normal nature of some of the mRNA distributions).
Figure 3. RNR transcript numbers show a cell-cycle dependent relation to protein levels and localization upon DNA damage. (A) Mean Rnr protein intensities with standard errors and (B) mRNA numbers and protein intensities on a cell-by-cell basis are plotted for Rnr1 (N=71 cells), Rnr2 (N=57 cells) and Rnr3 (N=64 cells). Equal numbers of cells were considered for the control and DNA-damage (1 hr) samples. The staining for Rnr3 in the absence of damage was non-specific. In every graph blue squares or bars indicate G1 cells while red circles or bars indicate S/G2 cells. Note while S/G2 cells have little or no RNR1 mRNA (like Figure 2) compared to G1 cells, the protein levels are similar in untreated control cells. A clear separation of G1 and S/G2 cells in MMS treated samples was observed. '*' indicates $p<10^{-3}$ in a Kolmogorov-Smirnov test.
Figure 4. RNR2 transcript numbers show a cell-cycle dependent relation to Rnr2 protein localization upon DNA damage. (A) In the control population RNR2 mRNA number in cells are uncorrelated with the nuclear to cytoplasmic ratio of Rnr2 and there is no obvious segregation in the cell-cycle. However, upon DNA-damage the S/G2 cells show a higher accumulation of Rnr2 in the cytoplasm and higher induction of RNR2 mRNA (N=53 cells each). (B) A typical image is shown for the small-subunit Rnr2 upon DNA-damage. Rnr2 is normally nuclear-localized in control cells. At the one-hour time-point there are still cells with nuclear Rnr2. The G1 cells with nuclear Rnr2 have fewer RNR2 transcripts, while the S/G2 cell shows visibly larger RNR2 expression and a homogenous distribution of the Rnr2 protein. The scale-bar shown is 2 μm. Z-projected images for the DNA, mRNA and protein are shown. The cell-cycle stages are indicated.
Figure 5. RNR2 induction correlates with variable Mec1 kinase activity in the cell-cycle.

(A) Two typical cells from an MMS-treated sample are shown. Note the higher H2A-S129p staining, indicative of Mec1 kinase activity, in the budded cell correlates with higher RNR2 mRNA numbers. The scale-bar shown is 2 μm. In the merged image, DNA is in blue, H2A-S129p in green, RNR2 mRNA in red and the phase image is grey. (B) RNR2 mRNA numbers are plotted against H2A-S129p stain intensity in control untreated cells and MMS-treated cells (N=85 cells each). The Pearson's r value for the untreated sample is 0.16 while it is 0.6 with DNA-damage. The H2A-S129p stain intensity is normalized by the DNA-intensity evaluated in the same nuclear mask to ensure that the differential response between G1 and S/G2 cells is not merely a function of DNA synthesis. (C) The mean values for the H2A-S129p stain intensity and RNR2 mRNA from the graphs in (B). '*' indicates p<10^{-3} in a Kolmogorov-Smirnov test.
Figure 6. mRNA histograms capture heterogeneity within the cell population. mRNA histograms and corresponding Fano factors for the studied RNR genes for (A) all cells (B) G1 cells (C) S/G2 cells. White bars denote control cells while black bars denote damaged cells. When expressed all RNR genes have Fano factors greater than 1, indicating non-Poissonian transcription processes. Note the higher Fano factors for damaged cells generally when parsed according to the cell-cycle, though this is within error-bars for RNR1 in G1. Also when they are expressed, R1 genes have higher Fano factors than R2 genes. The error-bars of the Fano factors are standard deviations obtained by bootstrapping from the distributions on the left.
A

Control

DNA-damage

# RNR2 mRNA vs Rnr2 Nuc/Cyt Ratio

B

Rnr2 protein

RNR2 mRNA

DNA

Phase contrast

G1

S/G2