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Selective killing of cancer cells with a small molecule targeting stress response to ROS

Lakshmi Raj¹, Takao Ide¹, Aditi U Gurkar¹, Michael Foley², Monica Schenone², Xiaoyu Li², Nicola J. Tolliday², Todd R. Golub², Steven A. Carr², Alykhan F. Shamji², Andrew M. Stern², Anna Mandinova^{1,2,*}, Stuart L. Schreiber^{2,*}, and Sam W. Lee^{1,2,*}

¹Cutaneous Biology Research Center, Massachusetts General Hospital and Harvard Medical School, Building 149 13th Street, Charlestown, MA 02129, USA

²Broad Institute of Harvard and MIT, 7 Cambridge Center, MA 02142, USA

Malignant transformation, driven by gain-of-function mutations in oncogenes and loss-of-function mutations in tumor suppressor genes, results in cell deregulation that is frequently associated with enhanced cellular stress (e.g., oxidative, replicative, metabolic, proteotoxic, and DNA damage)¹. Adaptation to this stress phenotype is required for cancer cells to survive, and consequently cancer cells may become dependent upon non-oncogenes that do not ordinarily perform such a vital function in normal cells. Thus, targeting these non-oncogene dependencies in the context of a transformed cell genotype may result in a synthetic lethal interaction and selective cancer cell death². Here, we used a cell-based small-molecule screening and quantitative proteomics approach that resulted in the unbiased identification of a small molecule that selectively kills cancer cells over normal cells. Piperlongumine (PL) increases reactive oxygen species (ROS) and apoptotic cell death in both cancer cells and normal cells engineered to have a cancer genotype, irrespective of p53 status, with little effect on either rapidly or slowly dividing primary normal cells. Significant anti-tumor effects are observed in PL-treated mouse xenograft tumor models, with no apparent toxicity in normal mice. Moreover, PL potently inhibits spontaneously formed malignant breast tumor growth and associated metastases in mice. The results of this study illustrate the ability of a small molecule to induce apoptosis selectively in cells having a cancer genotype by targeting a non-oncogene co-dependency acquired by the expression of the cancer genotype in response to transformation-induced oxidative stress^{3–5}.

Using a luciferase reporter gene fused with the CDIP (Cell Death Involved P53 Target) promoter⁶, we performed a small-molecule screen (Supplementary Fig. 1) to identify compounds acting through novel pro-apoptotic mechanisms. The compound with the highest composite Z value was piperlongumine (PL) (Supplementary Fig. 2a), which increased luciferase activity from the CDIP reporter at levels comparable to the positive control etoposide (Supplementary Figs. 2b, 3). PL is a natural product isolated from the plant species *Piper longum* L. (Fig. 1a) previously shown to have cytotoxic effects⁷. We examined the effects of PL on the viability of cultured cancer and normal cells (Fig. 1b;

*To whom correspondence should be addressed. swlee@partners.org. * amandinova@partners.org. * stuart_schreiber@harvard.edu.

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Author Contributions L.R. and T.I. conducted most of the experimental work. A.U.G., M.S., and X.L. made critical experimental contributions. N.J.T., A.M.S., T.R.G., S.A.C., A.F.S., and M.F. designed the experimental plans, analyzed and interpreted the data. A.M., S.L.S. and S.W.L. designed and directed the project and drafted the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. S.W.L., A.M. and M.F. are co-founders and consultants of Canthera Therapeutics Inc., which pursues cancer therapeutics that act through ROS mechanisms. All other authors declare that they have no competing financial interests..

Supplementary Figs. 4, 6). PL treatment significantly induced cell death in both wt-p53 and mutant-p53 cancer cells. When primary normal and non-transformed immortalized cells with diverse proliferative capacities were incubated with highly purified PL (Supplementary Fig. 5) for 24 h (under the indicated conditions that avoid spontaneous transformation and minimize stress), there was little apparent reduction in cell viability even at higher concentrations (15 μ M, a concentration of PL that approaches its solubility limit), indicating that PL may have a cancer cell-selective killing property. These results suggest that sensitivity to PL may result from the process of malignant transformation. To test this hypothesis we used a defined model⁸ of oncogenic conversion of normal cells through ectopic expression of the telomerase catalytic subunit (hTERT) in combination with small T antigen (ST), and an oncogenic allele of H-Ras (Fig. 1c) and observed sensitivity to PL upon oncogenic transformation of the normal cells. Similar results were obtained using serial transformation of spontaneously immortalized MCF10A breast epithelial cells by overexpression of ErbB2 and/or H-Ras⁹ (Fig. 1c).

Western blot analysis showed that wt-p53 expression was significantly enhanced by treatment with PL in different types of cancer cells (Fig. 1d). Moreover, a p53 proapoptotic target, PUMA, was significantly induced in response to PL even in p53-null cancer cells (Saos-2) (Fig. 1d). PL treatment was able to repress the levels of expression of several pro-survival proteins, including Bcl2, survivin and XIAP (Supplementary Fig. 7). Among 55 death/survival-related genes, we observed increased levels of apoptotic transcripts and decreased levels of pro-survival transcripts in cancer cells in the presence of PL, but no significant changes in normal cells (Supplementary Fig. 8). These results suggest that PL induces cell death/apoptosis (Supplementary Fig. 4a,e) preferentially in cancer cells by modulating expression of members of apoptotic and survival pathways, including p53 targets and p53 itself, and does not require p53 for this activity.

We next tested PL in established tumor xenografts in mice (human bladder, breast, lung tumors in nude mice and mouse melanoma in B6 mice; Supplementary Fig. 9). Significant anti-tumor effects were observed in PL-administered tumor-bearing mice as compared to DMSO-treated controls (Supplementary Fig. 9). PL treatment enhanced the expression of p21, PUMA and caspase-3 in EJ tumors (Supplementary Fig. 10a). Moreover, PL treatment inhibited blood-vessel formation in xenograft-tumor mice (Supplementary Figs. 9d; 10b). We also studied PL in a transgenic mouse model of spontaneous breast cancer, MMTV-PyVT¹⁰. When tumor sizes grew to ~5–6 mm in diameter (female MMTV-PyVT mice, 8–9 weeks age), PL was administered intraperitoneally (2.4 mg/kg) daily for two weeks; significant anti-tumor effects were observed (Fig. 2a). Furthermore there were no secondary tumors in PL-treated mice compared to vehicle-treated controls (Fig. 2b). At day 13, the vehicle treated control mice showed severe malignant progression indicated by the formation of aggressive adenocarcinoma (Fig. 2c). In contrast, the mammary glands of PL-treated mice were preserved, and the tissue showed a hyperplastic-like, non-malignant phenotype (Fig. 2c). Notably, PL seems more effective than paclitaxel (Fig. 2d). PL also showed excellent oral bioavailability and desirable exposure levels (C_{max} and AUC) in mice as observed after a single oral administration and intravenous injection (Supplementary Fig. 11). In order to examine potential cytotoxic side-effects of PL on normal tissues, CD-1 mice were intraperitoneally administered with PL (2.4 mg/kg) or DMSO, daily for 6 days, and whole blood samples as well as vital organs were collected for hematology and histopathological analyses, respectively. PL-treated CD-1 mice remained healthy throughout the treatment time and no significant differences between the vehicle and PL treated groups were evident (Supplementary Figs. 12, 13). High-dose acute toxicity studies demonstrated that PL did not cause any obvious clinical indications (Supplementary Table 1 and 2; Supplementary Fig. 14). Together, these results indicate that treatment with PL potently suppressed tumor growth in diverse tissues without affecting normal tissues in mice.

We next used a method combining affinity enrichment with stable isotope labeling with amino acids in cell culture (SILAC) and quantitative proteomics to identify the target proteins and their associated complexes that bind PL¹¹ (Supplementary Figs. 15, 16a and Methods). Twelve interaction partners of PL that were similar in both EJ and U2OS cells were identified (Supplementary Fig. 16b). Seven of these, including the top 4 high-signal outliers, are known to participate in the cellular response to oxidative stress caused by elevated ROS. GSTpi was the highest confidence hit followed by CBR1 (Supplementary Fig. 16b). Several of these proteins are known to be part of a common complex^{12, 13}, suggesting that the affinity purification may have identified direct and indirect partners.

These results suggest that, by binding to proteins known to regulate oxidative stress, PL may modulate redox and ROS homeostasis. Consistent with this hypothesis, we found that PL can 1) interact directly with purified recombinant GSTpi and inhibit its activity (Supplementary Figs. 17, 18) and 2) lead to a decrease in GSH and an increase in GSSG levels in cancer cells (Fig. 3a). PL treatment did not increase GSSG levels in normal cells (76N, NMEC) (Fig. 3a). Furthermore co-treatment of PL with the reducing agent, N-acetyl-L-cysteine (NAC, 3 mM), which quenches ROS, prevented PL-mediated GSH depletion (Fig. 3a).

We next determined the effect of PL on cellular ROS levels in several human cancer cells (EJ, MDAMB231, U2OS and MDAMB435) through flow cytometry using the redox sensitive fluorescent probe CMH2DCF-DA. Treatment with PL for 1 and 3 h caused a significant increase of ROS in these cancer cells (Fig. 3b; Supplementary Figs. 19, 20). Paclitaxel also caused an increase in DCF-DA fluorescence after 1 h, but PL enhanced ROS to nearly twice these levels (Fig. 3b). Co-treatment with NAC fully reversed PL-induced increase in ROS (Fig. 3b,d and Supplementary Fig. 21). Using a series of fluorescent probes specific for individual species of ROS we found that hydrogen peroxide and nitric oxide, but not superoxide anion, were among the ROS species induced by PL in cancer cells (Fig. 3b,c; Supplementary Figs. 22–24).

In contrast, PL did not cause an increase in ROS levels in normal cells (Fig. 4a; Supplementary Fig. 25). This selective induction of ROS in cancer cells distinguishes PL from other small molecules that affect ROS levels, such as the microtubule-stabilizing agent paclitaxel and the glutathione synthesis inhibitor buthionine sulfoximine (BSO) (Fig. 4a; Supplementary Fig. 25), and suggests that PL-induced ROS elevation is a consequence of cell transformation. Engineering normal cells to have a cancer genotype potentiates PL-induced increase in ROS (Fig. 4b; Supplementary Figs. 26, 27). Serial transformation itself leads to increased expression of the putative PL targets GSTpi and CBR1 (Supplementary Fig. 28), suggesting that these proteins may play a role in enabling the transformed cell to adapt to transformation-induced oxidative stress. Thus we hypothesized that over-expression of CBR1 or GSTpi might rescue transformed cells from both PL-induced ROS elevation and PL-induced apoptosis. Stably overexpressing CBR1 or GSTpi, and particularly both, in EJ cells significantly reduced PL-induced ROS levels and correspondingly partially rescued the PL-induced apoptotic phenotype (Supplementary Fig. 29). In a complementary study, knockdown of GSTpi or CBR1 did not affect PL-induced ROS levels (Supplementary Fig. 30). These results may reflect the fact that other members of the GST family were observed to bind PL in our affinity enrichment studies (Supplementary Fig. 16b) and may have partially overlapping functions in the cell. These data suggest that PL induces apoptosis by interfering with redox and ROS homeostatic regulators such as GSTpi and CBR1.

The ability of PL to inhibit the growth of tumors derived from rapid and highly invasive multifocal mammary tumors without general toxicity suggests that perturbing redox and ROS homeostasis is a promising strategy for cancer treatment. Our cell-based experiments

suggest that PL treatment selectively promotes ROS and apoptosis in cancer cells relative to normal cells. This correlates with selective induction of related phenotypes including DNA damage (Fig. 4c; Supplementary Figs. 27, 31, 32) and alterations in mitochondrial morphology and function selectively in cancer cells (Supplementary Fig. 33). This differential response to treatment with PL suggests that PL targets a dependency associated with ROS homeostasis that arises during transformation. Normal cells, including stem cells, have low basal levels of ROS^{1,4,5,15–18} and therefore a diminished reliance on the ROS stress-response pathway, whereas cancer cells, especially cancer stem cells, have high levels of ROS¹⁵ and might therefore be expected to have a strong reliance on the ROS stress-response pathway^{1,5,17,19,20}. The use of ROS-producing or -depleting small molecules such as β phenylethyl-isothiocyanate (PEITC) and buthionine sulfoximine (BSO)^{4,18} has been suggested for the treatment of cancer. Other small molecules such as curcumin²¹ and CDDO derivatives²² have been reported to promote ROS and reduce GSH levels in cancer cells, in one case in an oncogene-dependent manner¹⁸ and the activation of the KEAP1-NRF2 antioxidant pathway^{23,24} has been suggested to be involved.

The introduction of a single oncogene (H-Ras) leads to increased levels of ROS (Fig. 4b and²⁵), increased expression of GSTpi and CBR1 (Supplementary Fig. 27), increased apoptotic response to PL (Fig. 1c), and importantly to a substantial increase in levels of ROS following treatment with PL. In EJ cells, PL-induced cell death is rescued the anti-oxidant NAC (Fig. 3d). The increased dependence of cancer cells on the ROS stress-response pathway may be the basis for the selectivity of PL-induced apoptosis of cancer cells (Figs. 1 and 2). In further support of this hypothesis, the activation of Jnk pathway signaling has been implicated as an anti-tumorigenic response to oncogene expression²⁶. This response is coupled to oncogene-dependent oxidative stress through p53 stabilization and could also function independently of p53 through pro-apoptotic cJun-dependent transcription. In addition to its role in regulating ROS, GSTpi is also known to be a direct negative regulator of JNK²⁷ providing a possible mechanism for PL-induced apoptosis in both p53 wild type and mutant cancer cells.

A global investigation of the spectrum of cancer genotypes will be required to identify the range of cancer genotypes that impart PL sensitivity, but already our current results highlight a novel strategy for cancer therapy that preferentially eradicates cancer cells by targeting the ROS stress-response pathway.

METHODS SUMMARY

Apoptotic cell populations were determined by TUNEL assay and quantitated using flow cytometry. Cell viability was also determined by crystal violet staining (0.2% w/v in 2% ethanol), Trypan blue exclusion and Alamar-blue cell viability assay. For Crystal violet Staining, cells were plated in 6 -well and 12-well plates and after reaching 60–70% confluency; the cells were treated with PL for 12 and 24 h. For measurement of ROS production, cells were treated with PL or paclitaxel for 1 and 3 h and then incubated with 10uM 2', 7'-dichlorofluorescein diacetate (DCFH-DA) for 30 min at 37°C, washed twice with PBS and immediately analyzed by a FACScan flow cytometer. Cells were treated with PL and ETO for 18–24 h and processed for Comet assay following manufactures instruction (TREVIGEN). For xenograft tumor models, cancer cell lines, EJ, A549 and MDA-MB435 were injected subcutaneously into the flanks of nude mice. For the melanoma mouse model, B16F10 melanoma cells were injected to the flanks of C57BL/6 Ncr. FVB/N-Tg (MMTV-PyVT) 634Mul males were obtained from Mouse Models of Human Cancer Consortium (MMHCC) at NCI-Frederick and bred with FVB females. Female offspring were genotyped for the presence of the transgene using the primers published by MMHC. For PL-target

identification, we followed the SILAC-based affinity enrichment methodology as previously described¹¹²⁸. For further details see Full Methods in Supplementary Information.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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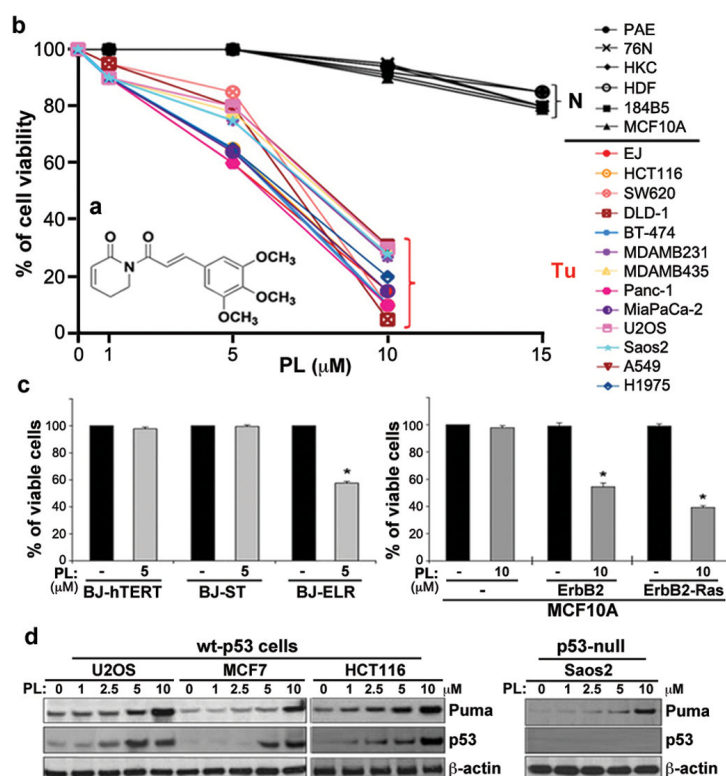


Figure 1. Selective killing effect of PL in cancer cells by a small molecule
a, Structure of PL. **b**, PL treatment induces cell death in cancer cells, but does not induce cell death in normal cells. Human normal cells, including aortic endothelial cells (PAE), breast epithelial cells (76N), keratinocytes (HKC), and skin fibroblasts (HDF), as well as two immortalized breast epithelial cell lines (184B5 and MCF10A), were grown in 12 or 24 well plates and treated with PL at 1–15 μM for 24 h. Cytotoxicity was measured by trypan blue exclusion staining (average of three independent experiments). A variety of human cancer cell lines were treated with PL or DMSO (control) for 24 h. PL was HPLC-purified (~99% purity) prior to the treatment. **c**, Selective cell death by PL in oncogenically transformed human BJ skin fibroblasts (the left panel) and MCF10A cell lines (right panel). A representative graph for cell viability is shown (mean \pm SD of three independent experiments; $*p < 0.0001$). **d**, The effects of PL on p53 and its target PUMA, and pro-survival proteins were measured by western blot analyses in several cancer cells.

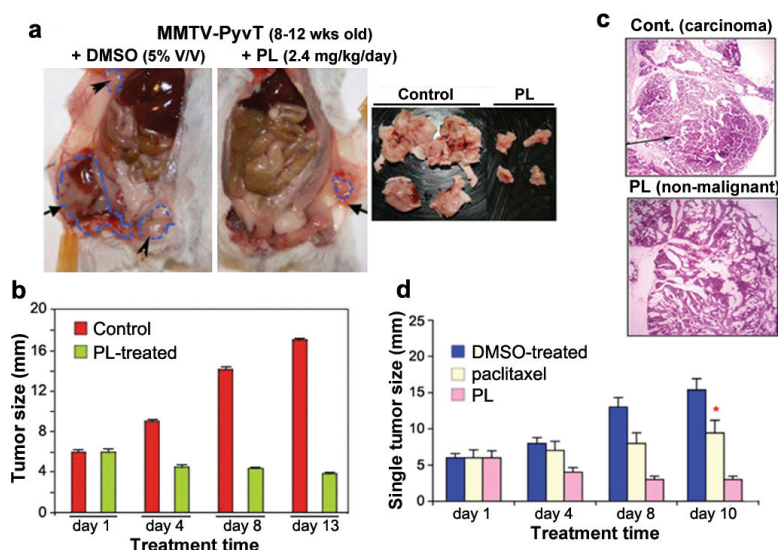


Figure 2. *In vivo* anti-tumor effect of PL

a, Mammary tumor growth inhibition by PL treatment in MMTV-PyVT transgenic tumor mice. MMTV-PyVT mice spontaneously developed breast adenocarcinoma by ~8 weeks of age. When tumor sizes grew to ~5–6 mm in diameter, the PL (total 2.4 mg/kg), paclitaxel (10 mg/kg) or DMSO (5% V/V) was administered intraperitoneally (i.p.) daily for 13 days (12 mice per group). Mice were then sacrificed and mammary tumors excised and processed for histological examination. **b**, The size of the grossly dissected tumors was measured. **c**, Histological morphology of hematoxylin-eosin-stained mammary tissue sections of MMTV-PyVT tumor mice treated with PL or DMSO after 13 days. **d**, After 13 days of PL treatment (*10 days treatment of paclitaxel was performed due to high toxicity in animals). Values in quantitative bar graphs are mean \pm SD of three independent experiments.

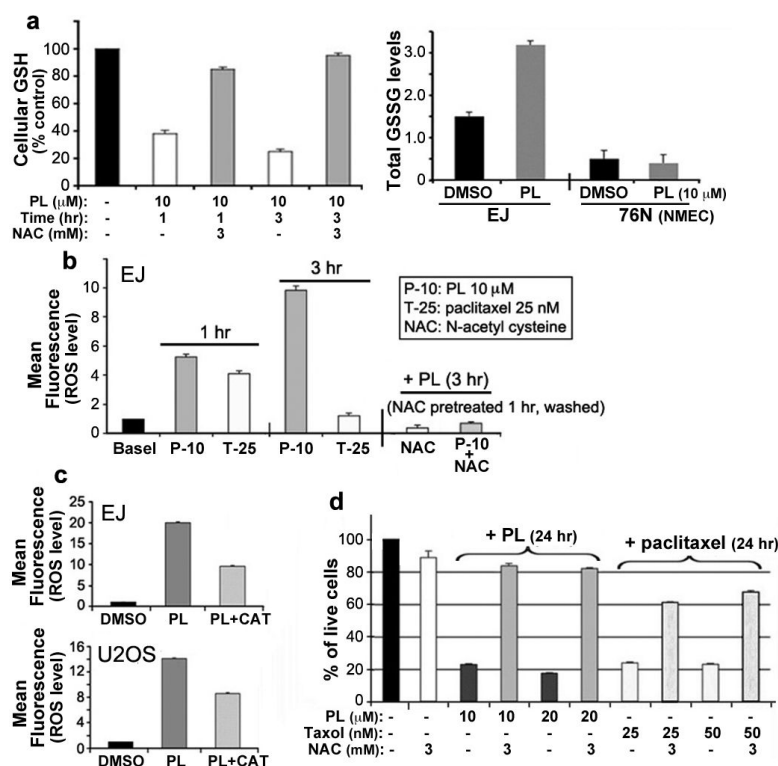


Figure 3. PL enhances ROS accumulation in cancer cells by targeting the stress response to ROS
a, PL-mediated modulation of GSH and GSSG. GSH levels were determined after EJ cells were treated with PL or pretreated with NAC for 1 h, followed by PL treatment for 1 h or 3 h. GSSG levels were also determined after EJ cells and 76N cells were treated with PL for 3 hr. **b**, PL-induced ROS elevation and reversion by NAC. EJ cells were treated with PL (10 μM), paclitaxel (25 nM), or DMSO (basal) for 1 h and 3 h, and also pretreated with 3 mM NAC for 1 h, followed by 10 μM PL for 3 h. **c**, Reversion of PL-induced ROS accumulation by catalase. EJ or U2OS cells were pretreated with catalase (CAT, 2,000U/ml) for 2 hr, followed by 10 μM PL for 3 h. Comparisons of ROS induced by PL and CAT+PL were also shown by quantitative bar graph. **d**, PL-induced cell death can be rescued by NAC. EJ cells were treated with PL for 24 h, or treated with 3 mM NAC for 1 h and followed by the treatment of PL or paclitaxel for 24 h. Cell viability was measured by trypan blue exclusion staining assay. Values in quantitative bar graphs are mean ± SD of three independent experiments.

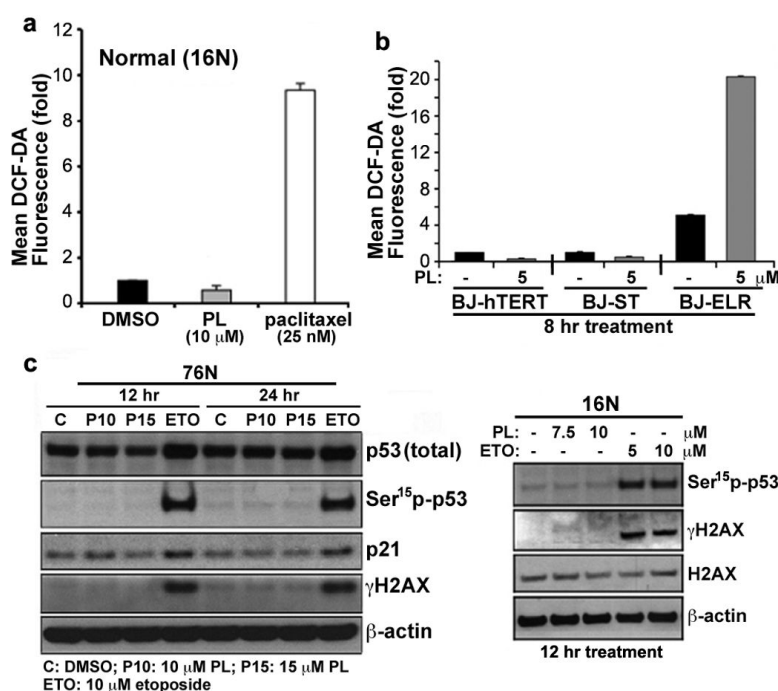


Figure 4. PL does not increase ROS and the ROS-induced DNA-damage response in normal and immortalized non-transformed cells

a, PL does not increase ROS in normal cells (16N). ROS were measured by flow cytometry and shown by quantitative bar graph. **b**, Selective induction of ROS by PL in oncogenically transformed BJ human fibroblasts (BJ-ELR) but not in non-transformed BJ fibroblasts (BJ-hTERT and BJ-ST). The ROS levels of BJ cells were measured after treating with PL (5 μ M) for 8 h. Values in quantitative bar graphs are mean \pm SD of three independent experiments. **c**, The effect of PL on stress-response targets was determined by western blot analysis of p53, p21 and γ -H2AX in PL in normal cells. Etoposide or DMSO as solvent control for 12 and 24 h. β -actin expression used as a loading control.