

Systems approaches identify the consequences of monosomy in somatic human cells

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Abstract

Chromosome loss that results in monosomy is detrimental to viability, yet, it is frequently observed in cancers. How cancers survive with monosomy is unknown. Using p53 deficient monosomic cell lines, we found that chromosome loss impairs proliferation and genomic stability. Transcriptome and proteome analysis revealed a partial compensation of the gene dosage changes that mitigates the effects of chromosome loss. Monosomy triggers global gene expression changes that differ from the effects of trisomy. We show that ribosome biogenesis and translation were commonly downregulated in monosomic cells, likely due to haploinsufficiency of ribosomal genes. The ensuing ribosome biogenesis stress triggers the p53 pathway and G1 arrest when *TP53* is reintroduced into monosomic cells. Accordingly, impaired ribosome biogenesis and p53 inactivation are associated with monosomy in cancer. Our first systematic study of monosomy in human cells explains why monosomy is so detrimental and how loss of p53 enables its incidence in cancer.

Keywords

Aneuploidy, Cancer, Gene dosage, Haploinsufficiency, Monosomy, Ribosome, *TP53*, Translation

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Introduction. Human cells contain two sets of homologous chromosome and maintaining this diploid chromosomal content is essential for their survival and proliferation. Errors in chromosome segregation that lead to a gain or a loss of chromosomes, so called whole chromosomal aneuploidy, are poorly tolerated in humans (1). Most cells arrest or die soon after chromosome missegregation and the aneuploid cells that escape this fate do not proliferate as efficiently as the diploid counterparts (2–5). The low fitness of aneuploid cells is well documented by the fact that non-diploid karyotype is among the main causes of spontaneous abortions (1). Most of our knowledge on the consequences of aneuploidy has been obtained by analysis of cells with extra chromosomes. Gain of even a single chromosome leads to marked physiological changes independent of the identity of the extra chromosomes in various species from yeasts to human cell lines (6, 7).

Much less is known about consequences of chromosome losses, or monosomy, mainly due to the lack of a defined model system and its detrimental effect on proliferation and viability. Murine monosomic embryos die significantly earlier than trisomic ones (8) and studies from *in-vitro* fertilized human monosomic embryos indicate that monosomy drastically impairs their viability and implantation potential (9, 10). Only rare partial monosomies or micro-deletions are viable, but with severe pathological consequences (11). This detrimental phenotypes is likely due to haploinsufficiency of some genes as well as due to unmasking of recessive mutations (12–14).

Monosomy of X chromosome is also lethal and the small percentage of embryos that survive suffer from severe pathological consequences (so called Turner syndrome) (15).

On the other hand, loss of an entire chromosome or its arm occurs in a substantial fraction of cancer types and associates strongly with hematopoietic cancers (16). Recurrent whole chromosome or arm level deletions are frequent in specific tumors, such as 1p deletion in neuroblastoma, 3p deletion in lung cancer or loss of 7, or 7q, in myeloid malignancies (16, 17), suggesting an important role of chromosome losses in cancer pathogenesis. It has been proposed that chromosome loss may instigate cancer initiation due to haploinsufficiency of tumor suppressor genes. For example, frequent chromosome 17p deletion in a broad spectra of tumors is attributed to loss of *TP53* tumor suppressor gene. However, modelling 17p loss in mice identified several other tumor suppressor genes that cooperate to generate more aggressive tumors (18).

In this study, using monosomic cells derived from the human immortalized hTERT- RPE1 lacking *TP53*, we analyzed the impact of monosomy on proliferation, genomic stability and how chromosome loss shapes the global transcriptome and proteome using multi-omics approaches. Strikingly, we show a consistent reduction of cytoplasmic ribosomal proteins and impaired protein translation in all monosomic cell lines. Reintroduction of *TP53* to monosomies further impaired their proliferation due to p53 pathway activation. Analysis of The Cancer Genome Atlas (TCGA) and Cancer Cell Lines Ency-

lopedia (CCLE) databases reveals a strong association of monosomy with p53 inactivation and ribosomal pathway impairment. Our first systematic analysis provides novel insights into the consequences of chromosome loss in somatic human cells.

Results

Monosomy impairs cell proliferation and leads to genomic instability. To study the consequences of monosomy in human cells, we analyzed monosomic cell lines derived from RPE1, a human hTERT-immortalized, retinal pigment epithelial cell line. The used monosomic cell lines arose from a chromosome missegregation in cells lacking p53 due to *TP53* deletion by CRISPR-Cas9 or by TALEN (see Methods for details), or due to expression of shRNA against *TP53* (2) (Fig. 1a). The chromosome losses were identified by whole genome sequencing of single-cell derived clones (Fig. 1b, (2)) and chromosomal painting further validated the karyotypes (Fig. 1c, Table S1). The monosomic cell lines were named **RPE1-derived Monosomy (RM)**, followed by the number of the monosomic chromosome, i.e. RM 13 for monosomy 13; cell lines with the shRNA mediated knock-down of p53 are additionally labeled with KD (i.e. RM KD 13, Fig. 1a, Table S1). Some monosomic cell lines showed variable partial or mosaic chromosome gains or losses, e.g. a gain of 22q in RM13 (Fig. 1b). These small chromosomal changes occurred likely due to the increased genomic instability of monosomic cells (see below) and the relaxed checkpoint control owing to the p53 loss (2, 3).

All monosomic cells proliferated slower than the respective parental diploids and this defect correlated with the number of open reading frames present on respective monosome (Fig. 1d, S1a). While parental RPE1 cells do not form colonies on soft agar, Deletion of *TP53* increased the cellular capacity of anchorage independent growth in RPE1 cell line. The monosomic p53 deficient cells formed significantly less colonies than the diploid parents (Fig. 1e). Notably, the loss of chromosome X from RPE1 impaired proliferation similarly as the loss of an autosome. In XX cells, one copy of the chromosome X is transcriptionally inactivated by XIST-mediated silencing, but there are approximately 100 – 130 genes located on chromosome X known to escape the X-inactivation (19). Our observation therefore suggests that the loss of these few escapees is sufficient to impair cellular proliferation.

Cell cycle profiling by flow cytometry showed no uniform changes in cell cycle distribution in monosomic cell lines (Fig. S1b). Strikingly, five out of seven monosomic cell lines suffered from significantly more mitotic errors than the parental cells, as manifested by the occurrence of lagging chromosomes and micronuclei (Fig. 2a, b). Approximately 20% of the micronuclei stained positively for centromere (CENP+), suggesting that only a small fraction contained whole missegregated chromosome; rather the micronuclei enclosed a chromosome fragment. The fraction of CENP+ micronuclei was similar in diploids and monosomic cell lines (Fig. S1c). Accordingly, the time from nuclear envelope break down till anaphase increased on average from 28 in diploids to 38 min in monosomic cells with exception of RM (Fig.2c). This finding also suggests that the spindle assembly checkpoint remains intact in monosomies. Significantly elevated occurrence of chromatin bridges, which form during anaphase

due to under-replicated or incorrectly repaired DNA, was observed in three out of four monosomic cell lines lacking *TP53*; RMX and the p53 KD showed no significant changes (Fig. 2d, S1d). Three out of four analyzed monosomic cell lines lacking *TP53* showed an accumulation of γH2AX foci that mark the double strand breaks (Fig. 2e, f). However, the DNA damage response was not activated, and the replication proteins were expressed at normal levels, as documented by immunoblotting of Chk1, pChk1 S345, RPA32, pRPA32 S4/S8, MCM2 and MCM7 (Figure S1f-i). Importantly, genomic and chromosomal stability was not impaired by the loss of chromosome X.

Chromosome gains cause increased proteotoxic stress in eukaryotic cells, manifested by impaired protein folding and increased sensitivity to inhibitors of protein folding and autophagy (17-AAG and chloroquine, respectively), as well as by increased autophagic and proteasomal activity (20–23). In contrast, the sensitivity to 17-AAG was not significantly altered in monosomic cells and the expression of heat shock and autophagy proteins was not uniformly deregulated (Fig. S2a-e). Taken together, a loss of single chromosome leads to proliferation defects and to heterogeneous changes in maintenance of genomic instability, but does not trigger replication defects and proteotoxic stress, implying that the affected molecular processes do not parallel the previously identified effects of chromosome gains.

Gene expression changes caused by monosomy are buffered at both mRNA and protein levels. To obtain a global view of the expression changes induced by chromosome loss, we performed transcriptome and proteome analyses of monosomic cell lines RM10;18, RM13, RM19p and RMX. The obtained transcripts were normalized to the parental control cell line and visualized as the \log_2 fold changes (FC) according to the chromosome positions (Fig. 3a, S3a, c, e). In the next step, we analyzed the proteome changes in monosomic cells. To this end, we used Tandem Mass Tag (TMT) labeling-based multiplexed quantitative proteomics to quantify the \log_2 FC compared to the parental cell line. The obtained values were normalized to the parental control cell lines and visualizes as the \log_2 fold changes, similarly as the transcriptome data (Fig. 3b, S3b, d, f; Table S2). The TMT labelling strategy suffers from ratio compression (24), which means that the quantified fold changes are often smaller than the real values. Therefore, we also performed a label free protein quantification (LFQ). Comparison of LFQ data with TMT data revealed a high correlation between the values obtained with these different approach (Fig. S4a, b), but a lower coverage of identified proteins was achieved with LFQ. Therefore, we used the TMT-determined values for the subsequent analysis.

The proteome analysis revealed, similarly as the transcriptome analysis, a reduced abundance of proteins encoded on the monosomes (Fig. 3a, b, S3a-f). To elucidate whether the gene expression scales linearly with the gene copy number, we analyzed all genes for which both transcript and protein values were quantified (Table S2). We compared the distribution of mRNA and protein \log_2 FC for genes encoded on the monosomic and disomic chromosomes in individual cell lines. If all genes on monosomic chromosome were expressed according to their DNA copy number at 50%, then the median of \log_2 FC should be -1. However, analysis of RNA-seq data showed that the abundance of mRNA encoded on the monosomes (chromosomes

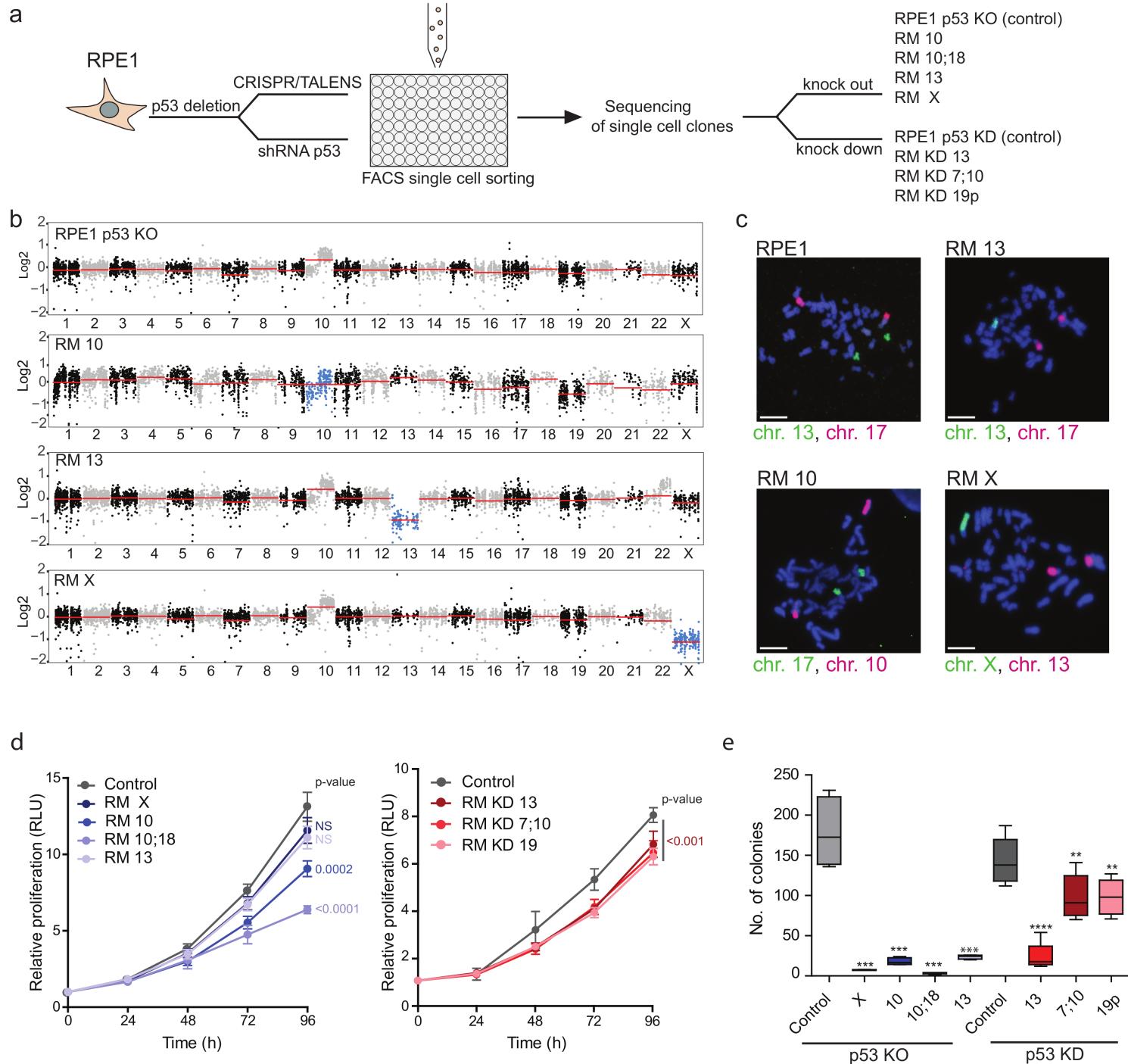


Figure 1. Chromosome loss in p53 deficient cells reduces proliferation and anchorage independent growth on soft agar. (a) Schematic depiction of the construction of monosomic cells. p53 was mutated or depleted in RPE1-hTERT cell line via CRISPR/Cas9, TALENS, or shRNA expression. Clones arising from single cells were subjected to whole genome sequencing and monosomic clones were selected to be used in further experiments. (b) Read depth plots of all chromosomes in control and RM samples. Chromosome losses are marked in blue. Red lines indicate the copy number of each individual chromosome. Note that the parental RPE1 contains an extra copy of 10q that is preserved in all monosomic derivatives. (c) Chromosomal paints of monosomic cell lines. The painted chromosomes are indicated with respective colors. Scale bar – 10 μ m. (d) Proliferation curves of monosomic cell lines in comparison to respective diploid controls. All the values are normalized to day 0. Each point represents the mean \pm SEM from at least 3 independent experiments. RLU-relative luminescence unit. (d) Proliferation curves of monosomic cell lines in comparison to respective diploid controls. All the values are normalized to day 0. Each point represents the mean \pm SEM from at least 3 independent experiments. RLU-relative luminescence unit. p-value was calculated using linear regression and shown in the plots. (d) Quantification of number of colonies growing on soft agar. Box and whiskers plot shows the mean, highest and lowest value of at least 4 independent experiments. T-test; ** \leq 0.002 ; *** \leq 0.0002, **** \leq 0.0001.

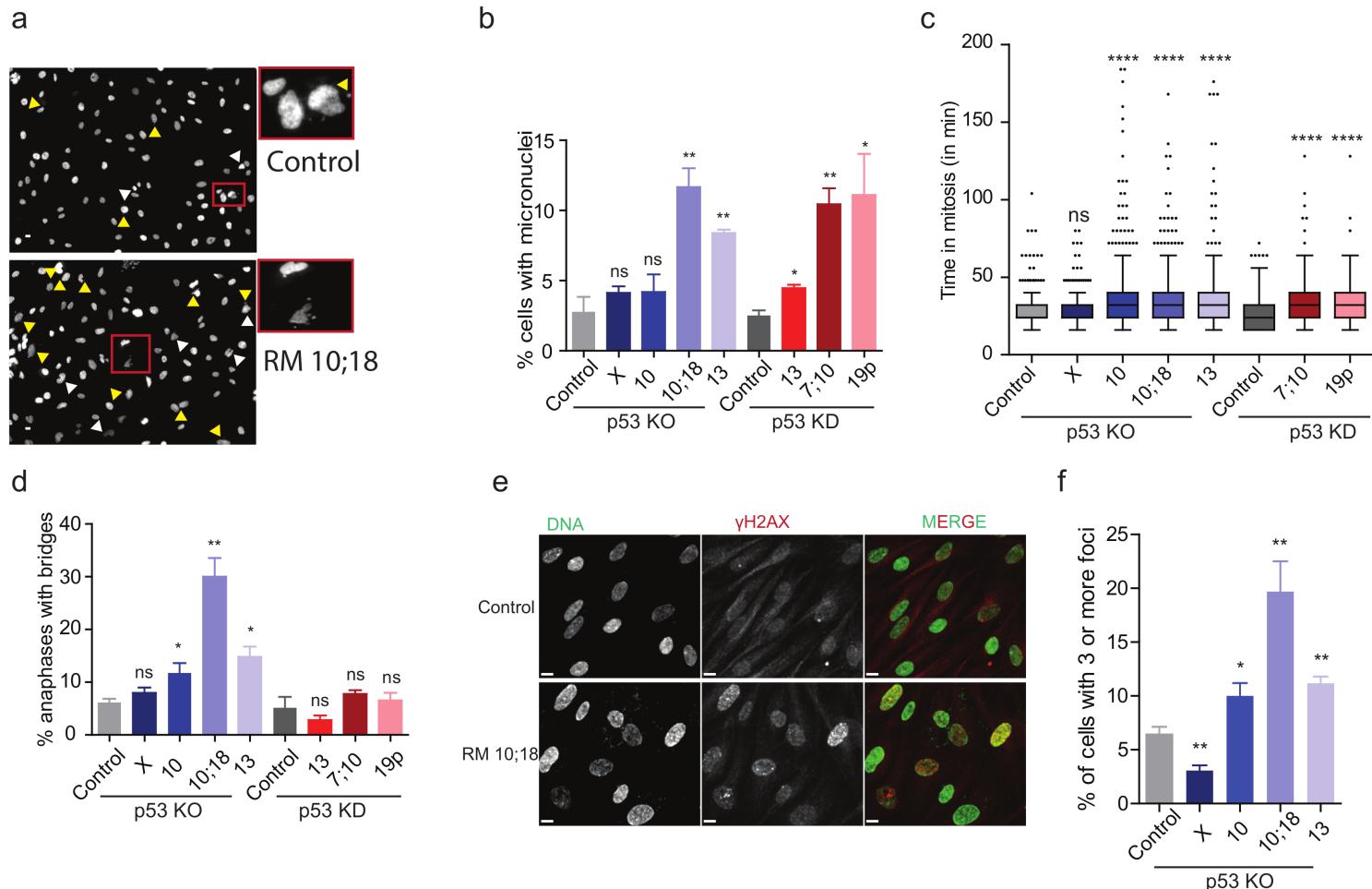


Figure 2. Genomic instability is increased in monosomic cell lines. (a) Representative images cells with micronuclei and nuclei structure abnormalities. Inset shows the enlarged field (white arrowhead – nuclear abnormalities, yellow arrowhead - micronuclei). Scale bar – 10 μ m. **(b)** Percentage of cells with micronuclei. Bar graphs display mean \pm SEM of at least 3 independent experiments. T-test; ns-not significant, * \leq 0.05; ** \leq 0.002. **(c)** Quantification of time spent in mitosis. Time from nuclear envelope breakdown (NEBD) until the end of anaphase was measured. Box and whiskers plot shows the mean and the outliers. T-test; **** \leq 0.0001. **(d)** Percentage of anaphases with bridges. Bar graphs display mean \pm SEM of at least 3 independent experiments. T-test; ns-not significant, * \leq 0.05; ** \leq 0.002. At least 150 anaphases per cell line were counted in each independent experiment. **(e)** Representative images shows immunofluorescence staining of the DNA damage marker γ H2AX in control and RM10;18 cell lines. DNA is stained with sytox green (green) and γ H2AX(red). Scale bar- 10 μ m. **(f)** Quantification of percentage of cells with \geq 3 γ H2AX foci per cell. Bar graphs display mean \pm SEM of at least 3 independent experiments. T-test; * \leq 0.02; ** \leq 0.003.

13, 10;18 and 19p, respectively) did not decrease to the expected levels. Instead, the mRNA median of monosomic gene expression ranged from -0.5 to -0.75 (Fig. 3c, *upper panels, dotted line*, S4b, Table S3). The median of mRNA expression from X chromosome in RM X remains close to zero, as expected (Fig. 3c). The relative abundance of proteins encoded on monosomes was further increased (Fig. 3c, *upper panels, full line*, S4b, Table S3). The distribution of mRNA and protein abundances for genes encoded on disomes was comparable in all monosomic cells line (Fig. 3c, *lower panels*, S4b, Table S3). When we combined the expression values from all genes encoded on the monosomic chromosomes, excluding chr. X, the median of \log_2 FC of protein abundance was -0.25, while the median of all corresponding transcripts was -0.59, both values being significantly higher than the expected -1 (Fig. 3d). We assigned the monosomically encoded genes into four categories with a cut off

set at -0.5: down;down (both mRNA and protein \log_2 FC less than -0.5), up;down (mRNA $>$ -0.5, protein $<$ -0.5), down;up (RNA $<$ -0.5, protein $>$ -0.5) and up;up (both mRNA and protein more than -0.5). This showed that the expression of approximately 30% of the genes encoded on the monosomes were adjusted to diploid levels transcriptionally (up; up); additional 45% were adjusted posttranscriptionally (down;up) (Fig.3e). Consequently, less than 20% of monosomically encoded genes were expressed at a relative abundance lower than -0.5 \log_2 FC of the parental control. Of note, analysis of LFQ dataset provided comparable results (Fig. S4c, d). Together, our data suggest an existence of mechanisms that alleviate the effects of monosity on gene expression at both transcriptional and posttranscriptional level.

Previous work on trisomic human cells uncovered that the protein abundance of approximately 25% of proteins encoded on the trisomes

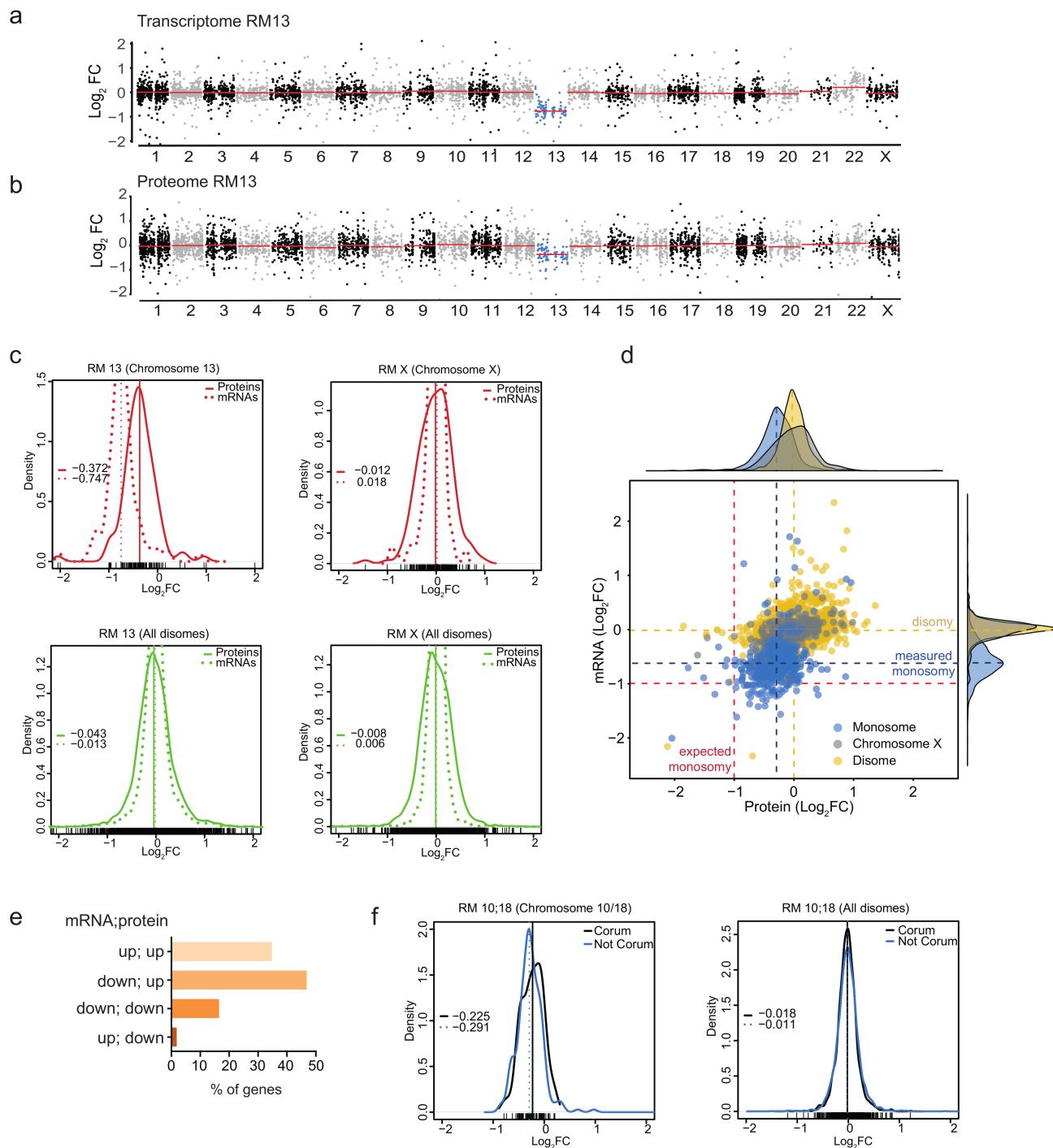
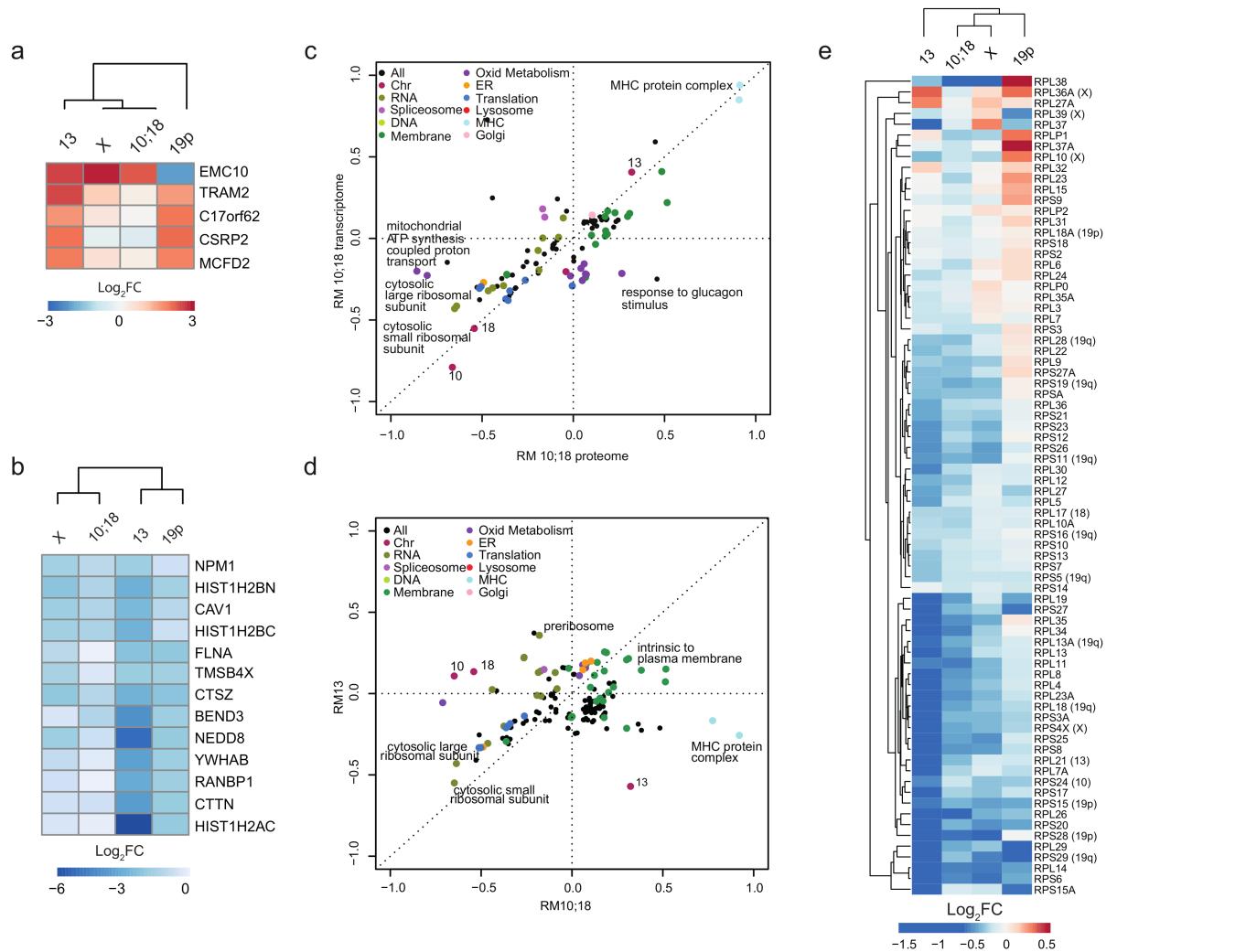


Figure 3. Expression of genes encoded on the monosomes is adjusted by transcriptional and posttranslational mechanisms. (a, b) The relative abundance of mRNAs and proteins of RM13 normalized to diploid isogenic parental control were plotted according to their chromosome location. The monosomic chromosome is marked in blue. Red line depicts the median for each chromosome. (c) Overlays of mRNA (dashed line) and protein (solid line) density histograms. Values of respective medians are plotted in the graph. Upper panels (in red) represent the monosomic chromosome; lower panel (green) display all other, disomic chromosomes. (d) Scatter plot showing the \log_2 fold change (FC) of mRNA and proteins encoded on monosomes (blue), disomes (yellow) and chromosome X (grey). The marginal density histograms show the distribution of respective mRNAs and proteins. The expected median fold change of monosomic genes is marked by red dashed lines. The measured median fold changes of monosomic and disomic genes is marked by blue and yellow dashed lines, respectively. (e) Bar plot shows the percentage of genes assigned to categories according to \log_2 FC with a cut off set to -0.5. up;up (both mRNA and protein more than -0.5), down;up (RNA<-0.5, protein>-0.5), down;down (both mRNA and protein \log_2 FC less than -0.5), up;down (mRNA>-0.5, protein<-0.5). (f) Density plots of subunit of macromolecular complexes as defined by CORUM database compared to non-CORUM proteins. Left panel displays the monosomic chromosome; the right panel shows the distribution for diploid chromosomes for RM 10;18. The median values are plotted in the graph.



was adjusted to closely match the disomic abundance and this was most strikingly prominent for proteins subunits of macromolecular complexes (25, 26). Comparison of the abundance of subunits of macromolecular complexes, as defined in the CORUM database, with the non-CORUM proteins revealed only a subtle shift towards diploid levels, suggesting that this mechanism is not important in monosomic cells (Fig. 3f, Table S3). There was no protein dosage adjustment of membrane proteins, cytosolic proteins or any other biological functions, cellular compartments or further categories as defined by Panther, GO or Perseus databases (PM, personal communication). Taken together, the effects of reduced gene copy numbers in monosomic cells are mitigated by both transcriptional and posttranscriptional mechanisms in human cells, but the mechanism remains to be investigated.

Genome-wide changes of gene expression in response to chromosome loss. We next analyzed the global gene expression changes in monosomic cells. Identification of proteins that were uniformly deregulated in response to monosomy revealed only five upregulated and 13 downregulated proteins with log₂FC greater than 1.5 or less than -1.5 folds and shared in at least two different monosomic cell lines (Fig. 4a, b, Table S2). Although the correlation between mRNA and protein abundance was rather modest (Fig. S5a), 2D annotation enrichment algorithm that identifies deregulated pathways (27) showed a similarity between transcriptome and proteome of individual monosomic cell lines (Fig. 4c, S5b-c, Table S4). Further comparison of proteome revealed that the individual monosomic cell lines deregulated mostly a unique set of pathways (Fig. 4d, S5d-e). For example, “MHC I and II protein complex” and “Interferon gamma mediated signaling” were upregulated in RM 10;18, but

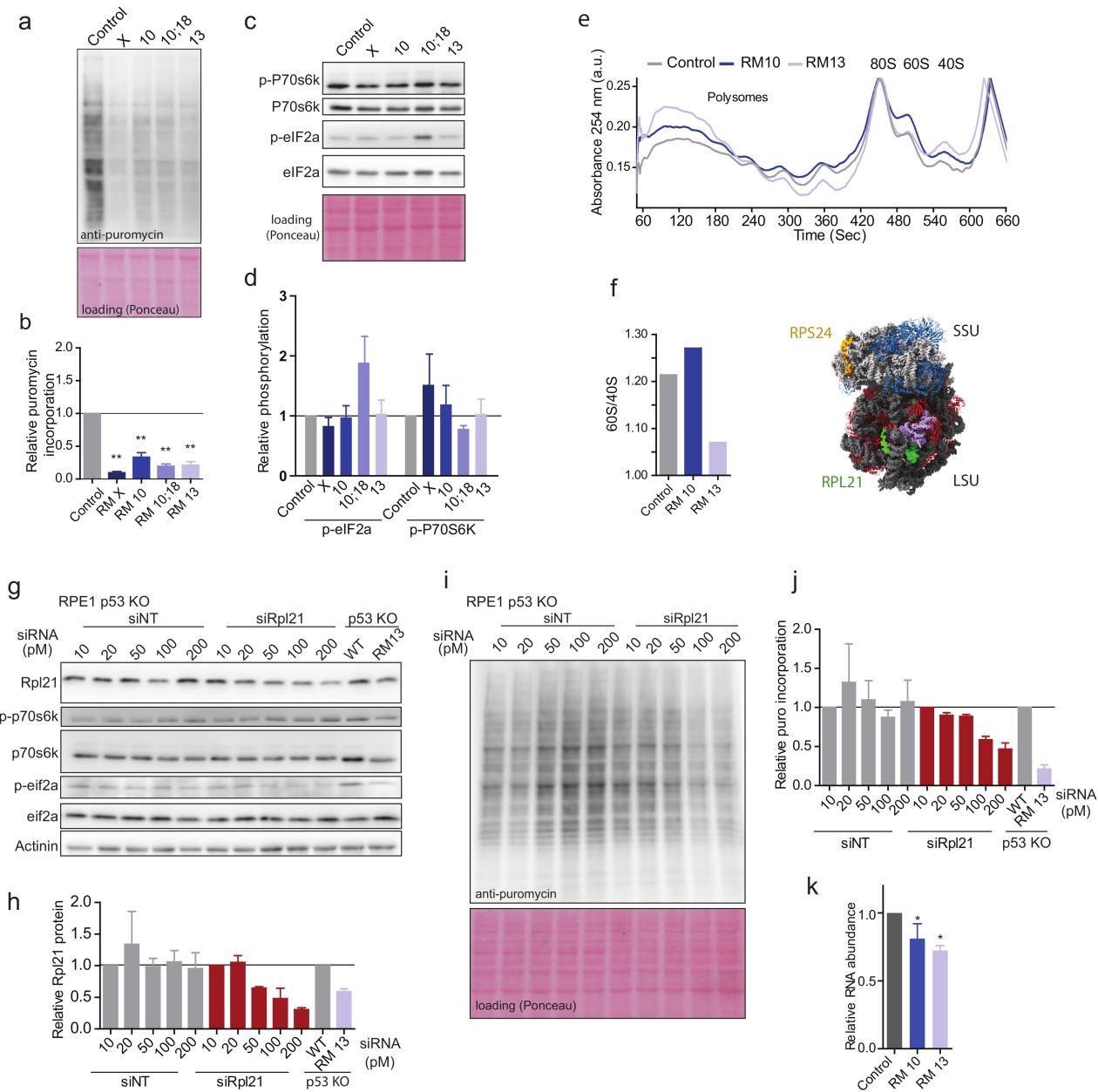


Figure 5. Ribosome and translation defects in monosomies. (a) Evaluation of protein synthesis rates in monosomies. Equal amounts of puromycin-labelled cell lysates were immunoblotted and analyzed using anti-puromycin antibody. Ponceau staining was used as a loading control. (b) Quantification of mean puromycin intensities from immunoblotting. The intensities were normalized to Ponceau staining. Bars display mean \pm SEM of at least three independent experiments. Non parametric t-test; $^* \leq 0.05$, $^{**} \leq 0.005$. (c) Immunoblotting of mTOR target p70S6K and phospho-p70S6K and the integrated stress response marker eIF2 α and phospho-eIF2 α . (d) Quantification of relative phosphorylation levels of P70S6K and eIF2 α normalized to total protein levels, respectively. Bar graphs display mean \pm SEM of at least 3 independent experiments. (e) Polysome profiles obtained from diploid and monosomic cell lines. Profiles are representative of at least two independent experiments. The profiles were adjusted to the 80S peak. (f) Quantification of 60S/40S ratio of the representative polysome profiles. Peak absorbance for 60S and 40S were used for the calculations. Ribosome model shows the location of RPS24 (yellow) and RPL21 (green) proteins within the small and large ribosome subunit, respectively. (g) siRNA mediated titrated knockdown of *RPL21* in RPE1 WT p53 KO cell line. siNT was used as a control; RPE1 p53 KO WT and RM 13 are shown as a non-transfected control. The western blots are representative of at least three independent experiments. (h) Quantification of *RPL21* knock down efficiency. siNT and siRPL21 values were normalized to respective 10 pm samples. Bars display the mean \pm SEM of at least 3 independent experiments. (i) The effect of siRNA mediated knockdown of *RPL21* on protein synthesis. Equal amounts of protein lysates from siNT and siRPL21 samples were immunoblotted against anti-puromycin antibody. Ponceau staining was used as a loading control. The western blots are representative of at least three independent experiments. (j) Quantification of translation rate after *RPL21* knockdown. siNT and siRPL21 values were normalized to respective 10 pm samples. Bars display the mean \pm SEM of at least 3 independent experiments. (k) Measurement of total RNA as a surrogate for rRNA levels and ribosome content. Bar graphs display the mean \pm SEM of at least 3 independent experiments. Non-parametric t-test; $^* \leq 0.03$.

downregulated in RM 13 (Fig. 4d, Table S4), which we confirmed by qPCR analysis (Fig. S6a, b). Similarly, “O-glycan processing” was upregulated in RM X, while down regulated in RM 10;18 (Fig. S5d, Table S4). Strikingly, one of the few uniform and consistent deregulation identified in all monosomic cell lines was the downregulation of cytosolic large and small ribosomal subunit and translation (Fig. 4d, e, S5d-e, Table S4). Therefore, we continued with a detailed analysis of ribosomal metabolism and translation changes in monosomic cells.

Ribosome biogenesis and translation is impaired in monosomic cells. To understand the impact of reduced translation and ribosome gene expression, we determined the translational activity by puromycin-incorporation assay in monosomies. In this assay, proliferating cells were treated with a short pulse of the antibiotic puromycin (15 min, 10 μ M) that is incorporated into nascent polypeptide chain. in Down syndrome mice models and Down syndrome patients' derived cell lines was attributed to integrated stress response (ISR) (28). Increased phosphorylation of eukaryotic initiation factor 2alpha (eIF2 α) is a marker for ISR. However, immunoblotting of p-eIF2 α showed no uniformly increased eIF2 α phosphorylation in monosomies (Fig. 5c, d). Thus, the decreased translational activity in monosomic cells does not occur due to reduced mTOR activity or activation of ISR.

To elucidate the nature of the translation defect in monosomic cells, we performed polysome profiling to determine the fraction of polysomes, monosomes (composed of one ribosome residing on an mRNA), as well as unassembled small (40S in eukaryotes, SSU) and large (60S in eukaryotes, LSU) ribosomal subunits. Strikingly, monosomic cell lines accumulated more individual ribosomal subunits than the parental diploid cell line and the ratio of unassembled large and small ribosomal subunits was changed (Fig. 5e, f). We observed a reduction of SSU and accumulation of LSU in RM 10 when compared to diploid control, which is consistent with *RPS24* (small ribosomal subunit protein 24) being the only RPG encoded on Chr.10 (Fig. 5e, f). In RM13 that encodes only LSU protein *RPL21*, we observed increased levels of free SSU. Interestingly, the monosomic cell lines appeared to contain more heavy polysomes than the parental control. While the increased polysome peak suggests increased ribosome numbers on mRNA, whether this is due to compensatory increase in the translation or caused by ribosome stalling leading to accumulation of multiple ribosomes on mRNA remains to be evaluated in future.

Each chromosome, with exception of chromosome 7 and 21, carries one or more genes encoding ribosomal proteins (RPG – ribosome protein genes) that are known for their haploinsufficiency (29). Therefore, we hypothesized that the translation in monosomic cells is impaired due to reduced ribosomal biogenesis caused by RPG haploinsufficiency. To test this hypothesis, we analyzed the consequences of *RPL21* depletion, which is the only RPG encoded on chromosome 13. Using siRNA, we titrated the levels of *RPL21* in parental diploid RPE1 to approximately 50% of the wild type abundance, which resulted in reduced puromycin incorporation, similarly as observed in monosomy 13 (Fig. 5g-j). No significant changes of phosphorylation of p70S6K (mTOR target) and eIF2 α (ISR marker) was observed upon *RPL21* depletion (Fig. 5g). Thus, in agreement with the observation in monosomic cells, the general translation

machinery is not inhibited. Knocking down *RPS24*, the only RPG encoded on chromosome 10, reduced the abundance of this protein to the levels observed in monosomy 10 cell lines (RM 10 and RM 10;18) and resulted in similar translation defect (Fig. S6c,d). Together, our findings further support our hypothesis that ribosomal haploinsufficiency caused by loss of RPG is responsible for the observed translation defects. Finally, we analyzed the amount of total RNA in monosomic cells compared to the parental control. Since rRNA represents approximately 80% of all RNA in eukaryotic cells (30), the total RNA amount can serve as a proxy for rRNA abundance and ribosome content (31). Strikingly, RM10 and RM13 comprised 70 - 80% of the total RNA abundance of the parental control (Fig. 5k). We propose that a loss of one gene copy coding for ribosomal proteins is responsible for the reduced translation in monosomic cells due to impaired ribosome biogenesis.

Loss of p53 is essential for the proliferation and viability of monosomies. To determine how *TP53* affects the cellular response to monosomy, we restored the p53 expression in monosomic cell lines using doxycycline inducible expression system (Fig. 6a, Table S1). The new cell lines were labeled with ip53 (e.g. RM13 ip53). We then titrated doxycycline in each cell line to determine the doxycycline concentration that restores the p53 abundance to the levels observed in the wild type RPE1 p53+/+ cell line (Fig. S7a). The expression of p21, a downstream target of p53, was similar as in the p53 proficient RPE1 (Fig. S7a). Having these cells at hand, we restored the p53 expression to the wild type levels and analyzed its impact on monosomic cells. Strikingly, we found that the expression levels of p53 quickly decreased in monosomic cells treated with doxycycline (Fig. 6b, c). Microscopy of cells expressing ip53 revealed that the cells expressing p53 were outgrown by the cells without p53 in monosomies (Fig. S7b, c, d). These findings demonstrate that monosomy is not compatible with functional p53 pathway in human cells.

Next, we analyzed transcriptome changes in monosomic cells with restored p53 expression by RNAseq of RPE1 ip53, RM10ip53 and RM13ip53 after 48 h of doxycycline treatment. Functional p53 does not alter the global response to monosomy, as most deregulations remained similar with restored p53 expression (Fig. 6d, Table S5). However, we identified a significant upregulation of 12 known downstream targets of p53 (Fig. 5e, Table S5), among which p21 (*CDKN1A*) and *BTG2* are the key pro-survival factors and early responders to p53 activation that mediate the cell cycle arrest. Accordingly, analysis of the cell cycle progression revealed an increased accumulation of G1 cells 24 h after restored *TP53* expression (Fig. S7e). We conclude that monosomic cells with restored p53 activate this pathway, which subsequently triggers the G1 cell cycle arrest and blocks proliferation.

Defective ribosome biogenesis is a known trigger for p53 activation (32). Since the monosomies suffer from impaired ribosome biogenesis, we hypothesized that ribosomal haploinsufficiency may be responsible for the p53 activation. Depletion of *RPL21* in diploid p53-positive cells to the levels similar as in RM13 (Fig. 6f, g) reduced the translational efficiency (Fig. 6h, i). Importantly, we observed that already a minor reduction of Rpl21 abundance resulted in a robust accumulation of p53 and p21 (Fig. 6f). Thus, a partial depletion of a single ribosomal protein to levels resembling its abundance in

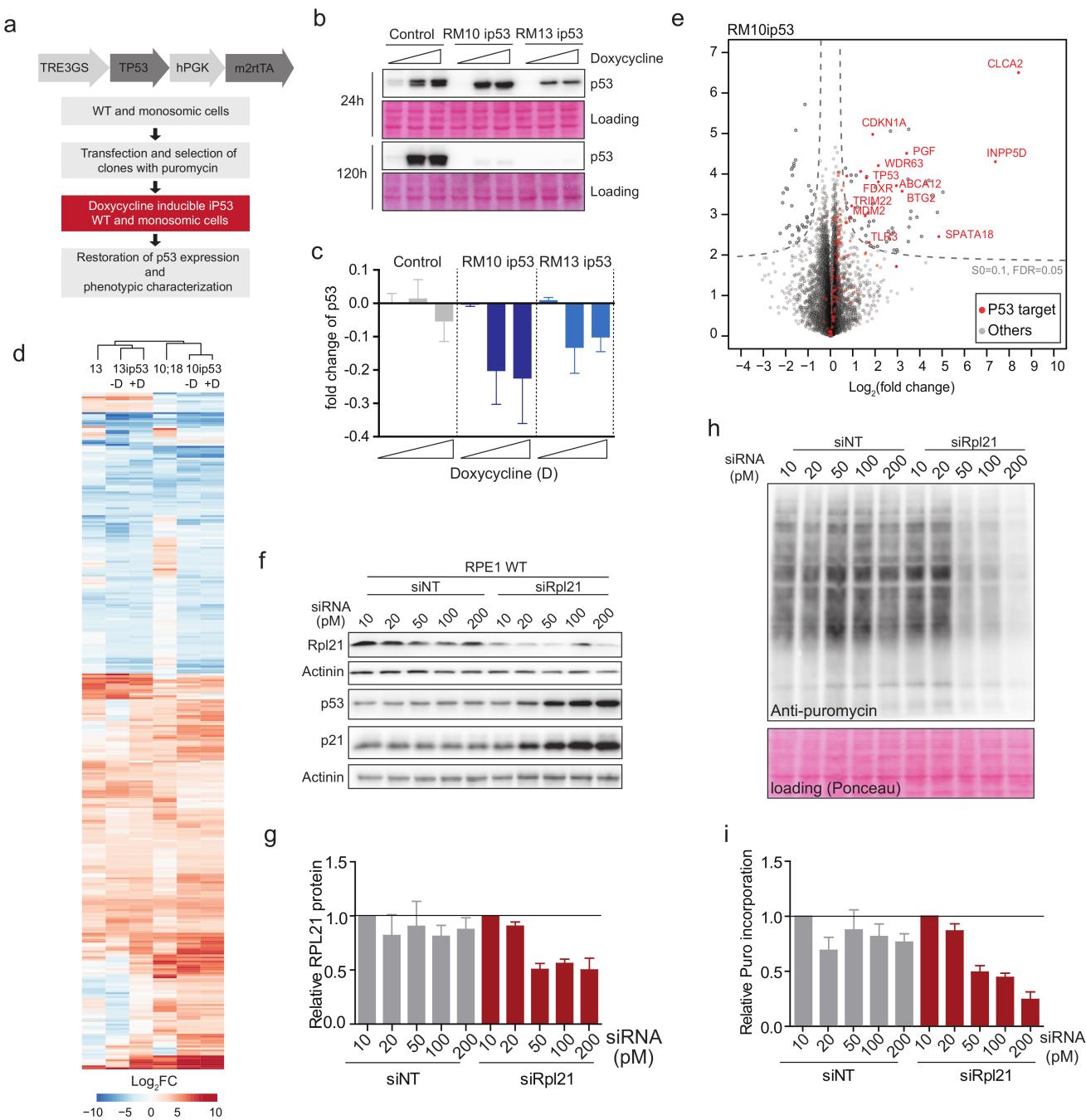


Figure 6. Loss of p53 is essential for proliferation of monosomies. (a) Schematics depicting the construction of monosomic cell lines with doxycycline inducible p53 expression. (b) Immunoblotting of p53 after induction with doxycycline for 24 h and 120 h. Ponceau staining was used as a loading control. (c) Quantification of the p53 intensities from (b). The plots display the mean differential expression of p53 at 24 and 120 h of doxycycline treatment. All values were normalized to the respective loading control. D denotes doxycycline. (d) Heat map depicts the differentially regulated mRNA expression in monosomies compared to diploids. Hierarchical clustering of Euclidean distance. Gene expression fold changes greater than 2 or less than -2 are used for heat map. (e) Volcano plot showing the transcripts of p53 targets upregulated in 10ip53 cell line with doxycycline treatment compared to no doxycycline (\log_2 FC). Red dots represents known p53 targets. (f) siRNA mediated titrated knockdown of *RPL21* in RPE1 induces p53 expression in a concentration-dependent manner. siNT was used as control. RPE1 p53 KO WT and RM 13 were used as a non-transfection control. The western blots are representative of at least three independent experiments. (g) Quantification of relative *RPL21* levels from immunoblotting. All values were normalized to respective 10 pm samples. Actinin served as a loading control. Bars display mean \pm SEM of at least three independent experiments. (h) siRNA mediated knockdown of *RPL21* reduces translation rate in RPE1 cells. The protein lysates from siNT and siRPL21 puromycin-labeled samples were immunoblotted with an anti-puromycin antibody. Ponceau staining was used as a loading control. The western blots are representative of at least three independent experiments. (i) Quantification of relative puromycin incorporation from immunoblotting. All values were normalized to respective 10 pm samples. Ponceau served as a loading control. Bars display mean \pm SEM of at least three independent experiments.

monosomic cells is sufficient to induce a robust p53 activation. This suggests that the incompatibility of functional p53 and monosomy is due to haploinsufficiency of the ribosomal genes.

Loss of p53 and ribosome deprivation are hallmarks of monosomic cancers. One prediction from the above described observations is that cancers with monosomy show reduced expression of ribosomal genes and enriched p53 pathway mutations. To test this, we analyzed transcriptomes from the Cancer Cell Line Encyclopedia (CCLE) (33). Cell lines were categorized into Monosomy and Disomy (see Methods). By single sample gene set enrichment analysis (ssGSEA) (34), we show that ribosome-related pathways are strikingly downregulated in Monosomy cancer cell lines compared to Disomy ones (Fig. 7a, S8a). Additionally, we found a significant downregulation of p53 signaling pathways (Fig. 7a). We then filtered the Monosomy category to two groups: a group with RPG expression lower than the median of the entire cohort, and a group with a higher RPG expression. Comparison of these groups revealed a significantly reduced *TP53* pathway activity in cells with reduced RPG abundance (Fig. S8b). Next, we examined the relationship between p53 loss and monosomy in vivo. We stratified the Cancer Genome Atlas (TCGA) pan-cancer samples into Monosomy, Disomy and Polysomy (see methods). We then calculated the “p53 classifier score” that quantifies the extent of phenocopying *TP53* loss in individual samples (35). Of 15 cancer types, Monosomy shows significantly higher *TP53* scores compared to Disomy in 13 cancer types, while Polysomy only in 3 cancer types (Fig. 7b). Previous studies showed that tumors with high SCNA are enriched for *TP53* mutations (36). To evaluate whether the increased *TP53* classifier score in Monosomy might be a confounding effect of increased SCNA in this category, we measured the aneuploidy score of Monosomy and Polysomy tumors and compared to *TP53* mutations. While the aneuploidy score defining the SCNA levels is comparable in Monosomy and Polysomy, the *TP53* mutations are enriched in Monosomy (Fig. 7c). Based on these results we propose that ribosome biogenesis defect is common in monosomic cancers due to the haploinsufficiency of ribosomal genes and that, therefore, monosomy is incompatible with functional p53 pathway.

Discussion

Recent years have witnessed a breakthrough in understanding the cellular consequences of chromosome gains, but examination of chromosome losses has been difficult. We were able to analyze seven human monosomies of chromosome 7, 10, 13, 18, 19p and X. While this is a limited number of monosomies, it provides a first insight to the consequences of monosomy in human cells. We demonstrate that monosomy leads to impaired proliferation, genomic instability and deregulated gene expression. All analyzed monosomies showed reduced expression of RPGs and impaired translation. We also show that loss of p53 function is a precondition for proliferation of monosomic cells. Our findings are further supported by computational analysis of CCLE and TCGA data, which revealed that monosomy in cancer cells correlates with reduced ribosomal functions and dysfunctional p53 pathway.

Monosomy induces genomic instability and impairs proliferation. Most of our understanding of cellular response to aneuploidy comes from analysis of trisomy that impairs proliferation and induces genotoxic and proteotoxic stress. Monosomy also impairs cell proliferation, but the underlying molecular mechanisms likely differ from the effects of trisomies, since no proteotoxic stress was observed in response to monosomy. The impaired proliferation of monosomic cells might be either due to haploinsufficiency of genes required for proliferation, or due to the fact that spontaneously arising deleterious recessive mutations can no longer be compensated by the second gene copy. We observed an increased chromosome missegregation and mitotic delay in several monosomic cell lines, while increased accumulation of DNA damage was observed in three monosomic cell lines. Intriguingly, the defects were generally milder in cells that were rendered p53 deficient by shRNA expression. Moreover, monosomy of chr. X showed no increase in genomic instability. This suggests that the changes in maintenance of genome stability are not a uniform outcome of monosomy. Genomic instability in trisomic cells is associated with replication stress (3, 22, 37); however, none of these phenotypes was observed in monosomies. The deregulation of proteins linked to DNA replication in trisomic cells likely depends on *TP53* – while p53 proficient trisomic cell lines downregulate DNA replication factors (3, 22, 37), the p53 deficient trisomic cell lines analyzed so far upregulated these factors (38). Whether the absence of replication stress in monosomies is due to the p53 loss is difficult to address because of the toxicity of p53 in monosomies. Thus, imbalanced chromosomal content, either due to a loss or a gain of chromosome, is detrimental for proliferation and for maintenance of genome stability in human cells, but the underlying molecular causes likely differ in monosomic and trisomic cells.

Gene expression changes induced by monosomy. Only little is known about gene expression changes due to monosomy. In a recent transcriptome analysis of human monosomic blastocysts, altered transcript abundances were observed for several hundreds of genes located on the affected monosome as well as genome wide, but the study was hampered by low numbers of analyzed transcripts, restrictions to embryonal cells and genetic diversity of the unrelated embryos (39). Our systematic transcriptome and proteome analysis of monosomic cell lines compared to their parental cell line showed that the expression of the genes located on the monosome is indeed reduced, but the expected lower levels were observed only for 20% of monosomically encoded proteins. Both transcriptional and posttranscriptional mechanisms contribute to this abundance changes. Study of gene dosage effects upon partial autosomal deletions in drosophila cell line S2 suggested gene-specific mechanism affecting mRNA levels (40). We observed that in human monosomies, the major gene expression adjustments occur on protein level. We envision two possible scenarios: first, the translation of mRNAs originating from genes encoded on monosomic chromosome might be selectively increased, or second, the protein degradation becomes reduced. Our findings indicate that cells utilize multiple routes to alleviate the consequences of gene expression changes.

Monosomy alters not only the expression of the genes encoded on monosomic chromosomes, but also affects the genome-wide expression landscape. The differentially regulated pathways revealed only

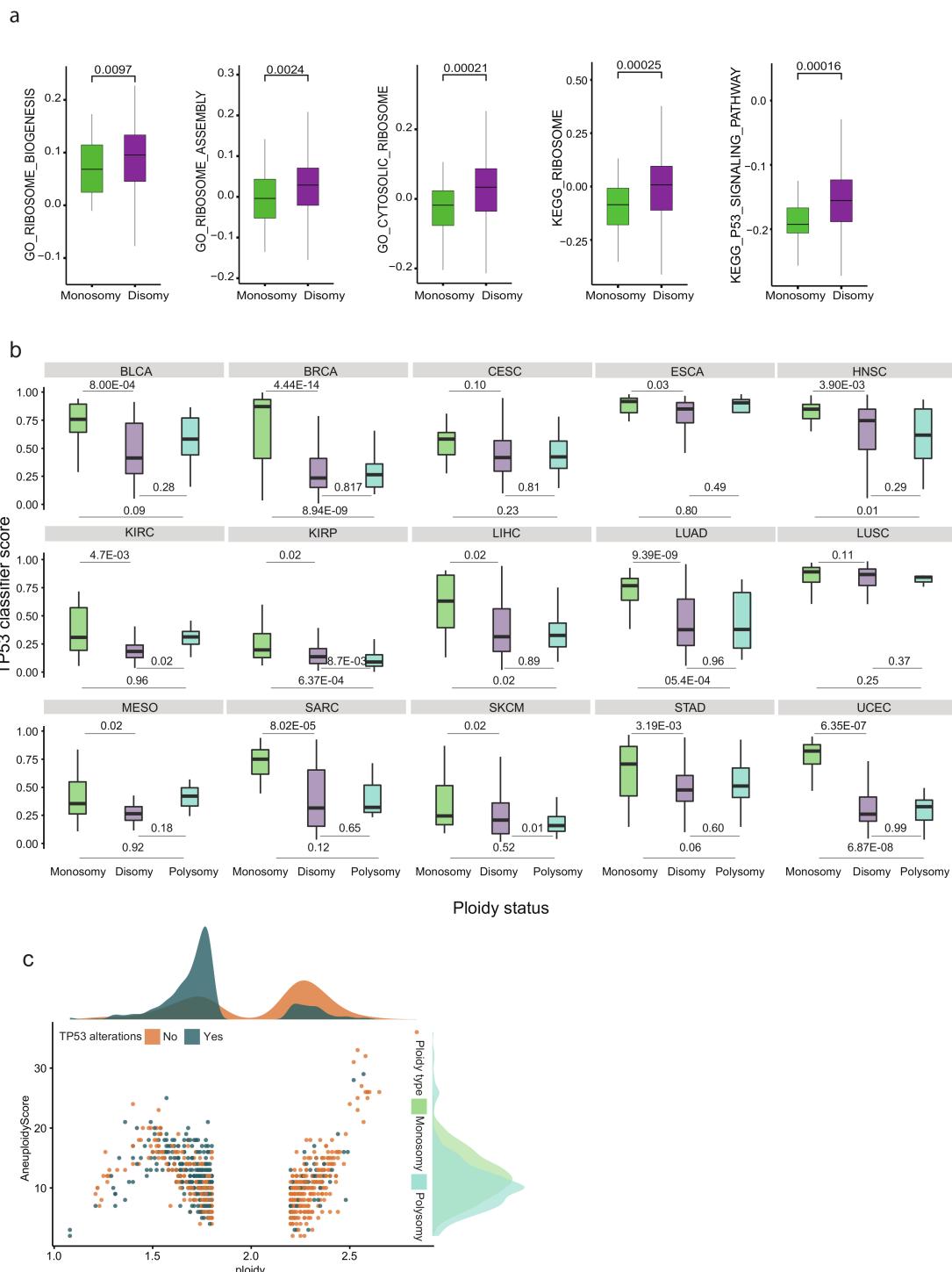


Figure 7. TP53 loss and impaired ribosome biogenesis are the hallmarks of monosomic cancers. (a) Transcriptome analysis revealed the downregulation “Ribosome biogenesis”, “Ribosome assembly” and “p53 pathway” in monosomic compared to disomic cell lines in CCLE datasets. The y-axis shows the ssGSEA derived enrichment scores for gene ontology (GO) terms “Ribosome biogenesis”, “Ribosome assembly” and “Cytosolic ribosome” and KEGG pathways “Ribosome” and “p53 signaling”, respectively. All p-values are based on Wilcoxon rank sum tests. (b) TP53 classifier score estimating the extent of phenocopying TP53 loss in monosomy compared to diploid and polysomy tumors across pan cancer TCGA dataset. Cancer types are annotated as follows: BLCA - bladder urothelial carcinoma; BRCA - breast invasive carcinoma; CESC - cervical squamous cell carcinoma; ESCA - esophageal carcinoma; HNSC - head and neck squamous cell carcinoma; KIRC - kidney clear cell carcinoma; KIRP - kidney renal papillary cell carcinoma; LIHC - liver hepatocellular carcinoma; LUAD - lung adenocarcinoma; LUSC - lung squamous cell carcinoma; MESO - mesothelioma; SARC - sarcoma; SKCM - skin cutaneous melanoma; STAD - stomach adenocarcinoma; UCEC - uterine corpus endometrioid carcinoma. (c) Scatter plot showing the ploidy distribution. Samples with ploidy ranging from 1.80 to 2.19 are defined as disomic, 1.66 to 1.90 as Monosomy and 2.0 to 2.27 as polysomy. The top marginal density histogram shows that TP53 alterations. The right marginal density histogram depicts the aneuploidy score in monosomy and polysomy.

limited overlap with our previous analysis of trisomic cells. It should be noted, however, that the trisomic cells were p53 proficient, while the monosome are p53 negative. Comparisons of monosomes with ip53 suggest rather that at least in monosomal cell, the p53 pathway has only mild effect on differential gene expression. Additionally, the deregulated genes and pathways largely differ among the monosomal cell lines. Thus, the identity of individual genes located on individual monosomes dominates over the shared consequences of chromosome loss.

Ribosomal insufficiency is a major detrimental consequence of chromosome loss. All analyzed monosomes downregulated cytoplasmic ribosomes and translation. Ribosome biogenesis and assembly are highly complex processes involving transcription, modification, and processing of precursor rRNAs, synthesis, import and export of ribosomal subunits. Even subtle shifts in the availability of ribosomes, such as those created by ribosome haploinsufficiency, impairs cellular growth and proliferation (41). Every human chromosome, with exception of chromosome 7, carries at least one gene that codes for ribosomal proteins or an rDNA cluster (29). This is also true for chromosome X and, importantly, one of the genes that escapes dosage compensation codes for ribosomal protein *RPS4X*. It has been proposed that haploinsufficiency of *RPS4X* contributes to the pathophysiology of monosomy X, or Turner syndrome (42), although the importance remains debated. Other pathways known to affect translation efficiency, such as integrated stress response (28, 43) or mTOR pathway (44) are not changed in response to monosity. Therefore, we propose that impaired ribosome biogenesis caused by the haploinsufficiency of ribosomal protein-coding genes as the common consequence of monosity. An ultimate test for our hypothesis would be a rescue of the translation defect in monosomal cell by restoring the levels of ribosomal proteins. Our attempts to rescue the *RPL21* expression were not successful, as the excessive protein was readily degraded by proteasome (N.K.C., personal communication). This is likely due to tight regulation of RPG expression that renders individual ribosome subunits generally resistant to overexpression (45, 46). Novel approaches will have to be developed to perform this experiment in future.

Loss of p53 is a precondition of monosity. Autosomal monosity appears to be incompatible with functional p53 pathway. Our original attempts to obtain monosomal cells in p53 proficient cell lines were unsuccessful (N.K.C., personal communication). Previously published CRISPR/Cas9-based technique was efficient only to generate monosity X (47). Monosity of 3p was engineered with CRISPR/Cas9 system in lung cells immortalized with the SV40 large T antigen, which perturbs the retinoblastoma protein and p53 tumor suppressor proteins 16. Previous observations also revealed anti-correlation between chromosome loss and functional p53 in patients with MDS, where *TP53* mutation was associated with chromosome 5q loss in 47% of patients, while only 1.5% (4/263) of patients without 5q aberrations carried *TP53* mutations (48). Tumors in zebrafish with ribosomal haploinsufficiency also require a loss of p53 expression (49). Together, the data suggest an important role of the p53 pathway in the viability of monosomal cells. Restoring the p53 function in monosomal cells gave us the unique opportunity to

evaluate the function of p53. While the global cellular response to monosity was not strikingly affected, we found expression changes in a small subset of factors enriched for direct p53 targets such as *CDKN1A*, *BTG2*, *FDXR*, *SPATA18*, *CLCA2* and others. Several of the induced factors, for example *CDKN1A* (p21) and *BTG2* regulate G1/S transition of the cell cycle or play an important role in cellular response to stress conditions (*BTG2*, *FDXR*). Computational analysis of cancer genomes confirms the principal incompatibility of functional p53 with monosity, as well as general downregulation of ribosomal pathways. We propose that the major consequence of chromosome loss is a defect in ribosome biogenesis that impairs cellular proliferation and activates cell cycle arrest and/or senescence via the p53 pathway. Additionally, the increased genomic instability may also contribute to the p53 activation. Our novel findings provide insights on how chromosome loss affects gene expression landscape in human cells and offers rationale why cancers with monosity frequently carry a mutation in the p53 pathway.

Methods

Cell lines and treatments. Human retinal pigment epithelium cell line RPE1 immortalized with hTERT overexpression was used. RPE-1 cells were cultured in DMEM + GlutaMAX™-I medium supplemented with 10% Fetal Bovine Serum and Pen strep (Gibco). RM 13 KO cell line was generated by pre-designed zinc finger nucleases (Sigma) as described previously (50). RM X, RM 10, RM 10;18 and RPE1 p53 KO cell lines were generated by CRISPR/Cas9-based targeting of the *TP53* gene. For these, the gRNA against *TP53* gene was cloned in pX330 vector (Addgene: 42230) according to a modified protocol from (51) and used to transfect RPE WT cells. Single cell clones were tested for the loss of p53 expression by sensitivity to Nutlin and immunoblotting for p53 and p21. To assess the copy number status, single cell derived clones were subjected to low-pass whole genome sequencing. Chromosome loss was further validated by chromosome painting. The monosomal clones (KD) derived from RPE1 p53 shRNA cell line were a kind gift from Dr. Rene Medema and are described in (2) (Netherlands Cancer Institute, The Netherlands).

For p53 rescue experiments, RM 10;18 and RM 13 cell lines were transduced with virus generated from an all-in-one tetracycline inducible plasmid with p53 (pMOV T11 p53) expressed under tet promoter (52), selected in the presence of 2 µg/mL puromycin for 72 h and subsequently maintained in the presence of 0.5 µg/mL puromycin. RPE1 WT cells were transduced with TP53 cloned into doxycycline inducible system (Tet on system, Clonetech) and selected with blasticidin (1 µg/mL) and puromycin (2 µg/mL). All lines were grown at 37°C in a humidified 5% CO₂ incubator. All cell lines were tested for mycoplasma contamination. To minimize the occurrence of secondary genomic changes, original stocks were thawed for every experiment and maintained for maximum of 4 to 5 passages. The used cell lines are listed in Table S1.

Lentivirus transfection and transduction. The pMOV T11 (kind gift of Dr. Bernhard Schiedlmeier, Medizinische Hochschule Hannover, Germany) and pRetroX-TRE3G and pRetroX-Tet3G vectors containing the *TP53* coding sequence were mixed with pMDLg/pRRE

(gift from Didier Trono, Addgene plasmid #12251) and pMD2.G (gift from Didier Trono, Addgene plasmid #12259) lentiviral plasmids and transfected to 80% confluent HEK293T cells using Lipofectamine 2000 (Thermo Fischer Scientific) according to the manufacturer's instructions. On the next day, the medium with transfection reagent was replaced with fresh medium. Forty-eight hours post medium change, the viral supernatant was collected.

RPE1 p53 KO and RM 10;18 and RM13 were transduced with viral supernatant supplemented with 5 mg/mL polybrene and incubated 12-16 h at 37°C in a humidified 5% CO₂ incubator. After 48 h, the medium was replaced with selection medium containing the respective antibiotics.

siRNA transfection. For the knockdown of *RPL21* using siRNA, 5x10⁵ were plated on 6 cm dishes on the day before transfection. Different concentrations (10 pm, 20 pm, 50 pm, 100 pm and 200 pm) of siNT (control) and siRPL21 were used. The transfection of siRNA was performed with Lipofectamine 2000 according to the manufacturer's instructions. 72 h post transfection, cells were collected for immunoblotting to verify the *RPL21* knockdown efficiency. The sequences of siRNAs are listed in Table S6.

Metaphase spread and chromosomal painting. Cells were grown to 70–80% confluence, treated with 400 ng/mL colchicine for 5-6 h, collected by trypsinization, and centrifuged at 1500 rpm for 10 min. Cell pellets were resuspended in 75 mM KCl and incubated for 10–15 min at 37°C. Cells were pelleted at 1000 rpm for 10 min and suspended in 3:1 methanol/acetic acid to fix the cells, washed several times in 3:1 methanol/acetic acid. Fixed cells were dropped on a glass slide and dried at room temperature for 15 min. Each sample was labeled with chromosome FISH probes (ChromBios) specific for a monosomic chromosome and a control chromosome as per manufacturer's instructions. Briefly, chromosome spreads were incubated with probe mixture (1 µL of each probe, adjusted to 10 µL with HybMix buffer). After denaturation at 72°C for 6 min, slides were kept at 37°C in a humid chamber overnight. Slides were washed for 5 min in 2x saline sodium citrate (SSC) solution and then for 1 min in prewarmed 70°C 0.4X SSC, 0.1% Tween solution, and, finally, in 4x SSC, 0.1% Tween solution for 5 min at room temperature. Then slides were incubated for 30 min at 37°C with 100 µL fluorescein isothiocyanate (FITC) mouse anti-digoxin (Jackson Immuno Research) solution (1:300 in 4X SSC/0.1% Tween) and washed twice in 45°C pre-warmed 4x SSC/0.1% Tween solution for 5–10 min. Finally, cells were stained with DAPI and microscopic analysis was carried out using 3i software and spinning disc confocal microscopy (see below). For each sample, at least 25 metaphases were captured and analyzed.

Immunofluorescence staining and microscopy. RPE1 p53 KO and monosomic cells (1x104 cells) were plated in black 96-well glass-bottom plates and grown in DMEM to the desired confluence. Cells were fixed with freshly prepared 3.7% formaldehyde for 15 min at RT and permeabilized with 0.5% Triton X-100 in PBS for 5 min. For blocking, cells were incubated with 3% BSA and 0.1% Triton X-100 for 30 min at RT and stained with anti-gamma H2AX (Abcam 2893), anti CENP B (Santa Cruz, sc376392), anti p53 (Santa Cruz, sc126) overnight at 4°C in humidified chamber. Next day, the

primary antibody was washed off and incubated with secondary antibody at room temperature in dark for 1 h. After secondary antibody was washed off, the nuclei was counter stained with Sytox green and DAPI. For micronuclei and anaphase bridge quantification, the cells were fixed as above and counter stained with DAPI and Sytox green.

Spinning disc confocal laser microscopy was performed using a fully automated Zeiss inverted microscope (AxioObserver Z1) equipped with a MS-2000 stage (Applied Scientific Instrumentation, Eugene, OR), the CSU-X1 spinning disk confocal head (Yokogawa) and LaserStack Launch with selectable laser lines (Intelligent Imaging Innovations, Denver, CO). Image acquisition was performed using a CoolSnap HQ camera (Roper Scientific) and a 20x-air (Plan Neofluar $\times 40/0.75$, Plan Neofluar $\times 20/0.75$) under the control of the SlideBook 6 x64 program (SlideBook Software, Intelligent Imaging Innovations, Denver, CO, USA).

Live cell imaging. For the live cell imaging, cells expressing H2B-Dendra2 were seeded in a 96-well plate at 1x10⁴ cells per well in standard cell culture medium. Cells lacking the fluorescent tag to visualize DNA were labelled with Hoechst 33342 (1 µg/mL). The medium was replaced with FluoroBrite medium before live-cell imaging. Imaging was performed using an inverted Zeiss Observer Z1 microscope (Visitron Systems) equipped with a humidified chamber (EMBLEM) at 37°C, 40% humidity, and 5% CO₂ using CoolSNAP HQ2 camera (Photometrics) and X-Cite 120 Series lamp (EXFO) and Plan Neofluar 20x, or 10x magnification air objective NA 1.0 (Zeiss, Jena, Germany). Cells were imaged for 24 hours with 8 min time-lapse. Images were analyzed using Slidebook (Intelligent Imaging Innovations, Inc., Goettingen, Germany) and ImageJ (National Institutes of Health). To determine the time spent in mitosis, the period from nuclear envelope breakdown (NEBD) until end of anaphase was quantified.

Cell proliferation and soft agar colony forming assay. For proliferation assay, cells were seeded in triplicates into the wells of a 96 well plate (1.5x10³ cells/well). In total 5 plates, one for each day, were prepared. To measure the proliferation, Cell Titer-Glo (Promega) was used according to the manufacturer's instructions. All the measurements were normalized to Day 0. For soft agar assay, 1% low melting agarose combined with an equal volume of DMEM was added to 12 well dish as a bottom layer. Subsequently, 0.7% low melting agarose was mixed with an equal volume of cell suspension containing 1000 cells and immediately layered on solidified agar base in duplicates per cell line. The wells were then filled with medium containing 10% FBS and 5% Pen-Strep. Medium was replaced every 3 days and the colonies were counted after 3 weeks. Each well was divided into eleven fields and colonies in each field were counted using an inverted microscope (Motic AE2000).

Immunoblotting. Whole-cell lysates were obtained using RIPA buffer supplemented with protease and phosphatase inhibitors (Roche). An amount of 10 µg of protein was then resolved on 10-12.5% polyacrylamide gels and transferred to nitrocellulose membranes using the semi-dry technique. Ponceau staining was performed by incubating the membrane for 5 min in Ponceau S solution (0.2 (w/v) in 1% (v/v) acetic acid). After blocking in low fat, 5% milk in Tris-Buffered Saline with Tween 20 for 1 h at room temperature, membranes were

incubated overnight at 4°C with the primary antibodies. Antibodies used in this study are listed in Table S6. After incubation with horseradish peroxidase-conjugated secondary antibodies, horseradish peroxidase substrate was added and luminescent signals were quantified using an Azure c500. Protein bands were quantified using ImageJ software. For the normalization of western blotting results, we used housekeeping gene α -actinin or Ponceau staining as indicated in the figure legends. For Ponceau – based normalization, we used a large region between 35 to 60 kDa that contains several bands for normalization.

RNA extraction and RT-PCR. mRNA was extracted using Qiagen RNeasy mini kit as per the manufacturer's instructions. 2 μ g of genomic DNA-free mRNA was used for cDNA synthesis. cDNA was synthesized using iScriptTM Advanced cDNA Synthesis Kit as per the instructions. As a control for cDNA synthesis efficiency, RNA spike (TATAA universal RNA spike I) was added in equal amounts into master mix of cDNA. cDNA was diluted 1:10 before using it for qPCR analysis. For qPCR, SYBR green based assay was used from Biorad (Sso advanced universal SYBR Green). The Ct values for the gene of interest is normalized either to RPL27 or Spike.

Cell cycle analysis. Cell cycle analysis was performed by labelling the replicating cells with EdU (5-ethynyl-2'-deoxyuridine) and DNA with DAPI (4',6-diamidino-2-phenylindole). Briefly, cells were cultured as described above and EdU was added 30 min before harvesting the cells. Subsequently, for EdU detection, the cells were fixed and permeabilized for 15 min with Fix perm (Thermo Fisher scientific), followed by incubation with EdU Click-iT cocktail (Invitrogen) as per the manufacturer's instructions. Cells were resuspended in PBS containing RNase (10 μ g/mL) and DAPI and measured using Attune Nxt acoustic focusing cytometer (Life Technologies, Carlsbad, USA).

Puromycin labelling to determine translation rate. To determine the translation rate, 1.5x10⁶ cells were plated in 10 cm dish on the day before the puromycin labelling. Next day, cells should be actively growing with desired confluence of 70-80%. For labelling, 10 μ M of puromycin was added directly to cell culture dish, mixed well and placed in incubator at 37°C for 15 min. Puromycin was washed off with PBS and the cells were collected for protein extraction and immunoblotting as described above. Equal amounts of protein lysates were loaded on 12.5% acrylamide gel and the puromycin incorporated nascent peptides were identified using anti puromycin antibody. The intensity of puromycin was normalized to ponceau, which served as loading control.

17AAG sensitivity. To analyze the sensitivity to protein folding inhibitor 17-AAG (inhibitor of HSP90), 1.5x10³ were plated in triplicates on white 96-well glass bottomed plate. On the following day, the medium was replaced with fresh medium containing 17-AAG at desired concentrations or DMSO. Immediately, cells were placed in incubator with 5% CO₂ at 37°C. After 72 h, the cell viability was measured using Cell Titer-Glo according to manufacturer's instructions. All the values were normalized to DMSO control.

Polysome profiling. Polysome profiling was performed as in (53). Cells were grown in 15 cm dishes (80% confluency at the time of

experiment) and 10 dishes were used for each cell line. Cells were treated with 100 μ g/ml cycloheximide (CHX) for 10 min and collected immediately by gently scraping with ice cold CHX/PBS. Cells were pelleted and flash frozen using liquid nitrogen and stored at -80°C until further use. Cells were lysed using ice cold low salt lysis buffer (50 mM KCL, 20 mM Tris HCl, pH 7.4, 10 mM MgCl₂, 1% Triton X-100, 1 mM DTT, 0.5% sodium deoxycholate, 100 μ g/ml cycloheximide, RNase inhibitors, protease and phosphatase inhibitors) and incubated on ice for 10 min. The lysate was centrifuged at 2000 g for 5 min to pellet nuclei and large debris. The supernatant was transferred to a fresh tube and centrifuged at 13000 g for 5 min and the supernatant was transferred to a fresh tube. In the meantime, a linear sucrose gradient (7-47%) was prepared using Biocomp Gradient Master 108. The RNA concentration of cleared lysate was measured using nanodrop and equal amounts of lysate was layered on the top of gradient and centrifuged at 39000 rpm on SW41 rotor for 90 min at 4°C. The UV absorbance of the gradients were measured starting at the bottom of the gradient using Bio Rad BioLogic FPLC system and BioLogic Optics Module OM-10.

The raw polysome profiles were smoothed using a Savitzky-Golay filter with a window size of 51 – 61 data points and a third order polynome in a Python script. For normalization by 80S maximum peak intensity, the data points of each monosomic cell line profile was multiplied by the ratio of its 80S maximum peak intensity to the wild types 80S maximum peak intensity. Based on the normalized profiles, the ratios of 80S, 60S and 40S maximum peak intensities between the wild type and monosomies were calculated. Ribosome structure modelling was performed using UCSF ChimeraX (54).

DNA libraries. Genomic DNA was extracted from the cells using the DNA Blood Mini kit (Qiagen). Library preparation was performed with a Beckman Biomek FX automated liquid handling system, with 500ng starting material using SPRIworks HT chemistry (Beckman Coulter). Samples were prepared with custom 6 base pair barcodes to enable pooling. Library quantification and quality control was performed using a Fragment Analyzer (Advanced Analytics Technologies, Ames, USA).

Genomic sequencing and analysis. WGS was pursued on an Illumina HiSeq 2500 platform (Illumina, San Diego, USA), using 50 basepair single reads for low-pass sequencing. For all samples the GC-normalized data was aligned against the Genome Reference Consortium Human Build 38 patch release 13 (GRCh38.p13) using the intersect function of bedtools2 (version 2.29.1) to map the known genes to the measured coverages. The values were converted into log₂ data and the median coverage per read was calculated for all known genes with at least one mapped coverage. To shift the values around zero, the median coverage of each cell line was subtracted for all values, resulting in a normalized population centered on 0.

RNA-seq library preparation and sequencing. NGS-Sequencing and library preparation was conducted at the NGS- Integrative Genomics Core Unit (NIG), Institute of Human Genetics, University Medical Center Göttingen (UMG).

Quality and integrity of RNA was assessed with the fragment analyzer from Advanced Analytical by using the standard sensitivity

RNA analysis Kit (DNF-471). All samples selected for sequencing exhibited an RNA integrity number over 8. RNA-seq libraries were performed using 200 ng total RNA of a non-stranded RNA Seq, massively-parallel mRNA sequencing approach from Illumina (TruSeq stranded total RNA Library Preparation, Illumina). Libraries were prepared on the automation (Beckman Coulter's Biomek FXP workstation). For accurate quantitation of cDNA libraries a fluorometric based system, the QuantiFluorTMdsDNA System from Promega were used. The size of final cDNA libraries was determined by using the dsDNA 905 Reagent Kit (Fragment Analyzer from Advanced Bioanalytical) exhibiting a sizing of 300 bp in average. Libraries were pooled and sequenced on the Illumina HiSeq 4000 (SE; 1 x 50 bp; 30-35 Mio reads/sample). Sequence images were transformed with Illumina software BaseCaller to BCL files, which was demultiplexed to fastq files with bcl2fastq v2.20.0.422. The quality check was done using FastQC.

Mapping & Normalization and analysis. Sequences were aligned to the genome reference hg38 sequence using the STAR aligner version 2.5.2a (55). Subsequently, read counting was performed using featureCounts (56) (version 1.5.0-p1). Read counts were analyzed in the R/Bioconductor environment (version 3.6.1, bioconductor.org) using the DESeq2 package version 1.14.1 (57). For further analysis, all counts were normalized by shifting the replicates to the same median, which was calculated without the monosomic genes to adjust the samples for the loss of a chromosome and the subsequent lower gene expression. For all monosomic cell lines, the log₂ median intensity of three replicates was calculated and the log₂ median intensity of three replicates of the wild type parental cell line was subtracted to calculate comparable fold changes.

Preparation of Tandem Mass Tag (TMT) labeled peptides and high pH fractionation. Cells were cultured as described above, 1x10⁶ cells were collected by scraping from plates and pellets were washed twice with PBS. Sample preparation and labelling peptides with TMT isobaric mass tags was performed as per the manufacturer's instructions. Briefly, cells were lysed in 100 µL lysis buffer (10% SDS in 100mM Triethyl ammonium bicarbonate (TEAB)) using strong ultrasonication. Lysates were cleared by centrifugation at 16,000 x g for 10 minutes at 4°C and protein concentration was determined using the BCA protein assay kit (Thermo Scientific). Fifty micrograms of protein was reduced with 5 mM Tris 2-carboxyethylphosphine (TCEP) for 1 h 55°C, and alkylated with 10 mM iodoacetamide for 30 min in the dark at 25°C. Reduced and alkylated proteins were precipitated over night by adding six volumes of acetone at -20°C. Acetone precipitated proteins were resuspended in 100 mM TEAB, pH 8.5 and digested by incubation with sequencing-grade modified trypsin overnight at 37°C.

For TMT labelling, trypsinized peptide samples were subsequently labeled with isobaric tags (TMT 6-plex, Thermo Fisher Scientific). All samples were labelled with individual tags: RPE1 p53 KO-TMT126, RM X- TMT127, RM 10;18- TMT128, RM 13 -TMT129, RPE1 p53 KD- TMT130, RM 19p-TMT131.

After pooling the TMT labeled peptide samples, peptides were desalted on C18 reversed-phase columns and dried under vacuum. TMT-labeled peptides were fractionated by high-pH reversed-phase

separation according to Wang et al., 2011 (58) using a YMC Triart C18 column (3 µm, 120 Å, 2.1 mm x 100 mm; YMC Co., Ltd., Japan) on an Agilent 1100 HPLC system. Peptides were loaded onto the column in buffer A (ammonium formate [10 mM, pH 10] in water) and eluted using a 30 min gradient from 3-90% buffer B (90% acetonitrile/10% ammonium formate [20 mM, pH 10]) at a flow rate of 0.3 ml/min. Elution of peptides was monitored with a UV detector (280 nm). For each replicate, 48 fractions were collected and pooled into four fractions using a post concatenation strategy as previously described (58), dried under vacuum and subjected to liquid chromatography (LC)-MS/MS analysis.

The concatenated and TMT-labelled peptide mixtures were analyzed using nanoflow liquid chromatography (LC-MS/MS) on an EASY nano-LC 1200TM system (Thermo Fisher scientific), connected to a Q Exactive HF (Thermo Fisher scientific) through a Nanospray Flex Ion Source (Thermo Fisher Scientific). 3 µL of each fraction was separated on a 40 cm heated reversed phase HPLC column (75 µm inner diameter with a PicoTip EmitterTM, New Objective) in-house packed with 1.9 µm C18 beads (ReproSil-Pur 120 C18-AQ, Dr. Maisch). Peptides were loaded in 5% buffer A (0.5% aqueous formic acid) and eluted with a 3 hour gradient (5-95% buffer B (80% acetonitrile, 0.5% formic acid) at a constant flow rate of 0.25 µl/mL. Mass spectra were acquired in data dependent mode. Briefly, each full scan (mass range 375 to 1'400 m/z, resolution of 60,000 at m/z of 200, maximum injection time 80 ms, ion target of 3E6) was followed by high-energy collision dissociation based fragmentation (HCD) of the 15 most abundant isotope patterns with a charge state between 2 to 7 (normalized collision energy of 32, an isolation window of 0.7 m/z, resolution of 30,000 at m/z of 200, maximum injection time 100 ms, AGC target value of 1E5, fixed first mass of 100 m/z and dynamic exclusion set to 30 s).

MS data was processed with the MaxQuant software, version 1.6.3.3. All data was searched against the human reference proteome database (UniProt: UP000005640) with a peptide and protein FDR of less than 1%. All raw files as well as all MaxQuant output tables and parameters have been uploaded to PRIDE.

Sample Preparation for Label Free Quantified Mass Spectrometry. The sample preparation for LFQ was performed similarly as for TMT labelling strategy, but following trypsin digestion, the digested peptides were desalted on C18 reversed-phase columns and dried under vacuum. Air dried peptides were analyzed using a nanoflow liquid chromatography (LC-MS/MS) on an EASY nano-LC 1200TM system (Thermo Fisher scientific), connected to a Q Exactive HF (Thermo Fisher scientific) through a Nanospray Flex Ion Source (Thermo Fisher Scientific). 2 µL of each fraction was separated on a 40 cm heated reversed phase HPLC column (75 µm inner diameter with a PicoTip EmitterTM, New Objective) in-house packed with 1.9 µm C18 beads (ReproSil-Pur 120 C18-AQ, Dr. Maisch). Peptides were loaded in 5% buffer A (0.5% aqueous formic acid) and eluted with a 3 hour gradient (5-95% buffer B (80% acetonitrile, 0.5% formic acid) at a constant flow rate of 0.25 µl/mL. Mass spectra were acquired in data dependent mode. Briefly, each full scan (mass range 300 to 1'650 m/z, resolution of 60,000 at m/z of 200, maximum injection time 20 ms, ion target of 3E6) was followed by high-energy collision dissociation based fragmentation (HCD) of the 15 most abundant iso-

ope patterns with a charge state between 2 to 7 (normalized collision energy of 28, an isolation window of 0.1.4 m/z, resolution of 15,000 at m/z of 200, maximum injection time 80 ms, AGC target value of 1.6E3, no fixed first mass and dynamic exclusion set to 20 s). MS data was processed with the MaxQuant software, version 1.6.3.3. All data was searched against the human reference proteome database (UniProt: UP000005640) with a peptide and protein FDR of less than 1%. All raw files as well as all MaxQuant output tables and parameters have been uploaded to PRIDE.

Analysis of proteome data. Identified protein groups were filtered to remove contaminants, reverse hits and proteins identified by site only. Next, Protein groups which were identified more than two times in at least one group of replicates (N=4) were kept for further processing resulting in a set of 5887 Protein groups in total. For LFQ, Protein groups which were identified more than three times in at least one group of replicates (N=4) were kept for further processing, resulting in a set of 5727 Protein groups in total. \log_2 TMT reporter intensities were cleaned for batch effects using the R package LIMMA (59) and further normalized using variance stabilization (60). Next, protein intensities obtained from LFQ and TMT of monosomic cell lines were normalized by shifting to diploid median and fold change calculation to the intensities of the wild type parental cell lines as described for the transcriptome analysis.

Combined analysis of genomic, transcriptomic and proteomic datasets. For further analysis comparing genomic, transcriptomic and proteomic datasets, the DNA and mRNA datasets were matched to the corresponding protein entries and merged into a single table (Supplementary table S2). To compare monosomic and trisomic cell lines, proteome data of trisomic RPE cell lines (25) was merged to the dataset. Chromosome/scaffold name, gene start (bp), gene stop (bp) and Ensembl gene stable ID (ENSG) were annotated through BioMart. Perseus was used to add additional annotation (GOBP, GOCC, CORUM) and to carry out 2D annotation enrichment analysis (61).

Density histograms were generated in R using the library k-density. The \log_2 ratios of the mRNA and proteome subsets were plotted as density histograms, including the median of both populations.

TCGA and CCLE data analysis. TCGA pan-cancer RNAseq data involving 11060 samples were downloaded from Pan-Cancer Atlas and filtered to remove tumors that underwent whole genome doubling (WGD). 5722 primary tumor samples were kept for further analysis. RNAseq profiles of 418 samples from the Broad-Novartis Cancer Cell Line Encyclopedia (CCLE) (33), filtered to remove cell lines with WGD, were used for the analysis. Ploidy value annotated from (35) was used to define -somy status of pan-cancer dataset. Separation of ploidy values into Monosomy and Polysomy status relies on two thresholds. As there are no clear minima in the distribution of ploidy values clearly separating monosomic, disomic and polysomic samples, we assessed how the thresholds affect the final results by varying them from 1.66 to 1.90 (monosomy-disomy) and from 2.0 to 2.27 (disomy-polysomy). All thresholds resulted in a significant enrichment of p53 alterations in monosomic samples. CCLE sample ploidy value was retrieved from CCLE database. Ploidy values of

both Pan-cancer and CCLE cohorts were inferred using ABSOLUTE algorithm (62) using copy number data.

Ribosome related pathway GO terms and KEGG pathway gene sets created by MsigDB6 (63) were collected. ssGSEA (34) was applied on CCLE RNA-seq data to calculate pathway activity scores. A lower pathway score indicates that the genes in a specific pathway for a sample are under-expressed compared to the overall population.

TP53 classifier scores of TCGA pan-cancer cohorts were annotated from (35). The p53 score is based on a logistic regression model where p53 functional inactivation status is the response and expression of genes are covariates. The logistic regression classifier is trained to estimate a set of parameters that can accurately predict the p53 alteration status. Given a new sample, this classifier uses a logistic sigmoid function to report a probability value representing to what degree p53 of a sample is likely to be altered, given the expression data of the sample.

Statistical analysis. Statistical analyses of cell biology data was performed in replicates and the number of the performed independent experiments are specified in respective figure legends. GraphPad Prism software was used for the statistic tests. Statistical analyses were performed using a two-tailed t-test or non-parametric t-test as indicated in the corresponding figure legend. Values are shown as the mean \pm sem or mean \pm sd of multiple independent experiments. For imaging analysis, the investigators were blinded to sample identity during assessment.

To identify significantly upregulated genes, a modified t-test adjusted for multiple testing (FDR = 0.05, S0 = 0.1, Perseus) was used to evaluate the normalized \log_2 mRNA intensities obtained for RM10ip53 cells treated with or without doxycycline.

Significance of TCGA and CCLE pathway score difference between different -somy groups was determined using Wilcoxon rank sum test.

Data availability. The mass spectrometry proteomics data have been deposited to the ProteomeXchange Consortium via the PRIDE partner repository with the dataset identifier PXD018440. LFQ data was deposited on PRIDE partner repository with the dataset identifier PXD022927. The transcriptome of RM X was uploaded on ENA with accession number PRJEB38328. All other transcriptomes are uploaded in NCBI Omnibus with accession number GSE150686.

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Author Contributions

NKC constructed and analyzed the monosomic ip53 cells lines, performed and evaluated the experiments, analyzed the bioinformatics data and wrote the manuscript; PM and MR performed the proteomics and analyzed the data; BRM, CB and JOK created the monosomic KO cell lines, performed the DNA sequencing and analysis; XZ and MK performed the CCLE and TCGA data mining; NKC, VLG and FW performed polysome analyses; ZS conceived and supervised the study, analyzed the data and wrote the manuscript. All authors commented on the manuscript.

Declaration of Interests

The authors declare no competing interests.

References

- (1) Nagaoka, S. I., Hassold, T. J., and Hunt, P. A. (2012). Human aneuploidy: mechanisms and new insights into an age-old problem. *Nat Rev Genet* 13, 493–504.
- (2) Soto, M., Raaijmakers, J. A., Bakker, B., Spierings, D. C. J., Lansdorp, P. M., Foijer, F., and Medema, R. H. (2017). p53 Prohibits Propagation of Chromosome Segregation Errors that Produce Structural Aneuploidies. *Cell Rep* 19, 2423–2431.
- (3) Santaguida, S., Richardson, A., Iyer, D. R., M'Saad, O., Zasadil, L., Knouse, K. A., Wong, Y. L., Rhind, N., Desai, A., and Amon, A. (2017). Chromosome Mis-segregation Generates Cell-Cycle-Arrested Cells with Complex Karyotypes that Are Eliminated by the Immune System. *Dev Cell* 41, 638–651 e5.
- (4) Pfau, S. J., Silberman, R. E., Knouse, K. A., and Amon, A. (2016). Aneuploidy impairs hematopoietic stem cell fitness and is selected against in regenerating tissues *in vivo*. *Genes Dev* 30, 1395–408.
- (5) Knouse, K. A., Wu, J., Whittaker, C. A., and Amon, A. (2014). Single cell sequencing reveals low levels of aneuploidy across mammalian tissues. *Proc Natl Acad Sci U S A* 111, 13409–14.
- (6) Zhu, J., Tsai, H.-J., Gordon, M. R., and Li, R. (2018). Cellular Stress Associated with Aneuploidy. *Developmental Cell* 44, 420–431.
- (7) Chunduri, N. K., and Storchova, Z. (2019). The diverse consequences of aneuploidy. *Nat Cell Biol* 21, 54–62.
- (8) Magnuson, T., Debrot, S., Dimpfl, J., Zweig, A., Zamora, T., and Epstein, C. J. (1985). The early lethality of autosomal monosomy in the mouse. *J Exp Zool* 236, 353–60.
- (9) McCallie, B. R., Parks, J. C., Patton, A. L., Griffin, D. K., Schoolcraft, W. B., and Katz-Jaffe, M. G. (2016). Hypomethylation and Genetic Instability in Monosomy Blastocysts May Contribute to Decreased Implantation Potential. *PLoS One* 11, e0159507.
- (10) Biancotti, J. C., Narwani, K., Mandefro, B., Golan-Lev, T., Buehler, N., Hill, D., Svendsen, C. N., and Benvenisty, N. (2012). The in vitro survival of human monosomies and trisomies as embryonic stem cells. *Stem Cell Res* 9, 218–24.
- (11) Watson, C. T., Marques-Bonet, T., Sharp, A. J., and Mefford, H. C. (2014). The Genetics of Microdeletion and Microduplication Syndromes: An Update. *Annual Review of Genomics and Human Genetics* 15, 215–244.
- (12) Schwartz, M., Sternberg, D., Whalen, S., Afenjar, A., Isapof, A., Chabrol, B., Portnoi, M.-F., Heide, S., Keren, B., Chantot-Bastaraud, S., and Siffroi, J.-P. (2018). How chromosomal deletions can unmask recessive mutations? Deletions in 10q11.2 associated with CHAT or SLC18A3 mutations lead to congenital myasthenic syndrome. *American Journal of Medical Genetics Part A* 176, 151–155.
- (13) Egloff, M., Nguyen, L. S., Siquier-Pernet, K., Cormier-Daire, V., Baujat, G., Attie-Bitach, T., Bole-Feysot, C., Nitschke, P., Vekemans, M., Colleaux, L., and Malan, V. (2018). Whole-exome sequence analysis highlights the role of unmasked recessive mutations in copy number variants with incomplete penetrance. *Eur J Hum Genet* 26, 912–918.
- (14) Poot, M., and Haaf, T. (2015). Mechanisms of Origin, Phenotypic Effects and Diagnostic Implications of Complex Chromosome Rearrangements. *Mol Syndromol* 6, 110–34.
- (15) Gravholt, C. H., Viuff, M. H., Brun, S., Stochholm, K., and Andersen, N. H. (2019). Turner syndrome: mechanisms and management. *Nat Rev Endocrinol* 15, 601–614.
- (16) Taylor, A. M., Shih, J., Ha, G., Gao, G. F., Zhang, X., Berger, A. C., Schumacher, S. E., Wang, C., Hu, H., Liu, J., Lazar, A. J., Cancer Genome Atlas Research, N., Cherniack, A. D., Beroukhim, R., and Meyerson, M. (2018). Genomic and Functional Approaches to Understanding Cancer Aneuploidy. *Cancer Cell* 33, 676–689 e3.
- (17) Ebert, B. L., Pretz, J., Bosco, J., Chang, C. Y., Tamayo, P., Galili, N., Raza, A., Root, D. E., Attar, E., Ellis, S. R., and Golub, T. R. (2008). Identification of RPS14 as a 5q- syndrome gene by RNA interference screen. *Nature* 451, 335–9.
- (18) Liu, Y. et al. (2016). Deletions linked to TP53 loss drive cancer through p53-independent mechanisms. *Nature* 531, 471–475.
- (19) Carrel, L., and Willard, H. F. (2005). X-inactivation profile reveals extensive variability in X-linked gene expression in females. *Nature* 434, 400–404.
- (20) Oromendia, A. B., Dodgson, S. E., and Amon, A. (2012). Aneuploidy causes proteotoxic stress in yeast. *Genes Dev* 26, 2696–708.
- (21) Donnelly, N., Passerini, V., Durrbaum, M., Stingle, S., and Storchova, Z. (2014). HSF1 deficiency and impaired HSP90-dependent protein folding are hallmarks of aneuploid human cells. *EMBO J* 33, 2374–87.
- (22) Ohashi, A., Ohori, M., Iwai, K., Nakayama, Y., Nambu, T., Morishita, D., Kawamoto, T., Miyamoto, M., Hirayama, T., Okaniwa, M., Banno, H., Ishikawa, T., Kandori, H., and Iwata, K. (2015). Aneuploidy generates proteotoxic stress and DNA damage concurrently with p53-mediated post-mitotic apoptosis in SAC-impaired cells. *Nat Commun* 6, 7668.

- (23) Tang, Y.-C., Williams, B. R., Siegel, J. J., and Amon, A. (2011). Identification of Aneuploidy-Selective Antiproliferation Compounds. *Cell* 144, 499–512.
- (24) Savitski, M. M., Mathieson, T., Zinn, N., Sweetman, G., Doce, C., Becher, I., Pachl, F., Kuster, B., and Bantscheff, M. (2013). Measuring and managing ratio compression for accurate iTRAQ/TMT quantification. *J Proteome Res* 12, 3586–98.
- (25) Stingele, S., Stoehr, G., Pepłowska, K., Cox, J., Mann, M., and Storchova, Z. (2012). Global analysis of genome, transcriptome and proteome reveals the response to aneuploidy in human cells. *Mol Syst Biol* 8, 608.
- (26) McShane, E., Sin, C., Zauber, H., Wells, J. N., Donnelly, N., Wang, X., Hou, J., Chen, W., Storchova, Z., Marsh, J. A., Valleriani, A., and Selbach, M. (2016). Kinetic Analysis of Protein Stability Reveals Age-Dependent Degradation. *Cell* 167, 803–815 e21.
- (27) Cox, J., and Mann, M. (2008). MaxQuant enables high peptide identification rates, individualized p.p.b.-range mass accuracies and proteome-wide protein quantification. *Nat Biotechnol* 26, 1367–72.
- (28) Zhu, P. J., Khatiwada, S., Cui, Y., Reineke, L. C., Dooling, S. W., Kim, J. J., Li, W., Walter, P., and Costa-Mattioli, M. (2019). Activation of the ISR mediates the behavioral and neurophysiological abnormalities in Down syndrome. *Science* 366, 843–849.
- (29) Kenmochi, N., Kawaguchi, T., Rozen, S., Davis, E., Goodman, N., Hudson, T. J., Tanaka, T., and Page, D. C. (1998). A map of 75 human ribosomal protein genes. *Genome Res* 8, 509–23.
- (30) Westermann, A. J., Gorski, S. A., and Vogel, J. (2012). Dual RNA-seq of pathogen and host. *Nat Rev Microbiol* 10, 618–30.
- (31) Ebright, R. Y. et al. (2020). Dereulation of ribosomal protein expression and translation promotes breast cancer metastasis. *Science* 367, 1468–1473.
- (32) Mills, E. W., and Green, R. (2017). Ribosomopathies: There's strength in numbers. *Science* 358, DOI: .
- (33) Barretina, J. et al. (2012). The Cancer Cell Line Encyclopedia enables predictive modelling of anticancer drug sensitivity. *Nature* 483, 603–7.
- (34) Hanzelmann, S., Castelo, R., and Guinney, J. (2013). GSVA: gene set variation analysis for microarray and RNA-seq data. *BMC Bioinformatics* 14, 7.
- (35) Knijnenburg, T. A. et al. (2018). Genomic and Molecular Landscape of DNA Damage Repair Deficiency across The Cancer Genome Atlas. *Cell Rep* 23, 239–254 e6.
- (36) Ciriello, G., Miller, M. L., Aksoy, B. A., Senbabaooglu, Y., Schultz, N., and Sander, C. (2013). Emerging landscape of oncogenic signatures across human cancers. *Nat Genet* 45, 1127–33.
- (37) Passerini, V., Ozeri-Galai, E., de Pagter, M. S., Donnelly, N., Schmalbrock, S., Kloosterman, W. P., Kerem, B., and Storchova, Z. (2016). The presence of extra chromosomes leads to genomic instability. *Nat Commun* 7, 10754.
- (38) Vigano, C., von Schubert, C., Ahrne, E., Schmidt, A., Lorber, T., Bubendorf, L., De Vetter, J. R. F., Zaman, G. J. R., Storchova, Z., and Nigg, E. A. (2018). Quantitative proteomic and phosphoproteomic comparison of human colon cancer DLD-1 cells differing in ploidy and chromosome stability. *Mol Biol Cell* 29, 1031–1047.
- (39) Licciardi, F., Lhakhang, T., Kramer, Y. G., Zhang, Y., Heguy, A., and Tsirigos, A. (2018). Human blastocysts of normal and abnormal karyotypes display distinct transcriptome profiles. *Sci Rep* 8, 14906.
- (40) Malone, J. H., Cho, D. Y., Mattiuzzo, N. R., Artieri, C. G., Jiang, L., Dale, R. K., Smith, H. E., McDaniel, J., Munro, S., Salit, M., Andrews, J., Przytycka, T. M., and Oliver, B. (2012). Mediation of Drosophila autosomal dosage effects and compensation by network interactions. *Genome Biol* 13, r28.
- (41) Dutt, S., Narla, A., Lin, K., Mullally, A., Abayasekara, N., Megerdichian, C., Wilson, F. H., Currie, T., Khanna-Gupta, A., Berliner, N., Kutok, J. L., and Ebert, B. L. (2011). Haploinsufficiency for ribosomal protein genes causes selective activation of p53 in human erythroid progenitor cells. *Blood* 117, 2567–76.
- (42) Fisher, E. M., Beer-Romero, P., Brown, L. G., Ridley, A., McNeil, J. A., Lawrence, J. B., Willard, H. F., Bieber, F. R., and Page, D. C. (1990). Homologous ribosomal protein genes on the human X and Y chromosomes: escape from X inactivation and possible implications for Turner syndrome. *Cell* 63, 1205–18.
- (43) Pakos-Zebrucka, K., Koryga, I., Mnich, K., Ljujic, M., Samali, A., and Gorman, A. M. (2016). The integrated stress response. *EMBO Rep* 17, 1374–1395.
- (44) Saxton, R. A., and Sabatini, D. M. (2017). mTOR Signaling in Growth, Metabolism, and Disease. *Cell* 168, 960–976.
- (45) Morrill, S. A., and Amon, A. (2019). Why haploinsufficiency persists. *Proc Natl Acad Sci U S A* 116, 11866–11871.
- (46) Sung, M. K., Reitsma, J. M., Sweredoski, M. J., Hess, S., and Deshaies, R. J. (2016). Ribosomal proteins produced in excess are degraded by the ubiquitin-proteasome system. *Mol Biol Cell* 27, 2642–52.
- (47) Zuo, E. et al. (2017). CRISPR/Cas9-mediated targeted chromosome elimination. *Genome Biol* 18, 224.
- (48) Kulasekaran, A. G., Smith, A. E., Mian, S. A., Mohamedali, A. M., Krishnamurthy, P., Lea, N. C., Gaken, J., Pennaneach, C., Ireland, R., Czepulkowski, B., Pomplun, S., Marsh, J. C., and Mufti, G. J. (2013). TP53 mutations in myelodysplastic syndrome are strongly correlated with aberrations of chromosome 5, and correlate with adverse prognosis. *Br J Haematol* 160, 660–72.

- (49) MacInnes, A. W., Amsterdam, A., Whittaker, C. A., Hopkins, N., and Lees, J. A. (2008). Loss of p53 synthesis in zebrafish tumors with ribosomal protein gene mutations. *Proc Natl Acad Sci U S A* 105, 10408–13.
- (50) Mardin, B. R., Drainas, A. P., Waszak, S. M., Weischenfeldt, J., Isokane, M., Stutz, A. M., Raeder, B., Efthymiopoulos, T., Buccitelli, C., Segura-Wang, M., Northcott, P., Pfister, S. M., Lichter, P., Ellenberg, J., and Korbel, J. O. (2015). A cell-based model system links chromothripsis with hyperploidy. *Mol Syst Biol* 11, 828.
- (51) Shalem, O., Sanjana, N. E., Hartenian, E., Shi, X., Scott, D. A., Mikkelsen, T., Heckl, D., Ebert, B. L., Root, D. E., Doench, J. G., and Zhang, F. (2014). Genome-scale CRISPR-Cas9 knockout screening in human cells. *Science* 343, 84–87.
- (52) Heinz, N., Schambach, A., Galla, M., Maetzig, T., Baum, C., Loew, R., and Schiedlmeier, B. (2010). Retroviral and Transposon-Based Tet-Regulated All-In-One Vectors with Reduced Background Expression and Improved Dynamic Range. *Human Gene Therapy* 22, 166–176.
- (53) Pringle, E. S., McCormick, C., and Cheng, Z. (2019). Polysome Profiling Analysis of mRNA and Associated Proteins Engaged in Translation. *Curr Protoc Mol Biol* 125, e79.
- (54) Goddard, T. D., Huang, C. C., Meng, E. C., Pettersen, E. F., Couch, G. S., Morris, J. H., and Ferrin, T. E. (2018). UCSF ChimeraX: Meeting modern challenges in visualization and analysis. *Protein Sci* 27, 14–25.
- (55) Dobin, A., Davis, C. A., Schlesinger, F., Drenkow, J., Zaleski, C., Jha, S., Batut, P., Chaisson, M., and Gingeras, T. R. (2013). STAR: ultrafast universal RNA-seq aligner. *Bioinformatics* 29, 15–21.
- (56) Liao, Y., Smyth, G. K., and Shi, W. (2014). featureCounts: an efficient general purpose program for assigning sequence reads to genomic features. *Bioinformatics* 30, 923–30.
- (57) Love, M. I., Huber, W., and Anders, S. (2014). Moderated estimation of fold change and dispersion for RNA-seq data with DESeq2. *Genome Biol* 15, 550.
- (58) Wang, Y., Yang, F., Gritsenko, M. A., Wang, Y., Clauss, T., Liu, T., Shen, Y., Monroe, M. E., Lopez-Ferrer, D., Reno, T., Moore, R. J., Klemke, R. L., Camp, 2., D. G., and Smith, R. D. (2011). Reversed-phase chromatography with multiple fraction concatenation strategy for proteome profiling of human MCF10A cells. *Proteomics* 11, 2019–26.
- (59) Ritchie, M. E., Phipson, B., Wu, D., Hu, Y., Law, C. W., Shi, W., and Smyth, G. K. (2015). limma powers differential expression analyses for RNA-sequencing and microarray studies. *Nucleic Acids Res* 43, e47.
- (60) Huber, W., von Heydebreck, A., Sultmann, H., Poustka, A., and Vingron, M. (2002). Variance stabilization applied to microarray data calibration and to the quantification of differential expression. *Bioinformatics* 18 Suppl 1, S96–104.
- (61) Cox, J., and Mann, M. (2012). 1D and 2D annotation enrichment: a statistical method integrating quantitative proteomics with complementary high-throughput data. *BMC Bioinformatics* 13 Suppl 16, S12.
- (62) Carter, S. L. et al. (2012). Absolute quantification of somatic DNA alterations in human cancer. *Nat Biotechnol* 30, 413–21.
- (63) Liberzon, A., Subramanian, A., Pinchback, R., Thorvaldsdottir, H., Tamayo, P., and Mesirov, J. P. (2011). Molecular signatures database (MSigDB) 3.0. *Bioinformatics* 27, 1739–40.