Translesion DNA synthesis polymerase κ is essential to a carcinogen-induced nucleolar stress response

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Abstract

DNA polymerase kappa (Polκ) has multiple cellular roles such as translesion DNA synthesis, replication of repetitive sequences and nucleotide excision repair. Since all polymerases insert the canonical deoxynucleotide triphosphates, it is difficult to determine which polymerase is active at a particular genomic site. To counter this difficulty, we utilized the selective Polκ substrate, N^2-(4-ethynylbenyl)-2'-deoxyguanosine (EBndG), as bait to capture proteins associated with Polκ synthesized DNA. Here we show that, Polκ is active in the nucleolus and Polκ synthesized DNA are enriched with nucleolar proteins. Exposure of cells to benzo[*a*]pyrene diol epoxide (BPDE) increases Polκ stability and induces hallmarks of

nucleolar stress. The expression and activity of Polκ is regulated by the polycomb complex protein Ring Finger Protein 2 (RNF2) and by the PARylation by poly(ADP)-ribose polymerase 1 (PARP1). This study provides insight into the novel role of Polκ in the nucleolus and in maintaining ribosomal DNA integrity after BPDE damage.

Introduction

DNA polymerase kappa (Polκ) is one of the sixteen DNA-dependent DNA polymerases expressed in humans [1]. The most-studied function of Polκ is translesion DNA synthesis (TLS), which is one of the mechanisms by which the cell responds to DNA damage that cannot be processed by high fidelity DNA polymerases. In this mechanism, Polκ can insert dCMP efficiently opposite bulky N^2-alkyl-dG adducts [2–5]. While the TLS function of Polκ has been the most-studied, other functions of Polκ are being elucidated. Polκ has been linked with nucleotide excision repair [6], cross-link repair [7,8], the production of short oligodeoxynucleotides in the ATR activation pathway [9] and in replication of repetitive DNA sequences [10,11]. A hurdle with determining when and where a specific DNA polymerase is active is that all polymerases utilize undamaged DNA and the four deoxynucleotide triphosphates as substrates. To counter this impediment, we utilized N^2-4-ethynylbenzyl-2´-deoxyguanosine (EBndG), a non-natural nucleoside that has high specificity for Polκ over other mammalian DNA polymerases [12]. Using this tool, we identified a role for Polκ in the repair of ribosomal DNA (rDNA).

rDNA is present in the human genome in hundreds of copies. The 5.8S, 18S, and 28S rDNA sequences are located within the nucleolar organizer regions (NORs) on the short p-arms of

chromosomes 13, 14, 15, 21 and 22. The rRNA is transcribed as a single transcript to form a 47S pre-rRNA that is processed in the nucleolus before being assembled as the ribosome in the cytoplasm. rDNA is the most actively transcribed regions in the genome and ribosome production comprises the bulk of the energy consumption of the cell [13].

The repetitive nature of the NORs, presence of rDNA genes in clusters on five different chromosomes, high transcription rate that creates conflicts with replication forks [13] lead to replication stress (RS) [14,15]. The transcription-associated R-loops that are formed due to negative supercoiling of DNA behind a transcription bubble and the opening of DNA strands forming stable RNA:DNA hybrids [16,17] are increased under replication stress [18]. Persistent RS and R-loops create replication fork slowing and stalling that can lead to long stretches of single-stranded DNA (ssDNA) and single-strand DNA breaks (SSBs). In situations that leads stalled forks to collapse, SSBs convert into double-strand breaks (DSBs) and make the rDNA genes highly vulnerable to DNA damage [19].

Active transcription of rDNA by RNA polymerase I (RNAPI) initiates nucleoli formation, a membrane-less compartment in the nucleus created by liquid-liquid phase separation. The nucleoli are dispersed during mitosis, and then small nucleoli containing individual NORs are reformed during telophase when rRNA transcription resumes. With progression of the cell cycle, nucleoli fuse and form larger nucleoli containing multiple NORs. The nucleolus is a "tripartite" nuclear structure with multiple sub-compartments, the fibrillar center (FC), the dense fibrillar component (DFC) and the granular component (GC) [20,21]. Transcription of pre-ribosomal RNA (pre-rRNA) occurs at the interface of the FC and DFC compartments. FCs are enriched in components of the RNAPI machinery, such as upstream binding transcription

factor (UBF1), DFC contains pre-rRNA processing factors such as t fibrillarin (FBL), and the GC where preribosome subunit assembly occurs contains nucleophosmin (NPM1).

The nucleolus responds to different types of DNA damaging agents by activating varied signaling pathways leading to activation of ATM and ATR activity that triggers the inhibition of RNAPI. The inhibition of RNAPI leads to the nuclear stress response, which comprises dramatic changes in nucleolar structure, protein composition and nucleolar function [22–25]. One consequence of nucleolar rearrangement is the formation of nucleolar caps in which the FC and the DFC segregate to the exterior of the nucleolus along with rDNA. DNA repair proteins have also been identified in the nucleolar caps. It is hypothesized that the localization of repair proteins with damaged DNA aids in the repair of the rDNA [26]. The nature of the DNA damage that causes the nucleolar stress response is not known, as DSBs, acrolein and oxaliplatin induce nucleolar cap formation while cisplatin does not [27–29].

Homologous recombination (HR), non-homologous end joining (NHEJ) and nucleotide excision repair (NER) are found to occur in rDNA. HR proteins are found in nucleolar caps, suggesting that HR occurs at these locations, while NHEJ proteins are found in the nucleoplasm [24]. Nucleolar NER is inhibited by XPC knockdown, indicating that the GG-NER pathway occurs on rDNA. However, CSB knockdown does not reduce NER, indicating that the traditional CSB-dependent TC-NER does not occur in rDNA [30].

The nucleolar DNA damage response is not limited to the repair of rDNA by these pathways. Over 4500 proteins have been found in the nucleolus including 166 DNA repair proteins [31–34]. For instance, almost half of the DNA damage response (DDR) protein poly(ADP)-ribose polymerase 1 (PARP1) is present in the nucleolus [35,36]. Mounting evidence suggests that the nucleolus is a stress response organelle that responds uniquely to different DNA damage and

stressors [37]. Several proteins are released from the nucleolus upon nucleolar stress [38,39], such as PARP1, which upon release to the nucleoplasm sensitizes cells to DNA damage-induced apoptosis [36]. NPM1, a chaperone protein that is involved in ribosome biogenesis is also released into the nucleoplasm upon stress where it binds to MDM2 and prevents the MDM2-initiated degradation of p53, leading to the activation of the p53 DDR pathway [40]. Additionally, NPM1 binds to and stabilizes DNA polymerase η (Polη), increasing its activity in TLS [41].

In this study, we report the role of Polκ in the nucleolar stress response. In response to (+/-)-*trans*-benzo[*a*]pyrene-7,8-dihydrodiol-9,10-epoxide (BPDE) treatment, cells undergo nucleolar stress in which nucleolar caps are formed, NPM1 is translocated from nucleolus to the nucleoplasm and the transcription of 47S pre-RNA is inhibited. In spite of the reduced transcription of POLK mRNA, levels of Polκ remain high and enhanced Polκ activity is observed in the nucleolus. The activation of Polκ is dependent on PARP1 PARylation and PRC1 activity.

Results

TLS Polymerase κ (Polκ) is active in the nucleolus

To identify novel cellular roles of Polκ, we employed an unbiased proteomics approach to determine the proteins associated with DNA that was replicated by Polκ in cells under normal growth conditions and after exposure to BPDE. We captured the DNA replicated by Polκ by incubating cells with the novel nucleotide analog EBndG, which we previously showed to be selectively incorporated into DNA by Polκ [12]. We developed a modified aniPOND (accelerated

native isolation of proteins on nascent DNA) [42] procedure, which we termed iPoKD (isolation of proteins on Polkappa synthesized DNA) (Paul *et al* manuscript in preparation), to capture proteins bound to the nascent DNA synthesized by Polκ. Two different human cell lines (HEK293 and GM12878) were treated with 0, 0.1 μM, medium 0.5 μM or high 2 μM BPDE and subsequently incubated with 100 μM EBndG. We noted that cell viability was not affected upon incubation with 100 μM EBndG (Figure S1A). The proteins bound to the DNA containing EBndG were identified by mass spectrometry. To compare the proteins associated with EBndG with proteins present at replication forks and replication-coupled DNA repair mechanisms, we complimented our iPoKD procedure with a traditional aniPOND experiment using BPDE and 5-ethynyl-2'-deoxyuridine (EdU) (Figure 1A).

A Gene Ontology (GO) analysis of our data identified DNA replication and repair proteins (Paul *et al* manuscript in preparation) previously identified with EdU pull-downs [43–45]. However, proteins associated with EBndG when compared with EdU pull-downs in both cell lines (Figure 1B, S1B) showed enrichment of nucleolar proteins required for ribosome biogenesis, processing and metabolism (Figure 1C, S1C, TableS1). Similar enrichment of nucleolar proteins was identified with Polκ synthesized DNA in U2OS human osteosarcoma cells using quantitative MS (TMT labelling) after iPoKD. Out of 511 proteins pulled-down with EBndG, 195 are nucleolar residing proteins (Figure S1D). A representation of the subset of proteins associated with nascent DNA synthesized by Polκ and their fold change compared to the beads control are shown in Figure 1D. Proteins associated with EBndG with and without BPDE damage, play roles in rDNA transcription and are present in each of the nucleolar sub-compartments (Figure 1D). The only DNA polymerase that was enriched with the iPoKD

technique was Polκ. This observation supports the specificity of EBndG to Polκ and no other DNA polymerase.

BPDE exposure induced nucleolar stress

Since nucleolar proteins are enriched with EBndG pull-down, we questioned whether Polκ is associated with the rDNA damage response pathway. To interrogate the novel role of Polκ in the nucleolus, super-resolution microscopy was used to locate and quantify EBndG in U2OS cells. These cells were utilized because they prominently display an average of 6 nucleoli per nucleus [21] and the BPDE treated S-phase arrested cells [46] show prominent DAPI-less nucleolar cavities. The incorporation of EBndG into DNA was visualized *in situ* by performing the copper(I)-catalyzed azide–alkyne cycloaddition (CuAAC) to covalently label the EBndG with an azide fluorophore. This approach is similar to visualizing 5-EU in nascent RNA [47] or EdU in nascent DNA by click reaction. EBndG treatment resulted in low levels of incorporation throughout the nucleus with some cells showing nucleolar incorporation (0μM BPDE panels in Figure 2A, B, D and S2A). Following increasing BPDE exposure, EBndG incorporation was increased in the nucleus (Figure 2Bii, S2Bi) and became noticeably enriched in the nucleolus compared with the nucleoplasm (Figure 2B-D, S2B-SD). Treatment with 2 μM BPDE resulted in nucleolar EBndG enrichment in all cells (Figure 2C, S2C). This striking observation led us to explore whether BPDE treatment causes nucleolar stress and if Polκ was involved in the DNA damage stress response in the nucleolus.

After treatment with various doses of BPDE followed by incubation with EBndG, we examined the localization of NPM1, as it's translocation into the nucleoplasm is a typical hallmark of the

nucleolar stress response [40]. In a dose-dependent effect, increasing concentrations of BPDE led to NPM1 becoming concentrated on the periphery of the nucleolus (Figure 2A) and then being totally excluded (Figure 2B-C and S2A-C). We also observed an increase in NPM1 protein expression after a 2 μM dose of BPDE (Figure 2Biii, S2Bii, S8A), and noted that some amount of NPM1 translocate to the cytoplasm (Figure 2C, S2C).

We next examined the nucleolar proteins UBF1 and FBL that are present in the FC and DFC, respectively, and translocate to nucleolar caps upon nucleolar stress[26]. A significant fraction of BPDE-treated cells contained distinct large nucleoli, with rearrangement of UBF1 and FBL proteins to nucleolar caps (Figure 2D-E, S2D-E). Altogether, our data suggest that BPDE exposure leads to nucleolar stress.

EBndG is inserted in rDNA and its nuclear incorporation is dependent on Polκ

To confirm that the EBndG incorporation in the nucleus and the nucleolar enrichment observed after BPDE damage is entirely dependent on Polκ, we utilized U2OS sgPolK cells that were previously shown to be deficient in Polκ [48]. We observed that U2OS sgPolK cells failed to incorporate EBndG in the nucleus or nucleolus (Figure 3A, S2A), and EBndG incorporation was rescued upon complementation with wild-type GFP-POLK (Figure 3B, S3A). We observed that even after 24 h of EBndG treatment, while the wild-type (WT) cells retained EBndG in the nucleolus, there was no trace of nucleolar EBndG in the Polκ deficient cells (Figure S3B).

In addition, we used siRNA to knockdown Polκ in U2OS cells (siPOLK) and observed significantly reduced EBndG incorporation (Figure 3C, 3Cii, S3C-D). The *POLK* transcript level was reduced by ~ 40% in siPOLK cells, and a similar decrease in *POLK* transcript level was

observed upon BPDE (2 μM) treatment. The combination of siPOLK and BPDE additionally decreased *POLK* transcript levels (Figure 3D). In contrast to mRNA levels, Polκ proteins levels increased ~2-3 fold upon BPDE treatment. We observed that the steady state Polκ protein levels were inherently lower in undamaged cells, which was stabilized upon BPDE damage (Figure 2Bi, S2Biii and 3E). This result suggests that BPDE treatment increases Polκ levels by protecting the protein from proteolytic degradation.

In comparison to EBndG enrichment in the nucleolus that is dependent on the presence of Polκ in the cell, EdU was incorporated as foci throughout the nucleus and was not reduced in Polκ compromised cells (Figure 3F, S3E). We also found that EBndG incorporation in the nucleolus/nucleus was not dependent on other Y-family polymerases. Cells compromised in Polη, Polι and Rev1 (transfected with respective siRNA pool) showed no reduction in EBndG incorporation (Figure 3G, S3F). Instead, we noted an increase in EBndG incorporation in Polη compromised cells (Figure 3G graph).

We next queried whether the Polκ dependent EBndG enrichment in the nucleolus is due to the incorporation of EBndG in the rDNA. To test this possibility, we treated the cells with deoxyribonuclease I (DNase I) and observed a significant reduction in total nuclear EBndG intensity and a loss of nucleolar accumulation (Figure 4A-B, S4). Upon treatment with RNase A, we observed a small decrease in total nuclear EBndG intensity (Figure 4B), while the nucleolar pattern remained intact (Figure 4A). In contrast, while RNase H treatment did not affect the total EBndG intensity (Figure 4B), the nucleolar pattern was destroyed (Figure 4A). This result suggests that EBndG is incorporated in rDNA, possibly in regions containing R-loops.

Polκ cellular expression and nucleolar activity are dependent on PARylation by PARP1

We identified from our iPoKD-MS data that PARP1 is associated with EBndG on DNA newly synthesized by Polκ (Figure 1D). Approximately 40% of PARP1 molecules reside within nucleoli [36] and the binding of PARP1 to DNA induces its catalytic activity, synthesizing poly(ADP)-ribose (PAR) chains on itself, histone and non-histone proteins ,[49–51] that recruits DDR proteins to the DNA lesions [52]. BPDE treatment induces cellular PAR formation by PARP1 in a time and dose-dependent manner, while inhibition of PARylation by Veliparib (ABT-888) sensitizes cells to BPDE [53].

Since we identified PARP1 on DNA synthesized by Polκ, we hypothesized that the activity of Polκ, especially in rDNA, is dependent on PARP1 PARylation. We inhibited PARylation with olaparib and then damaged the cells with BPDE (2μM) followed by incubation with EBndG. We found that olaparib treatment decreased EBndG incorporation both in BPDE-untreated and treated cells (Figure 5B, 5Ci and S5A-B). We also noted that in olaparib-treated cells, Polκ protein expression was significantly reduced (Figure 5B, Cii, D and S5A-B). With combinative treatment of olaparib and BPDE, cells showed excessive stress, as evident by distribution of PARP1 as patches in the cytoplasm indicating that the cells were undergoing apoptosis (Figure 5A, S5A).

Recruitment of RNF2 in the periphery of the nucleolus is mediated by PARP1 PARylation and essential for Polκ's nucleolar activity

To understand the mechanism by which PARylation by PARP1 is maintaining the recruitment of Polκ and its activity, we probed whether Polycomb Repressive Complexes (PRCs) proteins have a role in maintaining the activity of Polκ. There are two reasons to examine the involvement of PRCs. First, our iPokD-MS data identified the majority of the PRC canonical proteins including PRC1 protein Ring Finger Protein 2 (RNF2) as being associated with nascent DNA synthesized by Polκ (Figure 1D). Second, it was shown that recruitment of the RNF2 containing complex FBXL10-RNF68-RNF2 ubiquitin ligase complex (FRRUC) to DNA lesions is mediated by PARP1 and is an early and critical regulatory step in HR [54]. As we predicted, inhibition of PARylation by olaparib significantly reduced RNF2 foci all throughout the nucleus, as well as the larger RNF2 discrete foci near nucleolar periphery (Figure 5B, 5Ciii and S5B), which possibly are polycomb bodies [55]. It has already been established that PRC proteins play a role in the formation of facultative heterochromatin in the nucleolar-associated domains (NADs) located at the nucleolar periphery [56]. We observed that upon BPDE treatment, large discrete RNF2 bodies were present near the nucleolar periphery compared to untreated cells (Figure 5B and S6A), suggesting the presence of RNF2 in NADs. We observed enrichment of H2AK119Ub1 near the nucleolar periphery in a manner similar to RNF2 bodies (Figure S6A), consistent with RNF2-catalyzed ubiquitination in NADs after BPDE damage. This activity is known to be critical for polycomb-mediated transcriptional repression [57].

Since inhibition of PARP1 PARylation reduced the number of RNF2 containing NADs (Figure 5B, Ciii and S5B), we examined if the nucleolar activity of Polκ is mediated by RNF2 in the NADs. Transfection of cells with siRNF2 significantly reduced RNF2 expression (Figure 6A, Biii, S6B and S8D). The RNF2 knockdown cells were untreated or damaged with BPDE followed by incubation with EBndG. Surprisingly, we observed that RNF2 knockdown cells

have reduced Polκ protein expression (Fig 6A, Bi, C and S6B) and these cells failed to incorporate EBndG in the nucleolus and overall nucleus (Figure 6A, 6Bii and S6B). These results indicate that Polκ levels and activity are dependent on PARP1 and RNF2 activities. However, this regulation is not at the *POLK* mRNA level, as siRNF2 treatment increased POLK gene transcription (Figure 6D). Altogether, our data suggest that PARP1 PARylation increases the RNF2 foci formation that in turn maintain Polκ activity.

Polκ plays an essential role in recovering from nucleolar stress after BPDE damage

Since our experiments provide evidence that Polκ is active in the nucleolus, we next investigated whether Polκ participates in the recovery of cells from BPDE-induced rDNA damage and nucleolar stress. It was previously shown that persistent S-phase arrest in BPDE (0.1 μM) treated Polκ -/- mouse embryonic fibroblasts (MEFs), led to DSBs as detected by increased levels of γH2AX [58]. In U2OS cells, we observed a similar increase in γH2AX in undamaged Polκ compromised cells compared to cells transfected with scrambled siRNA, that profoundly increased after BPDE damage (Figure 7A, S7A). We also noticed γH2AX foci inside and in the periphery of the nucleolus, indicating DSBs in rDNA as shown by the arrows in the +BPDE panels in Figure S7A. Since rDNA damage will hinder rRNA transcription, using RT-qPCR we detected reduced 47S primary pre-rRNA transcript (Figure 7B) in Polκ compromised cells. In addition, we incubated cells with 5-ethynyluridine (EU) to examine rRNA transcription in the nucleolus. We observed robust nucleolar EU incorporation in undamaged cells (Figure 7Ci-ii and S7B), indicating rRNA transcription. However, after BPDE damage, EU incorporation

was significantly reduced in Polκ compromised cells (Figure 7Ci-ii and S7B). These experiments suggest that Polκ is important for repairing rDNA damage caused by BPDE.

We next examined whether Polκ participates in the recovery from BPDE-induced nucleolar stress. We treated Polκ wild-type and knockdown cells with 0.5, or 2 μM BPDE for 2 h, then fixed the cells immediately (t=2 h) or allowed them to recover for 36 h in growth media (t=36 h) (schematic in Figure 7D). As observed before (Figure 2B-C), wild-type cells at t=2 h showed NPM1 translocated from the nucleolus to the nucleoplasm. After 36 h of recovery, NPM1 returned to the nucleolus and showed enrichment at the nucleolar periphery. However, BPDE-treated Polκ compromised cells or Polκ deleted, NPM1 redistributed throughout the cell with a majority of NPM1 in the cytoplasm (Figure 7E, S7C, S2A, S3C-D). Although Polκ expression in the siPOLK cells was recovering after 36 h due to the exhaustion of the siRNA, the recovery from nucleolar stress is still impaired (Figure 7E, S7C).

To further examine the role of Polκ in recovering from nucleolar stress, we examined the formation and recovery of nucleolar caps. As illustrated in Figure 7F, treatment of 0.5 μM BPDE led to the translocation of UBF1 from the interior of the nucleoli to the periphery, an indication of nucleolar cap formation, in both siScrambled and siPOLK cells after 2 h. After 36 h, UBF1 returned to the nucleolus in siScrambled cells, while Polκ compromised cells retained UBF1 in the nucleolar caps (Figure 7F, S7D). This result supports a role of Polκ in the recovery from BPDE-induced nucleolar stress.

Discussion

We demonstrated that the Y-family TLS polymerase, Polκ, is active in the nucleolus, and its activity profoundly increased upon BPDE damage, and protected the cell from nucleolar stress. This conclusion relies on two independent experimental approaches. First, by establishing a novel tool, iPoKD-MS, nucleolar proteins were surprisingly discovered to be highly enriched in DNA that had been synthesized by Polκ. Second, by using super-resolution confocal microscopy, the activity of Polκ in the nucleolus was increased after exposure to BPDE.

Enrichment of PARP1 and the canonical PRC proteins in the iPoKD-MS data, led us to examine their involvement in the activity of Polκ. Our data identified PARylation by PARP1 and the presence of RNF2, the E3 ubiquitin ligase in the PRC1 complex, were required to maintain Polκ levels and its activity in the nucleus/nucleolus (Figures 5 and 6). We noted PARP1 in the cytoplasm of cells treated with both olaparib and BPDE. This result suggests that ablation of PARylation led to the inability of cells to respond to BPDE-induced damage by triggering the apoptosis pathway, in which the caspase fragmentation of PARP1 produces a smaller PARP1 fragment that translocates to the cytoplasm, and induces apoptosis [59].

Lack of PARylation also reduced RNF2 foci formation. When PARylation is inhibited and RNF2 is down regulated, the Polκ levels decreased with a consequent decrease in activity. The effect of RNF2 is complex, because siRNF2 cells showed an increased *POLK* transcript but a decreased Polκ protein level.

Using the specificity of EBndG for Polκ, we showed that Polκ has activity even in untreated cells (Figure 2). Since Polκ activity is observed in all cells, the activity of Polκ is not cell-cycle dependent and may accompany a DNA repair process. Cells are constantly exposed to

endogenous damage [60] and the EBndG incorporation may be related to its NER [6] or cross-link repair [7,8] activity.

The initial damage produced by BPDE is primarily the 10-(deoxyguanosin-N^2-yl)-7,8,9-trihydroxy-7,8,9,10-tetrahydrobenzo[*a*]pyrene (N^2-BP-dG) adduct, but these adducts led to DSBs as shown by an increase in γH2AX [58,61](Figure 7). BPDE damage induces transcription arrest at the sites of damage [62] as well as genome-wide [63,64]. We showed that BPDE treatment also induced the nucleolar stress response by the formation of nucleolar caps (Figure 2), the release of NPM1 from the nucleolus into the nucleoplasm (Figure 2), inhibition of RNAPI transcription of pre 47S rRNA and reduced nucleolar EU incorporation (Figure 7). It is not clear whether the N^2-BP-dG adduct or the induced DSBs led to the nucleolar stress response.

We found that the level of *POLK* mRNA was reduced by BPDE damage. However, the Polκ protein level was increased. The half-life of Polκ is 5 hours [65], thus the reduced mRNA levels should lead to lower Polκ levels unless the protein is stabilized. Our finding that the activity of Polκ did not decrease over 36 h therefore suggests that Polκ protein was stabilized (Figure 7). NPM1 has been shown to regulate TLS by preventing proteasomal degradation of DNA Polη [41]. It is possible that NPM1's upregulation and translocation into the nucleoplasm in BPDE exposed cells helps in maintaining Polκ protein stability, increasing its activity in maintaining genomic stability and thus promoting cell survival. Upon BPDE damage, while the nuclear activity of Polκ increased slightly, there was an increase of the activity of Polκ in the nucleolus as detected by increased EBndG incorporation. We noted that this increase in activity was not due to an increased localization of Polκ to the nucleolus relative to the nucleoplasm (Figure 2), indicating Polκ's role throughout the nucleus including the nucleolus.

Treatment with DNase I and RNase A indicated that the primary location of the EBndG localization is DNA. The loss of the nucleolar signal with RNase H treatment suggests an association with R-loops in which hydrolysis of the RNA allowed the DNA-bound EBndG to diffuse throughout the nucleus (Figure 4). R-loops are transient, reversible structures that form in many regions of the genome. Predictors of R-loop presence include high transcriptional activity, open DNA and high GC content, all present in rDNA [66,67]. R-loops participate in the regulation of transcription, but they also represent a potential source of damage, and their presence must be carefully regulated [68]. The regulation of R-loops depends on RNA-methylation, including METTL3/14 dependent 6-methyladenine (m^6A) and METTL8 dependent 3-methylcytosine formation [69–71]. m^6A RNA was shown to selectively recruit Polκ to UV-damage sites to facilitate repair [72]. Thus, Polκ may interact with nucleolar R-loops.

Down regulation of Polκ resulted in BPDE sensitivity, with an apparent increase in DSBs and nucleolar stress. Additionally, the cells with Polκ were able to respond to BPDE-induced nucleolar stress more rapidly than Polκ deficient cells (Figure 7).

In summary, our data suggest that BPDE exposure leads to genomic lesions including rDNA damage that trigger nucleolar stress. During the nucleolar stress response, nucleolar caps forms as foci to repair damaged rDNA, NPM1 expression increases and translocates to the nucleoplasm, potentially enhancing Polκ protein stability and its activity in the DNA repair process. The BPDE-induced DNA lesions induced PARP1 activity that promoted polycomb body formation near nucleolar periphery, which potentially induces facultative heterochromatin regions at the NADs to promote inhibition of rDNA transcription. The activity of Polκ was critical in recovering cells from BPDE-induced nucleolar stress and S-phase arrest (Figure 8). This

report provides an understanding of the novel role of Polκ in repairing damaged rDNA and recovering from nucleolar stress, opening a new direction and raising several questions: by what mechanism does Polκ play in repair of rDNA, whether NPM1 directly regulates Polκ's stability, and how RNF2 facilitates Polκ protein stability. Since recent evidence connect nucleolar stress as a hallmark in a variety of cancers, neurological and aging-associated diseases [73,73–75], our report demonstrating the critical role of Polκ in nucleolar stress recovery and rDNA maintenance reveal new therapeutic strategies for multiple disease conditions.

Methods

Cell culture, drug treatments and plasmid transfection

HEK293, U2OS and U2OS sgPolK (gift from Tony Huang's laboratory, NYU) [48] cell lines were cultured in Dulbecco's modified Eagle medium (DMEM), supplemented with 10% fetal calf serum (FCS), GM12878 cells were cultured in Roswell Park memorial Institute (RPMI) 1640 medium with 15% FCS. Both the media contained 2mM L-glutamine and penicillin–streptomycin antibiotics and cells were grown under standard cell culture conditions in a CO_2 incubator (37 °C; 5% CO2). BPDE stock (obtained from the Organic Synthesis Core of the Penn State Cancer Institute) was diluted in DMSO concentrations to prepare 0.1, 0.5 or 2 μM from stock by diluting and added immediately to the media. The cells with BPDE added media were incubated for 2 hours in a CO_2 incubator. For olaparib treatment, cells were incubated for 72 hours with 4 μM of olaparib (Sigma-Aldrich, gift from George Lucian Moldovan's lab) added to DMEM media. BPDE damage for 2 hours was performed in 72 hours of olaparib treated cells. Transient plasmid WT-PolK GFP [48] (gift from Tony Huang's laboratory) transfections

were performed using FuGene six reagent (Promega), according to manufacturer's instructions. Analyses were done between 24–48 hr after plasmid transfection.

Isolation of protein on nascent pol κ synthesized DNA (iPoKD)

This procedure is a modification of the native iPOND procedure described by [76]. GM12878 cells (~8X10^6) after treatment with 0, 0.5 μM or 2 μM for 2 hours were incubated with 20 μM EdU (15 mins) or 100 μM EBndG (30 mins) and harvested by centrifugation at 200g for 7.5 mins. HEK293 cells (~4-6x10^8) were incubated after BPDE damage with EdU (15 mins) or EBndG (180 mins). U2OS cells were incubated after 2 μM BPDE damage 100 μM EBndG for 30 mins and immediately harvested (sample "Pulse"). From another set the media containing EBndG was removed and fresh media added and incubated for 180 mins then harvested (sample "Wash-Chase"). Sample for "Beads control" had no nucleotides (EdU or EBndG) added to the cells. Pellets were resuspended in 10 ml of pre-chilled freshly prepared NEB (20mM HEPES-KOH pH 7.2, 50mM NaCl, 3mM MgCl2, 300mM sucrose, 0.5% NP 40 substitute or TX100) and rotated at 4°C for 15 mins. The nuclei were pelleted by centrifuged for 10 mins at 500g at 4°C to pellet. The nuclei pellets were resuspended in 10 ml ice-cold PBS with a serological pipette to wash (10 μl used to check the nuclei under microscope) and collected by by centrifugation at 500×g for 10 min at 4°C. The nuclei pellets were completely resuspended in 10 ml of freshly prepared click reaction mixture [1 mM CuSO4, 2 mM tris(3-hydroxypropyltriazolylmethyl)amine (THPTA), 10 uM azido-PEG3-biotin (Alfa Aesar #J 64996) 10 mM sodium ascorbate, complemented with PBS] and incubated for 1.5 hours at room temperature (RT). The nuclei were centrifuged for 10 mins at 500g at 4°C and the pellet washed 3X with 10 ml ice-cold PBS. The nuclei pellet was either immediately frozen in liquid nitrogen and kept in -80°C or were immediately lysed as described below.

The nuclei pellets were resuspended in 0.5 ml of ice-cold freshly prepared buffer B1 (25 mM NaCl, 2 mM EDTA, 50 mM Tris-HCl-ph8, 1% NP-40 substitute or TX100) supplemented with protease inhibitors (Roche cOmplete Protease Inhibitor Cocktail) and transferred to a 1.5 mL tube and rotated at 4°C for 30min. The nuclei were pelleted by centrifuged at 500g for 10 mins at 4°C supernatant saved as low soluble chromatin and nucleoplasm fraction. The pellets were resuspended again in 0.5 ml of ice-cold buffer B1 and rotated at 4°C for 30 mins. The chromatin was solubilized with a microtip sonicator (Fisher Scientific Model 500 Sonic Dismembrator) by keeping the tubes on ice and performing 6 rounds of 2 X10s on, 10s off (~20A with 1min Rest output). The samples were centrifuged for 10 mins at 16100xg at 4°C and the solubilized chromatin fraction was collected. An aliquot was saved as an input sample. The rest of the sample was supplemented to 1 mL with ice-cold buffer B1 containing protease inhibitors, 50 μL of MyOne Streptavidin T1 Dynabeads (MyOne Streptavidin T1 65602, Thermo-Fisher) were added, and rotated overnight at 4°C. The beads were washed 6 times with buffer B1. The protein was eluted by boiling in 1X Laemmli buffer.

Mass Spectrometry and Proteomics data analysis

The eluted proteins were loaded on a 10% SDS-PAGE gel, resolved for approximately 5mm, and Coomassie stained. Gel bands containing the protein samples were excised from the gel, reduced using 3 mM tris(2-carboxyethyl)phosphine (TCEP) in 100 mM ammonium bicarbonate, and cysteine residues were alkylated using 3 mM 2-Carboxyethyl Methanethiosulfonate (CEMTS). Proteins were then in-gel proteolyzed using Sequencing grade modified porcine trypsin (Promega), and peptides were eluted (80% acetonitrile, 1% TFA) and lyophilized. Peptides were resuspended in 30 μl 0.1% acqueus formate, loaded on a

20 cm x 75 μm ID column packed with Reprosil 1.9 C18 silica particles (Dr. Maischt), and resolved on a 5-35% acetonitrile gradient in water (0.1% formate) at 250 nl/min.

Eluting peptides were ionized by electrospray (2200V) and transferred into a Thermo Lumos Orbitrap mass spectrometer. The MS was set to collect 120,000 resolution precursor scans (m/z 380-2000 Th). Precursor ions were selected for HCD fragmentation at stepped 28,33,38% normalized energy in data-dependent mode. Spectra were collected in the linear trap at "normal" (unit) resolution, with first mass locked to 100 Th. The reversed phase column was washed after each sample injection to prevent carry over.

Files searched using the Mascot scoring function within ProteomeDiscoverer, with mass tolerance set at 5 ppm for MS1, and 0. 5 Da for MS2. Spectra were matched against the UniProt human database and a database of common contaminants (cRAP). M-oxidation, and N/Q-deamidation, were set as variable modifications. CEMTS adduct on cysteine was set as fixed modification. Peptide-spectral matches were filtered to maintain FDR<1% using Percolator. Extracted ion chromatograms of precursor ions intensities were integrated for label-free quantification (LFQ_ across samples and used as quantitative metric for protein relative quantification.

Proteins with peptide count 2 and above were further analyzed. The ribosomal proteins (RPL proteins) were removed from all data sets as they are highly expressed in all cells. The abundance value of each protein that are pulled down by either EdU or EBndG were divided by the abundance value of beads control to attain the fold change (FC). To permit calculation of LFQ ratios for proteins with missing values in the bead controls, an arbitrary value (2222, chosen to be slightly smaller than the lowest empirical value) was used for imputation. The FC was further calculated as log base 2, and proteins that have FC log2 = 1 and higher are

considered as the final number of proteins pulled down. EdU pull-down were compared with the EBndG pull-down proteins that were represented in Venn diagrams. The GO analysis of the unique EdU and EBndG-associated proteins were analyzed by ToppGene. The full ToppGene analysis were shown in Supplementary Table S1.

The U2OS cells iPoKD samples in-gel digested as described above, replacing ABC buffer with Triethylammonium bicarbonate buffer (TEAB), and encoded with Tandem Mass Tag (TMT) according to manufacturer's protocol (ThermoFisher). Labelled peptides were chromatographically resolved as above, and analyzed using an Exploris 480 quadrupole-orbitrap mass spectrometer (Thermo). The MS was set to collect 120,000 resolution precursor scans (m/z 380-2000 Th). Precursor ions were selected for HCD fragmentation at stepped 28,33,38% normalized energy in data-dependent mode. Spectra were collected in the orbitrap at 60,000 resolution, with first mass locked to 100 Th. Peptide-spectral matching and reporter ion intensity extraction were performed using Proteome Discoverer, with Mascot as scoring function set as above (MS2 mass tolerance 20 ppm). The Abundance of each protein identified in "Pulse" and 'Wash-Chase" samples were normalized with "Beads Control". The "Pulse"/"Wash-Chase" proteins with peptide count 2 and above were used for ToppGene analysis.

RNA transfection and Real-time PCR

Gene knockdown was performed using Lipofectamine RNAiMAX transfection reagent according to the manufacturer's protocol. The cells were harvested after 72 hours for RNA isolation using Zymo Research RNA isolation kit. cDNA prepared using SuperScriptIII Reverse

Transcriptase kit (Thermo Fisher) and OligodT primers. To check for the transcript level of pre-rRNA the cDNA was synthesized using random hexamer primers. Realtime PCR was performed using 10 ng of cDNA with SYBR Green Master mix. Samples were analyzed on a LightCycler480 and quantified with LightCycler480 quantification software. The fold change calculated by delta-delta Ct method with GAPDH as the housekeeping gene control. The primers used are:

GAPDH primers (5'CGACCACTTTGTCAAGCTCA3' and 5'AGGGGAGATTCAGTGTGGTG3'), 47S pre-rRNA (5'TGTCAGGCGTTCTCGTCTC3'

and 5'GAGAGCACGACGTCACCAC3'), POLK [77](5'TGAGGGACAATCCAGAATTGAAG 3' and 5'CTGCACGAACACCAAATCTCC)

SDS-PAGE and western blotting

Cells were harvested and lysed in lysis buffer (50mM Tris pH8, 20mM NaCl, 10mM MgCl2, 0.1% SDS, EDTA-free Protease Inhibitor-Roche), centrifuge for 10mins and supernatant collected. Proteins were quantified by nanodrop and boiled in Laemmli buffer. Proteins were separated with 4–20% Precast SDS–PAGE gels (Biorad #4561093), transferred to PVDF membranes and were blocked with 5% milk in TBS-T buffer. Bands were detected using various antibodies at 4°C overnight. The membranes were incubated with peroxidase-conjugated secondary antibodies for 1 hour at RT before detection using ECL system. For Polκ detection supersignal west pico PLUS chemiluminescent was used (ThermoFisher). Images captured with ChemiDoc imaging system (Biorad), and the bands quantified using

ImageJ with either GAPDH or Vinculin as control. All the uncropped versions of images were showed in Supplementary Figures.

Immunofluorescent staining and click fluorophore labelling

Cells were grown overnight on glass coverslips coated with poly-D lysine. After 2 hours treatment with either DMSO or variable concentration of BPDE diluted with DMSO (0.1 to 2μM), fresh media was added with either 5-EU (1 mM for 1 h) [47], EdU (20 μM for 10 mins) or EBndG (100 μM for 30 mins) and the control with DMSO for 30 mins. The cells were gently washed 2X with PBS and fixed with 4% buffered paraformaldehyde at room temperature for 20 mins. Cells were washed twice with PBS containing 1% BSA or kept in 1% BSA overnight at 4°C, then permeabilized with 0.5% (v/v) Triton X-100 in PBS for 15 mins. Cells were washed with PBS and click fluorophore labelling was performed by incubating with click reaction 1 mM CuSO4, 2 mM THPTA, 10 mM sodium ascorbate, 0.2 μM Alexa Fluor 594 azide (Thermofisher A10270) complemented with PBS for 1.5 hours at RT in dark. The cells were washed 3x with PBS and incubated in blocking buffer containing 10% donkey serum (JacksonImmunoResearch 017-000-121) in PBS for 1 hour, washed with PBS and incubated with primary antibody solution in 1% blocking buffer overnight at 4C. Cells were washed 3X with PBS and incubated with secondary antibody solution, consisting of 1: 2000 (v/v) donkey anti-mouse Alexa Fluor 647 (A-31571) or donkey anti-rabbit Alexa Fluor 488 (A-21206) for 2 hours at room temperature. Washed 3X with PBS followed by 5 mins incubation in 4′,6-diamidino-2-phenylindole DAPI (1:2000) and mounted with Vectrashield mounting medium.

RNase A, RNase H and DNase I digestion

U2OS cells grown on coverslips overnight were treated either with DMSO or 2 μM BPDE for 2 hours, then incubated with fresh media with only DMSO (no nucleotide control) or 100 μM EBndG for 30 minutes. After washing with PBS, cells were incubated for 15 mins either with PBS (control) or DNase I (10U) (NEB M0303) or RNase A (2mg/ml) (NEB T3018) or RNase H (NEB M0297) at 37C, fixed in 2% paraformaldehyde for 20 minutes and incubated in blocking buffer (1% BSA in PBS). Cells were permeabilized and click reaction performed for 1.5 hours as described above. Cells were again incubated with either PBS (control) or DNase I or RNase A or RNase H for 15 minutes, followed by two more washes with PBS buffer. Cells were further processed for immunofluorescence as described above.

Confocal Microscopy, Image Analysis, Quantification and Statistical analysis

Confocal Microscopy, Image Analysis, Quantification and Statistical analysis

Imaging was performed by super resolution confocal microscopy using Zeiss LSM910 with AiryScan2 in multiplex mode SR-2Y using a 20X (NA 0.8), 40X (NA 1.2) water and 63X oil (NA 1.4) objectives. Imaging parameters such as laser power, digital gain, digital offset, scan speed was kept constant for the same experimental batch of treated and untreated cells. Resulting images were quantified through a custom image analysis pipeline using CellProfiler version 4.2.1 [78]. Briefly, individual imaging channels were first split for object detection. In all images DAPI channel was used for nuclei object detection. RNF2 foci was identified as a independent object within each nuclei and related to the original nuclei object as a child object using relate object function. The nuclei objects were further used as masks on EBndG, EdU, EU, PolK, UBF1 and gamma-H2AX channels using the image mask function to isolate and

measure the intensity within the individual nuclear object boundaries. The RNF2 foci counts, and fluorescence intensities of EBndG, EdU, EU, Polκ, UBF1 and γH2AX were exported as spreadsheet for statistical analysis using GraphPad Prism version 9 software. In box plot graphs, boxes represent the 25–75 percentile range with median, and whiskers represent the 9–95 percentile range. Statistical tests were applied as described in the Figure legends and were calculated with Prism 9. In all quantitative immunofluorescence studies, random cells per group were scored and mentioned in the figure legends.

Cell viability assay

Cell viability was determined using the CellTiter-Glo® 2.0 Luminescent Cell Viability Assay. Briefly, U20S cells were seeded in a 96-well plate (2,000 cells/well) and allowed to adhere overnight. The following day, cells obtained varying concentrations of EBndG or DMSO in triplicate and were incubated for 3 days. On day 3, CellTiter-Glo® Reagent was added at half the volume of cell culture media present in each well. Plates were rocked for 2 minutes and then incubated at room temperature for 10 mins and analyzed with a luminometer (GloMax® Navigator Luminometer). Background signal from the media and CellTiter-Glo® Reagent control was subtracted from sample values. To ensure the CellTiter-Glo® Reagent was not oversaturated with ATP in the sample wells, a solution of ATP disodium salt (Sigma) at a final concentration of 1 mM was used to evaluate the luminescent value near saturation.

List of antibodies used:

anti-POLK or anti-DinB (sc-166667, IF 1:100, WB 1:1000), anti-POLH (sc-17770, IF 1:100), anti-POLI (sc-101026, IF 1:100), REV1 (sc-393022, IF 1:100), anti-RNF2 (Bethyl laboratories A302-869A, IF 1:1000, WB 1:5000), anti-PARP1(gift from George Lucian Moldovan lab, Ab-

95425 IF1:500), anti-NPM1 (HPA011384 Sigma, IF 1:250, WB 1:2500), anti-UBF1 (sc-13125, IF1:100), anti-FBL (ab137422 IF 1:250), anti-H2K119ub (gift from Zhonghua Gao lab, Millipore D27C4 IF 1:1600), anti-γH2AX (sc-517348, IF 1:150), anti-GAPDH (Invitrogen 39-8600 WB 1:2500) , anti-vinculin (gift from George Lucian Moldovan lab sc-73614, 1:1000)

Secondary antibody used with anti-DinB is m-IgGκ BP-HRP (sc-516102).

List of siRNA used:

siRNF2 [79], siPOLK (pool of 3 siRNAs sc-60537), siScrambled (santa cruz), pool of 3 custom made Dicer-Substrate Short Interfering RNAs (DsiRNAs) from IDT.

Figure 1. EBndG-bound proteins enriched in the nucleolus, ribosomal biogenesis and in transcriptional repression.

A. Experimental design to identify proteins enriched at nascent DNA synthesized with Polκ captured by EBndG (iPoKD) compared to traditional aniPond. Chemical structures of EdU and EBndG shown.

B. Venn diagrams depicting number of proteins associated with EdU (in green) compared to EBndG-pull downs (in red) using GM12878 cells. EdU-pull down in untreated cells identified less unique proteins (25) and failed to be analyzed by ToppGene Suite.

C. GO analysis (ToppGene) of EdU and EBndG-bound unique proteins (non-overlapping protein list from venn diagrams in Fig1B analyzed). Gene counts from each pathway shown in the graph and the p-value for each pathway is indicated within each bar. EdU (in green) and

EBndG-pull downs (in red) from cells treated with 0, 0.5 and 2 μM BPDE. See TableS1 for complete results.

D. Representative list of proteins bound to Polκ synthesized DNA and their fold change compared to the beads control. The protein list of the EBndG-pull downs from HEK293 cells treated with 2 μM BPDE and GM12878 cells treated with (0, 0.5 and 2 μM) BPDE were analyzed with their respective beads control. Proteins grouped according to their known interacting protein complex and presence in nucleolar sub-compartments.

Figure 2. BPDE exposure induces nucleolar stress and increases the activity of Polκ in the nucleolus

A. Representative images of U2OS cells from *N* = 2 independent experiments showing EBndG (in red), NPM1 (in cyan) and DAPI (in gray). EBndG and DAPI overlay panel showing prominent nucleolus enriched with EBndG (red, marked by arrows) in DAPI-less regions. NPM1 in the nucleolar periphery (shown with arrows) in cells after BPDE treatment (0.1 μM).

(i) Quantification of nuclear EBndG intensity in untreated (n=103) and BPDE-treated (n=63) cells, represented as box plots. Boxes represent the 25–75 percentile range with median and whiskers represent the 5–95 percentile range. Data points outside of this range are shown individually. Statistical significance calculated using Mann Whitney U test. *P <0.0192

B. Representative images of untreated and BPDE-treated (0.5 μM) cells from *N*=2 independent experiments. A prominent nucleolus enriched with EBndG (red) in BPDE-treated cell (shown with an arrow). Quantification of total nuclear (i) Polκ, (ii) EBndG and (iii) NPM1

intensity, in 30-60 untreated and BPDE-treated cells represented as box plots. Statistical significance calculated using Mann Whitney U test. ****P <0.0001. Full images shown in S2A, an independent experiment shown in S2B.

C. Representative images of BPDE-treated (2 μM) cells from *N*=3 independent experiments. NPM1 (in cyan) in nucleoplasm and some in cytoplasm. Nucleus shown by DAPI (in blue). Overlay panel of DAPI and EBndG, with prominent EBndG enriched (in red) in all DAPI-less nucleoli. Full image shown in S2C.

D. Representative images of untreated and BPDE -reated (2 μM) cells from *N* = 2 independent experiments. Untreated cell with UBF1 (in green, shown with an arrow) in nucleoli and after BPDE treatment, UBF1 in the nucleolar caps (green, shown by arrows). The EBndG enriched nucleoli shown in red. Full images shown in S2D.

E. Representative cells showing FBL (magenta foci) with UBF1 (in green) in nucleolar caps (shown by arrows) following BPDE treatment (2 μM). Full images shown in S2E.

All scale bars = 10 μm.

Figure 3: Polκ dependent incorporation of EBndG in the nucleus and nucleolus

A. Representative images of wild type (WT) U2OS and U2OS sgPolK cells (Polκ -/-) treated with BPDE (0.5 μM). Quantification of total nuclear Polκ , NPM1and EBndG intensity in wild-type (WT) cells (n=63) and Polκ -/- cells (n=47), represented as box plots. Statistical significance calculated using Mann Whitney U test. ****P <0.0001, ***P <0.0004, *P <0.0193. Full image shown in S2A.

B. Expression of WT Polκ in Polκ -/- showing nucleolar EBndG (red, shown by arrows). Images of more cells shown in S3A.

C. Representative images of cells transfected with siScrambled and siPOLK, showing EBndG (red, nucleolar EBndG shown by arrows), Polκ (magenta), and DAPI (blue). **(i)** Quantification of total nuclear Polκ and EBndG intensity of siScrambled (n=80) and siPOLK (n=74) transfected cells, represented as box plots. Statistical significance calculated using Mann Whitney U test. ****P <0.0001. Full image shown in S3D.

D. Relative expression of POLK transcript in siScrambled (siSc) and siPOLK transfected cells after treatment with 0 and 2 μM BPDE. GAPDH mRNA as internal control. Calculated with the comparative CT method (mean ± SEM). All comparisons are relative to siSc 0 μM BPDE.

E. Western blot analysis of Polκ expression in siSc and siPOLK transfected cells, after treatment with 0 and 2 μM BPDE. Fold change (FC) of Polκ after normalization with vinculin and compared to siSc (BPDE=0). Full blots are shown in Figure S8B.

F. EdU (in red) incorporation in siScrambled and siPOLK transfected cells, after treatment with 0 and 2 μM BPDE, DAPI (in blue). Quantification of nuclear EdU intensity in 0 μM BPDE-treated cells [siScrambled (n=102) and siPOLK (n=103)], 2 μM BPDE-treated cells [siScrambled (n=56) and siPOLK (n=82)]. Results represented as box plots. Statistical significance calculated using a one-way analysis of variance and Kruskal-Wallis test. Full image in S3E.

G. Representative images of cells and their nuclear EBndG intensity quantification. Cells were transfected with siScrambled (n=45), siPOLι (n=29), siPOLη (n=46), siREV1(n=49). Nucleolar

EBndG (in red, shown by arrows) and DAPI (in gray). Statistical analysis as 3F. ****P <0.0001, *P <0.0178. Full image in S3F.

All scale bars = 10 μm.

Figure 4: EBndG incorporation in nucleolar DNA

A. Representative images of BPDE-treated (2 μM) cells from *N* = 2 independent experiments showing EBndG (red) enriched nucleolus, Polκ expression (magenta), NPM1 in the nucleoplasm (cyan) and DAPI (blue) followed by either treatment with buffer, RNase A, RNase H or DNase I.

B. Quantification of nuclear EBndG intensity in cells treated with buffer (n=177), RNase A (n=203), RNase H (n=236) and DNase I (n=214) represented by box plots. Statistical analysis as 3F. ****P <0.0001. Full image in S3F. Scale bar = 10 μm.

Figure 5: Inhibition of PARylation by PARP1 inhibitor (olaparib) reduced recruitment of RNF2 and decreased the activity of Polκ

A. Representative images from *N*=2 independent experiments. Cells either treated with DMSO (control) or 10 μM Olaparib (for 3 days) (PARP1 PARylation inhibitor) were incubated with 0 or 2 μM BPDE. EBndG (red), PARP1 (cyan), Polκ (magenta) and DAPI (gray). Full image in S5A.

B. Similar experiment as 5A, immunofluorescence with Polκ (magenta) and RNF2 (green). DAPI shown in blue and EBndG in red. Full image in S5B. Scale bars = 10 μm.

C. Quantification of 5B, total nuclear intensity of EBndG (i), Polκ (ii) and number of nuclear RNF2 foci (iii) in cells treated with olaparib and 0 μM BPDE (n=40) compared to BPDE-treated (2 μM) cells that were earlier incubated with either DMSO (n=125) or olaparib (n=153). Statistical analysis as described in Figure 3F. ****P <0.0001, ***P = 0.0002, **P = 0.0064 .

D. Western blot analysis of Polκ expression in BPDE-treated with or without olaparib. Quantification of Polκ bands after normalization with GAPDH, FC compared to control (no olaparib treated) cells. The full blots are shown in Figure S8C.

Figure 6: The activity of Polκ in the nucleolus is associated with peripheral accumulation of Polycomb Protein, Ring Finger Protein 2 (RNF2)

A. Representative images from *N*= 2 independent experiments with siScrambled or siRNF2 transfected cells. Immunofluorescence with Polκ (magenta) and RNF2 (green). DAPI shown in blue and EBndG in red. Scale bar = 10 μm.

B. Quantification of 6A, total nuclear intensity of Polκ (i), EBndG (ii) and RNF2 (iii) in cells transfected with siSc or siRNF2. siRNF2 cells without BPDE-treatment (n=188), compared to 2μM BPDE treated siRNF2 (n=184) and siScrambled (n=168) cells. Statistical analysis as described in Figure 3F. ****P <0.0001, *P = 0.0408

C. Western blot analysis of Polκ and NPM1expression in U2OS cells treated with 0 or 2 μM BPDE. Vinculin as loading control. Low and high exposure of the western blots.

D. Relative expression of POLK transcript in siSc and siPOLK transfected cells, after treatment with 0 and 2 μM BPDE. GAPDH mRNA as internal control. Calculated with the comparative CT method (mean ± SEM). All comparisons are relative to siSc 0 μM BPDE.

Figure 7: Polκ participates in recovering from nucleolar stress after BPDE damage

A. Quantification of nuclear γH2AX intensity in cells transfected with siSc or siPOLK after treatment with 0 and 2 μM BPDE. [siSc, BPDE 0 μM (n=136)], [siSc, BPDE 2 μM (n=96)], [siPOLK, BPDE 0 μM (n=259)], [siPOLK, BPDE 2 μM (n=141)]. Statistical analysis as described in Figure 3F. ****P <0.0001. Image of the cells in Figure S7A.

B. Relative expression of 47S pre-rRNA transcript in siSc and siPOLK transfected cells, after treatment with 0 and 2 μM BPDE. GAPDH mRNA as internal control. Calculated with the comparative CT method (mean ± SEM), three technical replicates from *N*=2. All comparisons are relative to siSc 0 μM BPDE.

C. (i) Representative images of EU incorporation (red) in nascent RNA in cells transfected with siScrambled or siPOLK. Polκ expression (magenta) and DAPI (blue). **(ii)** Quantification of these cells (n=25-40) treated with 0, 0.1, 0.5 μM BPDE. Full images in Figure S7B. Statistical analysis as described in Figure 3F. ****P <0.0001, ***P = 0.0002.

D. Experimental design to identify the role of Polκ in BPDE-induced nucleolar stress recovery after 36 hours.

E. Representative images of cells transfected with siScrambled or siPOLK, treated with BPDE (0.5 or 2 μM) and fixed for immunofluorescence (t=2 h) or recovered after t=36 h. Immunofluorescence showing NPM1 (cyan), Polκ (magenta), EBndG (red) and DAPI (gray). Full images in Figure S7C, S3C, S3D.

F. Representative images of cells transfected with siScrambled or siPOLK, treated with BPDE (0.5 or 2 μM) and fixed for immunofluorescence (t=2 h) or recovered after t=36 h. Immunofluorescence showing UBF1 (green), EBndG (red) and DAPI (gray). Full images in Figure S7D. All scale bars 10 μm.

Figure 8: Working model on the role of Polκ in recovering from nucleolar stress after BPDE damage

Upon BPDE exposure, BP-dG adducts are formed on genomic DNA including rDNA, recruiting PARP1 that creates PARylation on chromatin. This initiates PRC1 proteins (including RNF2) to form Polycomb bodies near NADs. Cells undergo nucleolar stress, with inhibition of rDNA transcription, nucleolar protein NPM1 release to nucleoplasm and nucleolar cap formation for rDNA repair. In wild type cells (left), PARylation by PARP1 and PRC1 body formation regulates Polκ protein stabilization and therefore higher Polκ activity in the nucleolus, evident by enrichment of EBndG in the nucleolus. Presence of Polκ facilitates cells to gradually recover from BPDE-induced nucleolar stress. However, in Polκ-depleted cells (right), the nucleolar stress is retained, and cells fail to recover from BPDE-induced nucleolar stress.

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Author contributions

The project was conceived by TES and S.P. EBndG reagent was designed and generated by T.S. All experiments were designed and performed by S.P. Cell viability assay, western blots and cell culture were maintained by A.R. Proteomics experimental guidance were provided by D.P and P.C. Mass spectrometry experiments were performed and data analyzed by P.C. Super-resolution confocal microscopy was performed under guidance of A.P. The cell profiler pipelines were generated by A.P. Polk knockout cells were provided by T.T.H. The paper was written by S.P and T.S with contributions from other authors.

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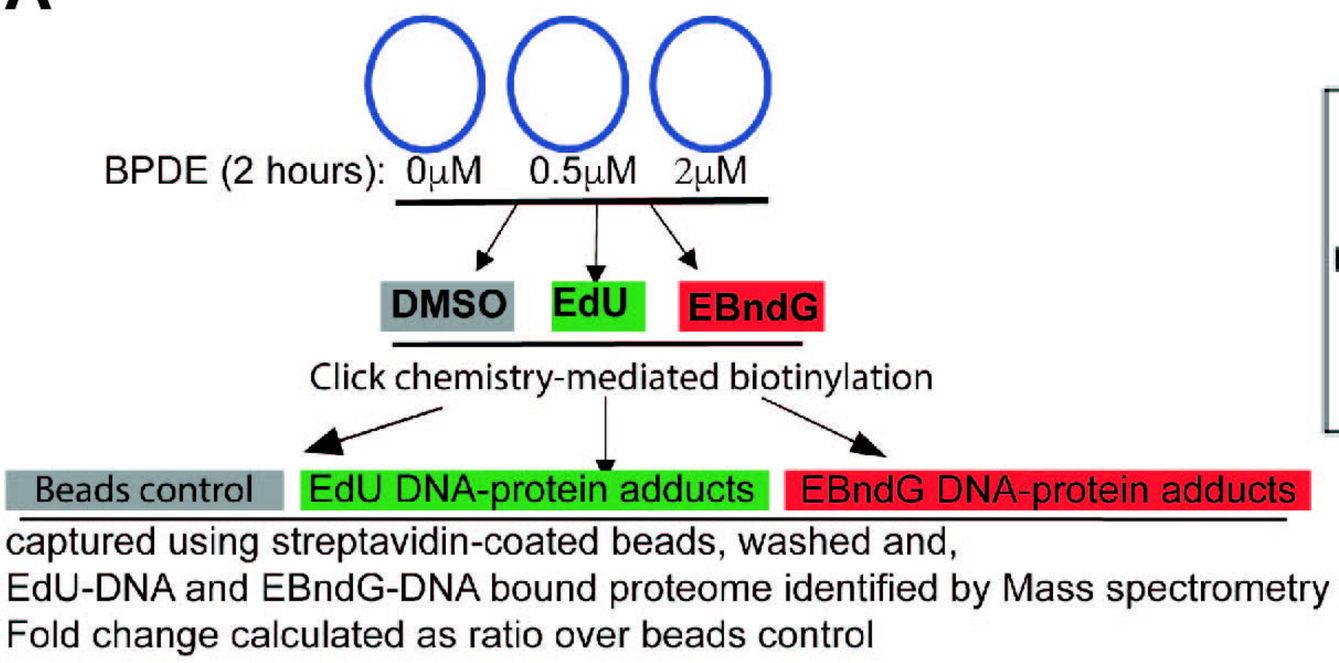
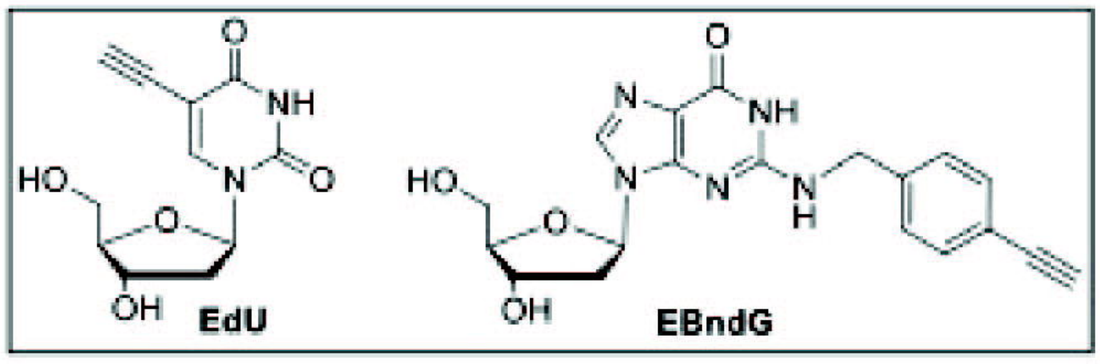
A





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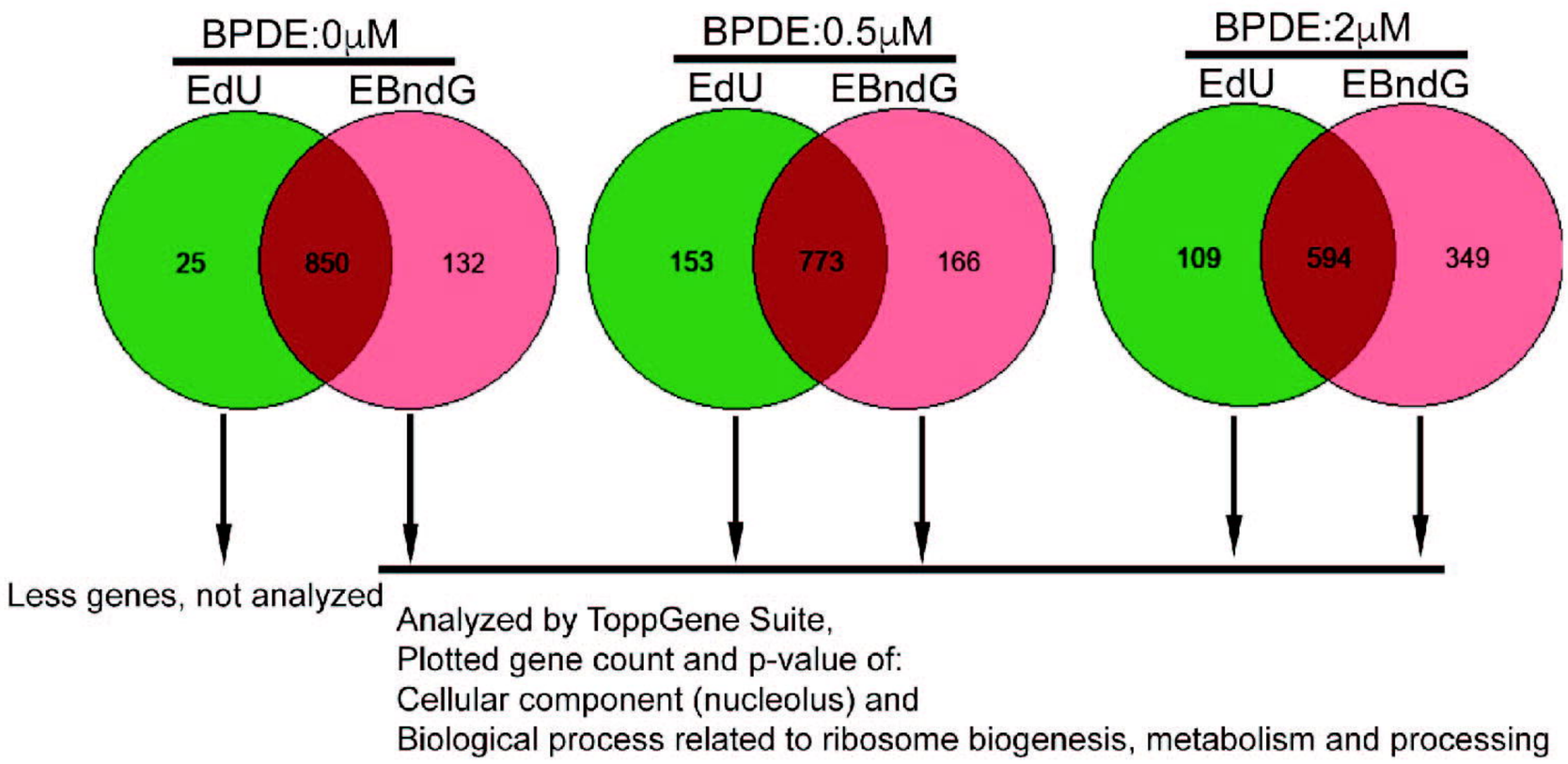

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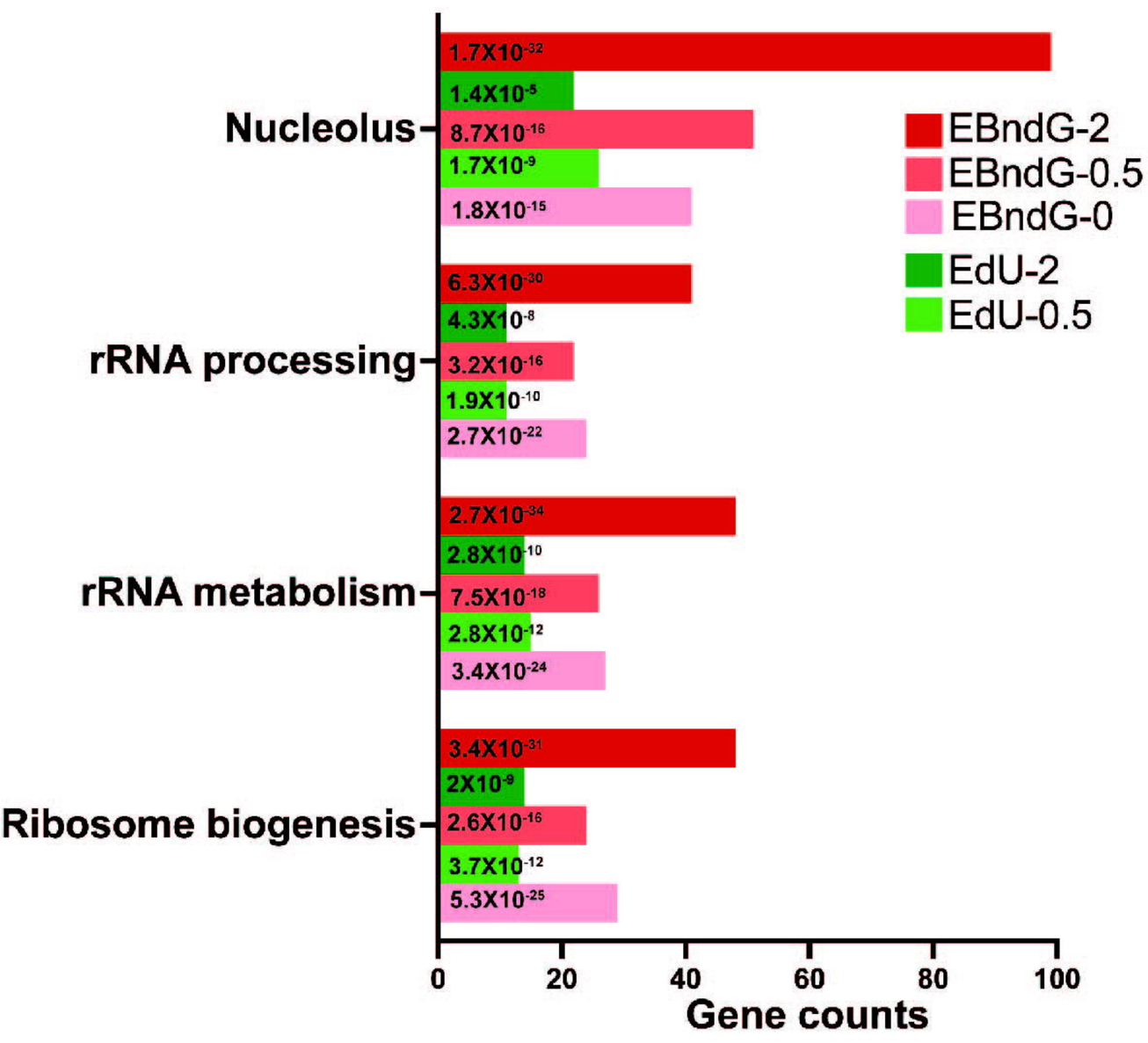

D

	GM12878			HEK293	
Symbol	0μM*	0.5μM *	2μM *	2μM *	
BOP1	9.5	7.7	8	8.4	PeBoW complex
PES1	11.8	10.6	11.4	8.5	
WDR12	9.2	7.6	7.7	3.4	
NPM1	6.8	5.7	6	7	GC FC DFC
UBTF	16	15.4	16.4	11	
FBL	13.6	12	12.4	12.8	
TCOF1	2	0	1.7	6.8	
POLR1B	3	4.4	4.4	4.6	RNA Pol I
POLR1A	9.3	8.5	8.5	8.8	
PARP1	7.2	6	6.7	5.4	
RNF2	4.2	3.8	6.8	7.2	PRC
CBX8	6.3	4.3	5.6	8.6	
SUZ12	7.2	6.1	6.4	6	
EED	7.2	6	6.8	5.6	
POLK	6.9	5.4	6.7	3	

* BPDE concentration

FIGURE1

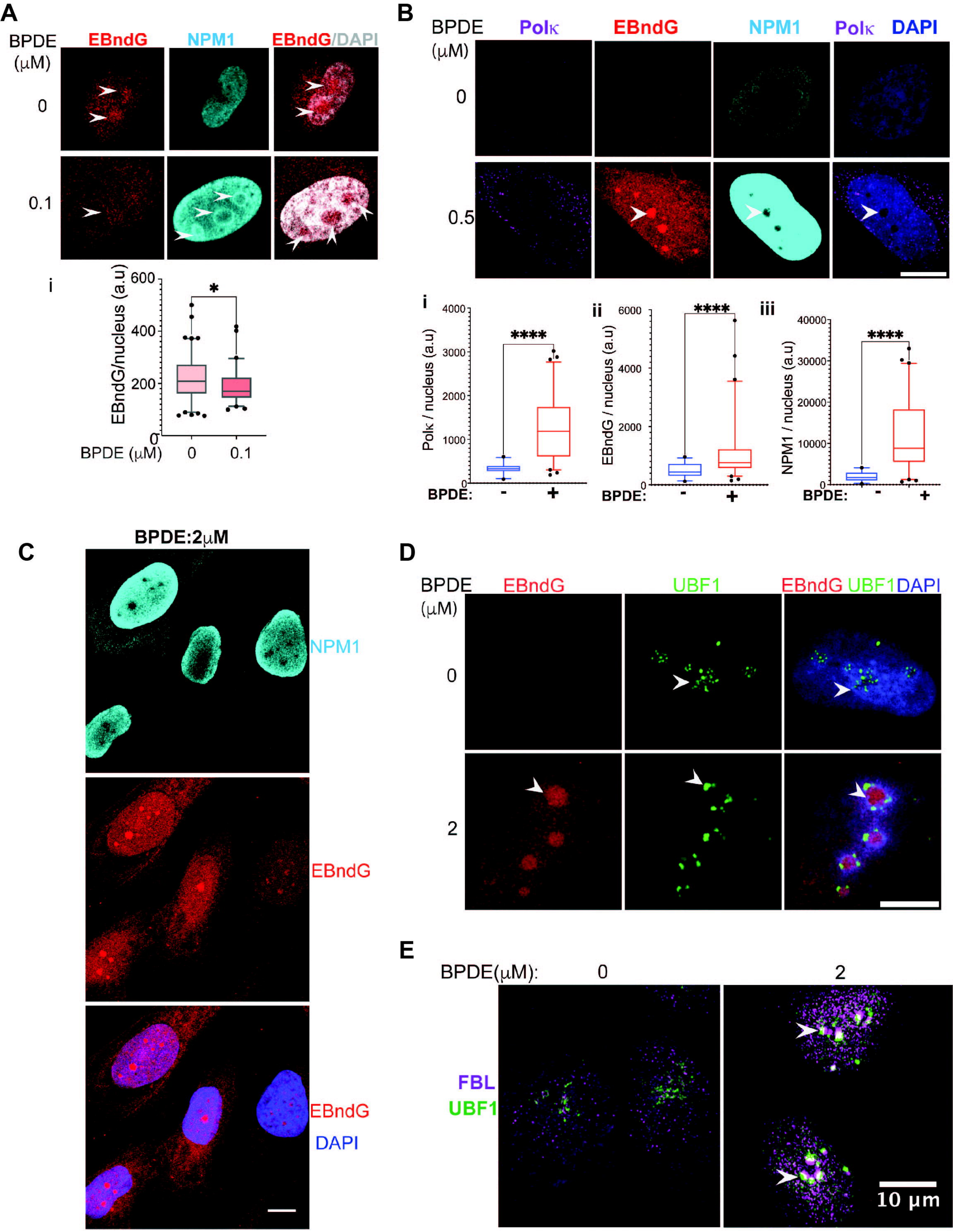
A
BPDE (μM)
EBndG
NPM1
EBndG/DAPI
0
0.1
i
EBndG/nucleus (a.u)
600
400
200
0
*
BPDE (μM)
0
0.1
B
BPDE (μM)
Polκ
EBndG
NPM1
Polκ
DAPI
0
0.5
i
Polκ / nucleus (a.u)
4000
3000
2000
1000
0
****
BPDE:
-
+
ii
EBndG / nucleus (a.u)
6000
4000
2000
0
****
BPDE:
-
+
iii
NPM1 / nucleus (a.u)
40000
30000
20000
10000
0
****
BPDE:
-
+
C
BPDE:2μM
NPM1
EBndG
EBndG
DAPI
D
BPDE (μM)
EBndG
UBF1
EBndG UBF1DAPI
0
2
E
BPDE(μM):
0
2
FBL
UBF1
10 μm

FIGURE 2

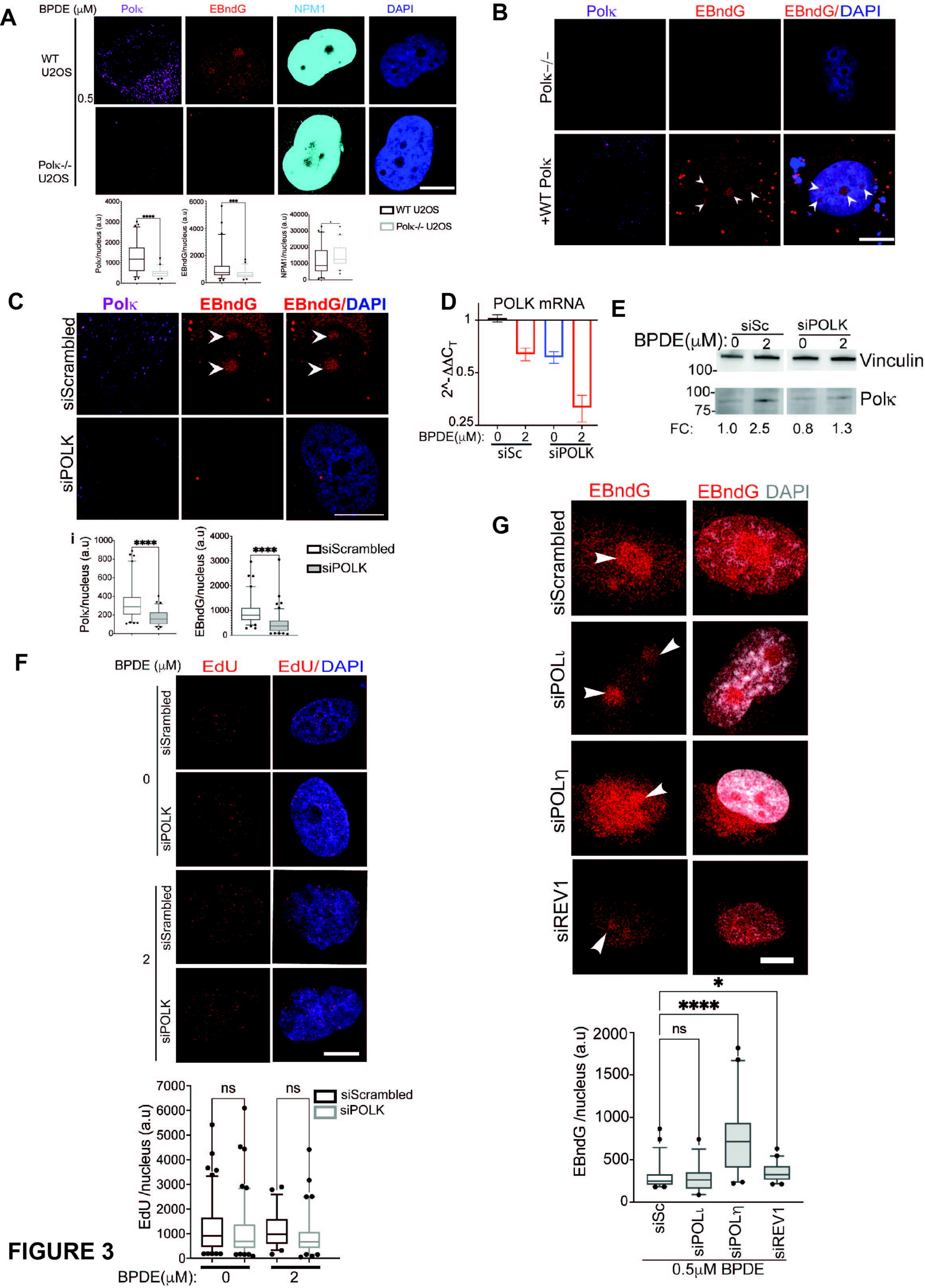
A
BPDE (μM)
Polκ
EBndG
NPM1
DAPI
WT U2OS
0.5
Polκ-/- U2OS
Polκ/nucleus (a.u)
EBndG/nucleus (a.u)
NPM1/nucleus (a.u)
WT U2OS
Polκ-/- U2OS
B
Polκ
EBndG
EBndG/DAPI
Polκ-/-
+WT Polκ
C
Polκ
EBndG
EBndG/DAPI
siScrambled
siPOLK
siScrambled
siPOLK
D
POLK mRNA
2^-ΔΔC_T
BPDE(μM): 0 2 0 2
siSc
siPOLK
E
siSc
siPOLK
BPDE(μM): 0 2 0 2
Vinculin
Polκ
FC: 1.0 2.5 0.8 1.3
F
BPDE (μM)
EdU
EdU/DAPI
siSrambled
siPOLK
siSrambled
siPOLK
EdU /nucleus (a.u)
ns
ns
siScrambled
siPOLK
BPDE(μM): 0 2
G
EBndG
EBndG DAPI
siScrambled
siPOLι
siPOLη
siREV1
EBndG /nucleus (a.u)
ns
siSc
siPOLι
siPOLη
siREV1
0.5μM BPDE

FIGURE 3

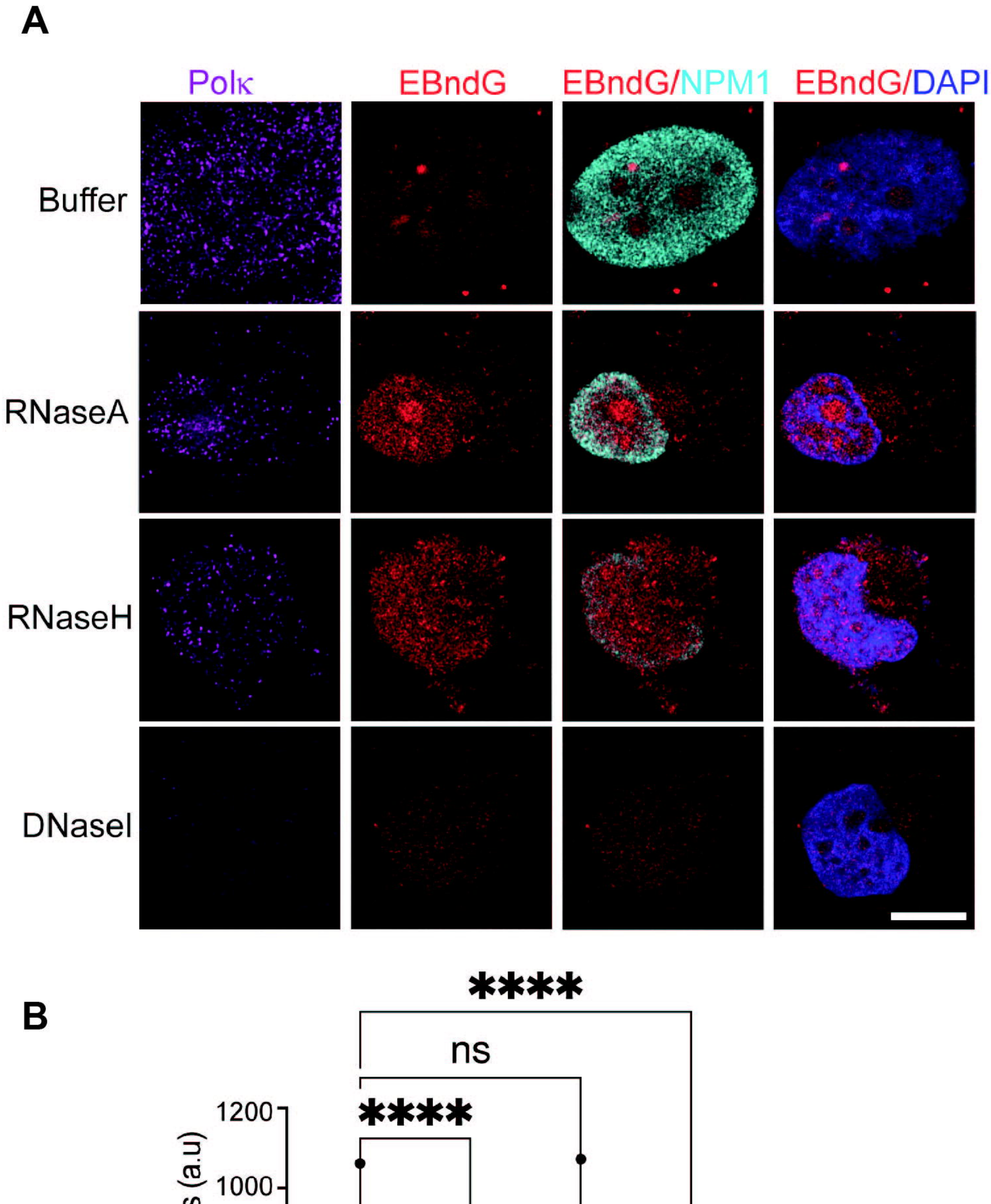
A
Polκ
EBndG
EBndG/NPM1
EBndG/DAPI
Buffer
RNaseA
RNaseH
DNaseI
B
****
ns
****
EBndG Intensity/ nucleus (a.u)
1200
1000
800
600
400
200
0
Buffer
RNaseA
RNaseH
DNaseI

FIGURE 4

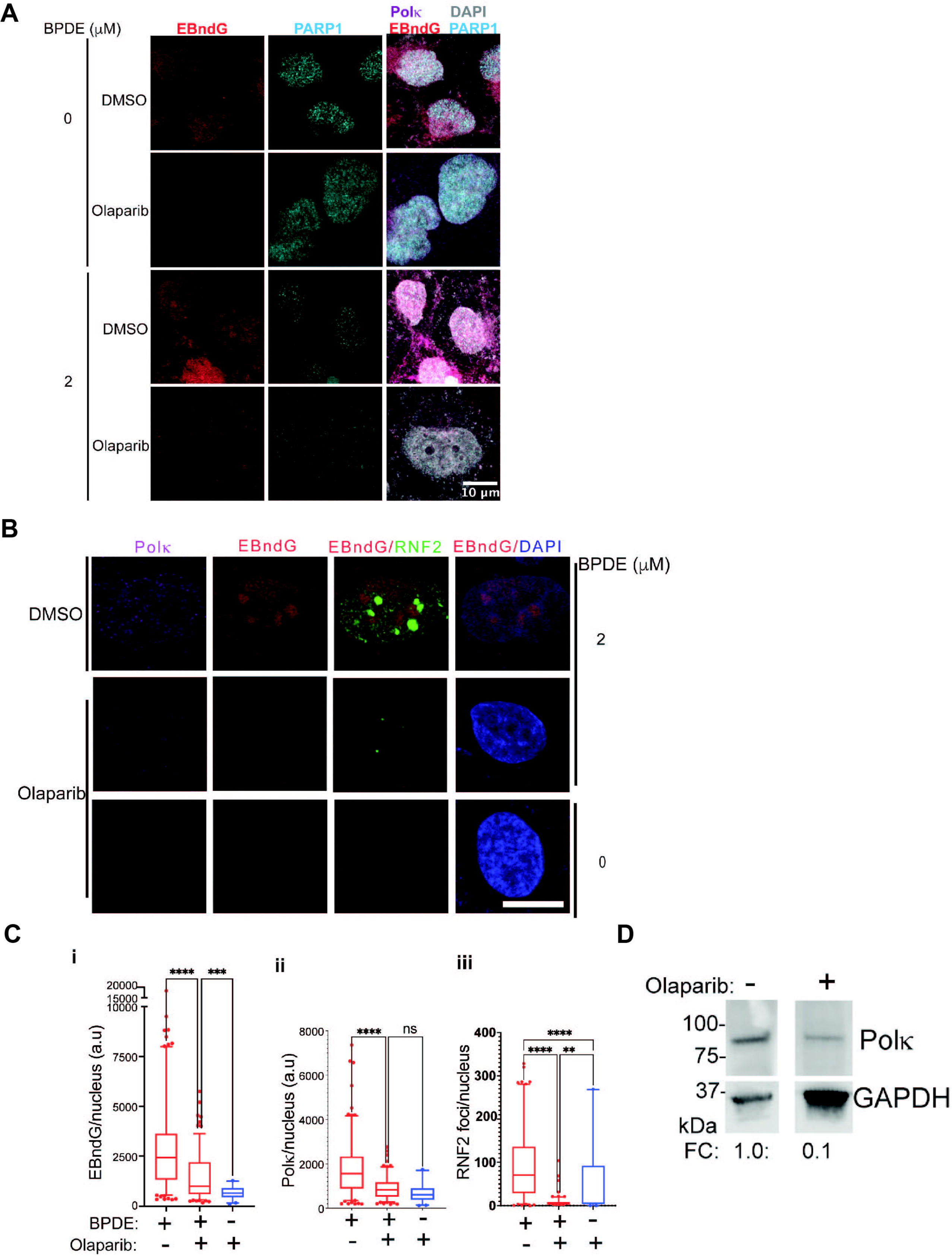
A
BPDE (μM)
EBndG
PARP1
Polκ
EBndG
DAPI
PARP1
0
DMSO
Olaparib
2
DMSO
Olaparib
10 μm
B
Polκ
EBndG
EBndG/RNF2
EBndG/DAPI
BPDE (μM)
DMSO
2
Olaparib
0
C
i
ii
iii
EBndG/nucleus (a.u)
Polκ/nucleus (a.u)
RNF2 foci/nucleus
****
***
ns
**
BPDE:
Olaparib:
D
Olaparib: - +
100-
75-
37-
kDa
Polκ
GAPDH
FC: 1.0: 0.1

FIGURE 5

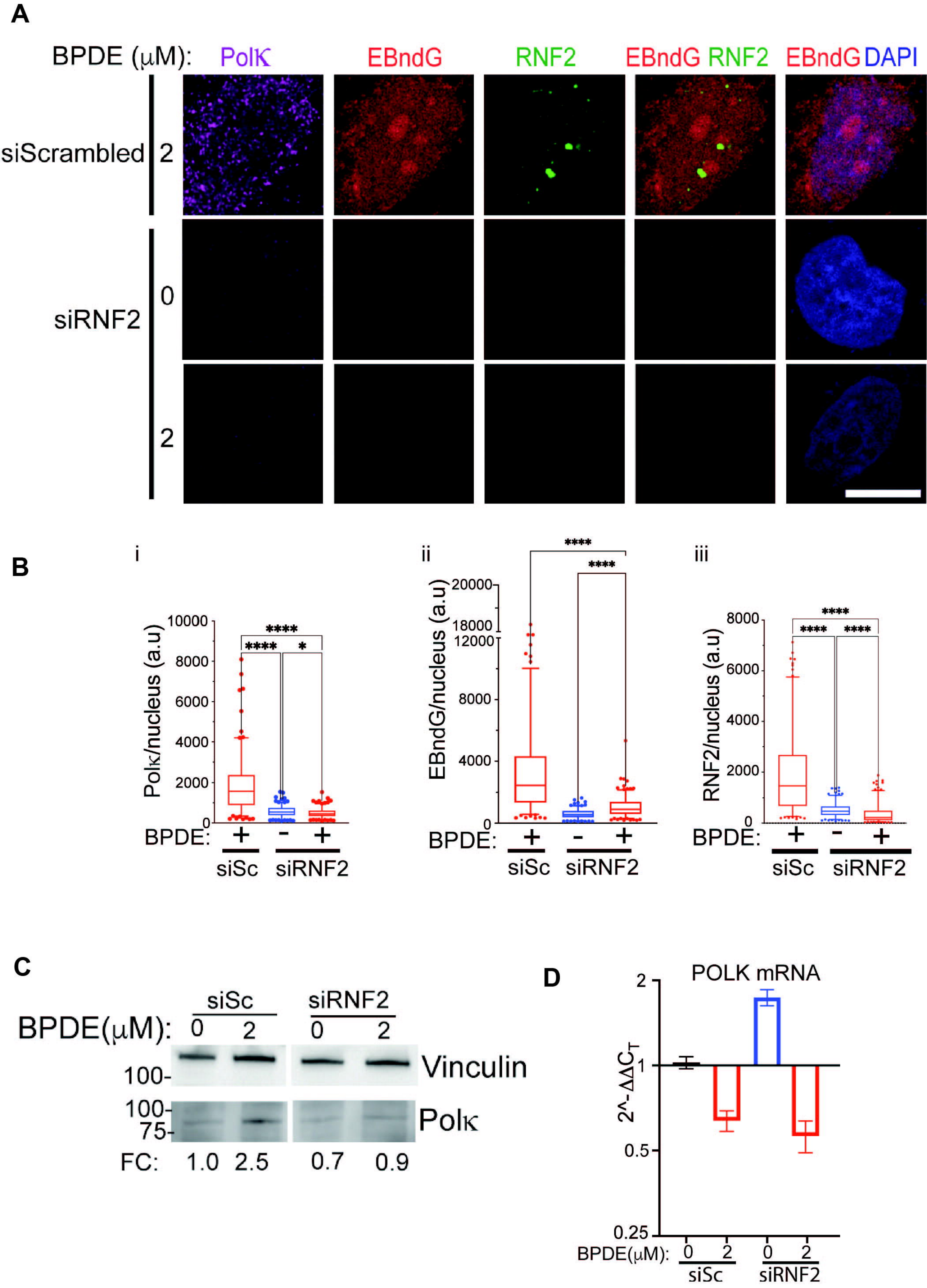
A
BPDE (μM):
PolK
EBndG
RNF2
EBndG RNF2
EBndG DAPI
siScrambled
2
siRNF2
0
2
B
i
ii
iii
Polκ/nucleus (a.u)
EBndG/nucleus (a.u)
RNF2/nucleus (a.u)
****
*
BPDE:
siSc
siRNF2
C
siSc
siRNF2
BPDE(μM):
0
2
100-
Vinculin
Polκ
75-
FC:
1.0
2.5
0.7
0.9
D
POLK mRNA
2^-ΔΔC_T
0.25
0.5
1
2

FIGURE 6

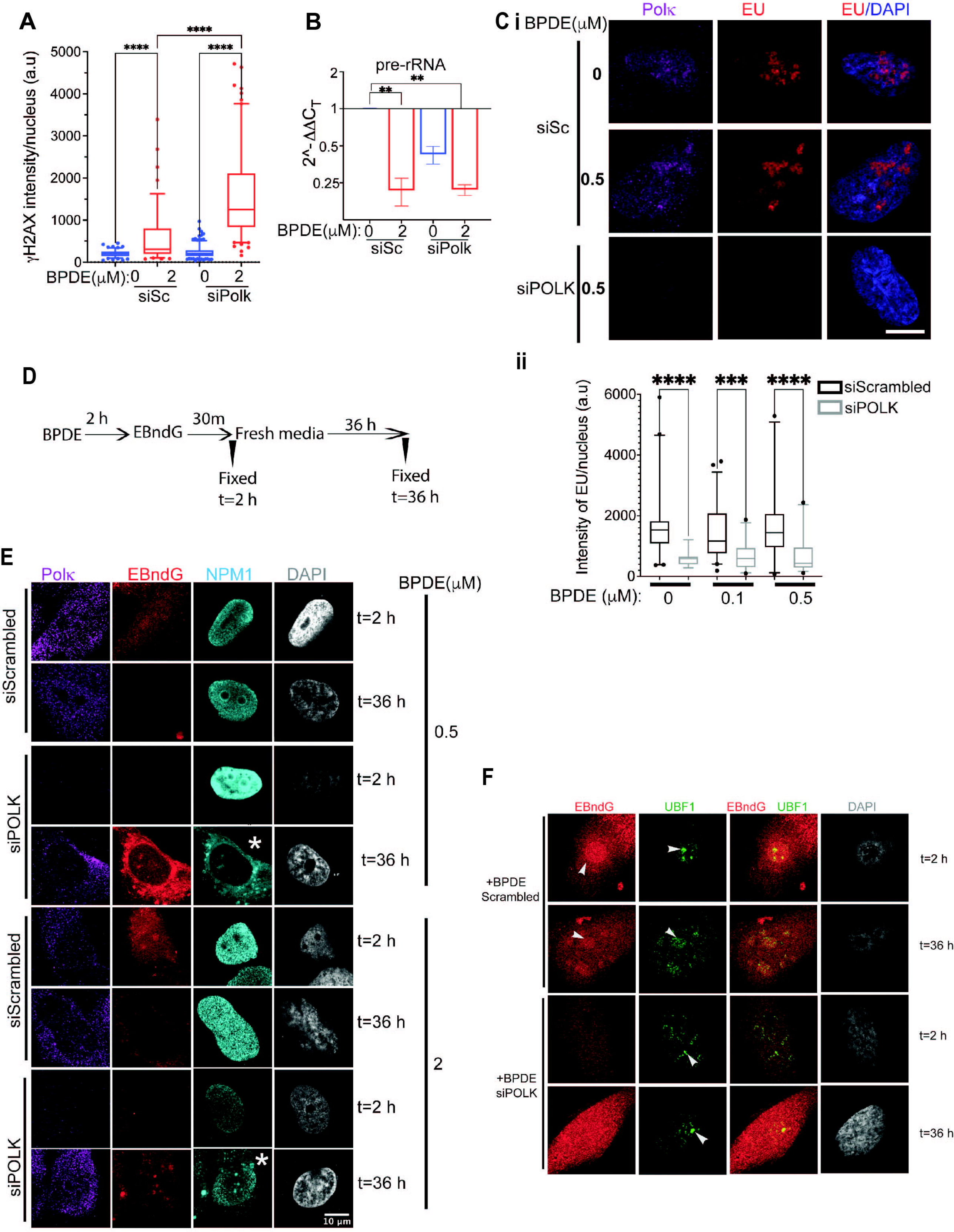
A
γH2AX intensity/nucleus (a.u)
5000
4000
3000
2000
1000
0
****
****
****
BPDE(μM): 0 2 0 2
siSc
siPolk
B
pre-rRNA
2^-ΔΔC_T
2
1
0.5
0.25
**
**
BPDE(μM): 0 2 0 2
siSc
siPolk
C i
BPDE(μM)
Polκ
EU
EU/DAPI
siSc
0
0.5
siPOLK
0.5
ii
Intensity of EU/nucleus (a.u)
6000
4000
2000
0
****
***
****
siScrambled
siPOLK
BPDE (μM): 0 0.1 0.5
D
BPDE
2 h
EBndG
30m
Fresh media
36 h
Fixed
t=2 h
Fixed
t=36 h
E
Polκ
EBndG
NPM1
DAPI
BPDE(μM)
siScrambled
t=2 h
t=36 h
0.5
siPOLK
t=2 h
t=36 h
siScrambled
t=2 h
t=36 h
2
siPOLK
t=2 h
t=36 h
10 μm
F
EBndG
UBF1
EBndG UBF1
DAPI
+BPDE
Scrambled
t=2 h
t=36 h
+BPDE
siPOLK
t=2 h
t=36 h

FIGURE 7

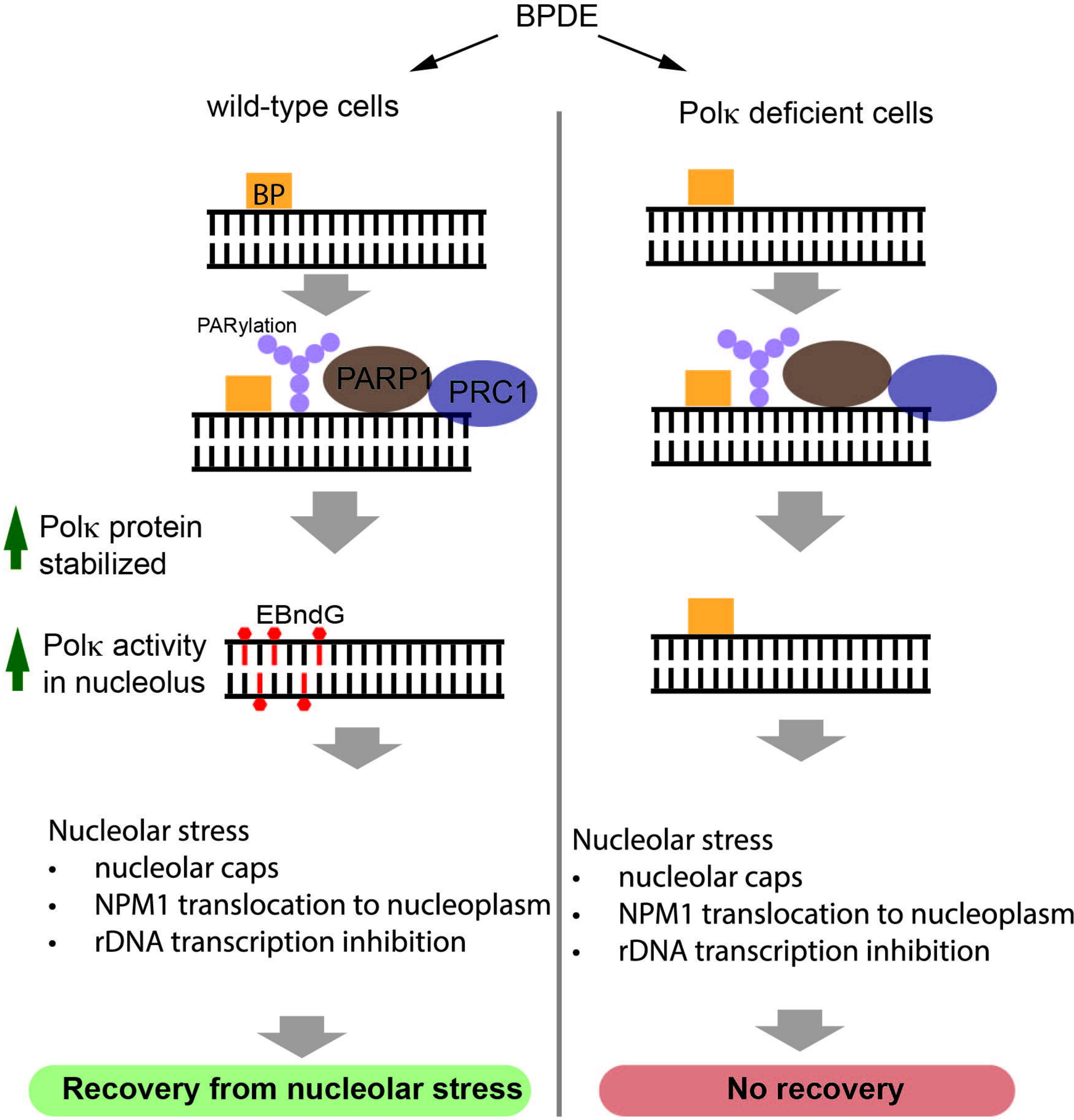
BPDE
wild-type cells
Polκ deficient cells
BP
PARylation
PARP1
PRC1
Polκ protein stabilized
Polκ activity in nucleolus
EBndG
Nucleolar stress
• nucleolar caps
• NPM1 translocation to nucleoplasm
• rDNA transcription inhibition
Recovery from nucleolar stress
Nucleolar stress
• nucleolar caps
• NPM1 translocation to nucleoplasm
• rDNA transcription inhibition
No recovery

FIGURE 8