

AD_____

Award Number: W81XWH-08-1-0509

TITLE: The Role of BRCA1 Domains and Motifs in Tumor Suppression

PRINCIPAL INVESTIGATOR: Aneliya Velkova

CONTRACTING ORGANIZATION: Moffitt Cancer Center
Tampa, FL 33612

REPORT DATE: August 2009

TYPE OF REPORT: Annual Summary

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
Distribution Unlimited

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.				
1. REPORT DATE (01-08-2009)		2. REPORT TYPE Annual summary		3. DATES COVERED 1 Aug 2008-31 July 2009
4. TITLE AND SUBTITLE The Role of BRCA1 Domains and Motifs in Tumor Suppression		5a. CONTRACT NUMBER W81XWH-08-1-0509		
		5b. GRANT NUMBER BC083181		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Aneliya Velkova Email: aneliya.velkova@moffitt.org		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Moffitt Cancer Center & Research Institute, Inc. 12902 Magnolia Drive Tampa Fl 33612		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Medical Research and Materiel Fort Detrick, Maryland 21702-5012		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT The purpose of this research is to classify <i>BRCA1</i> variants for which cancer association is not known (unclassified variants UCV). To approach this problem we hypothesized that poorly characterized but conserved domains in <i>BRCA1</i> directly participate in its tumor suppression function. To test this hypothesis we choose a global approach analyzing several <i>BRCA1</i> domains and point mutants in functions that have previously been attributed to <i>BRCA1</i> : long term survival after irradiation, early G2/M checkpoint, intra S phase checkpoint, and spindle assembly checkpoint. We successfully optimized conditions for expression of full-length <i>BRCA1</i> mutants in two different cell lines by electroporation. We also optimized all the checkpoints assays in our laboratory and are now ready to analyze <i>BRCA1</i> mutants proposed in this grant. This will have a significant impact not only to understand <i>BRCA1</i> role as a tumor suppressor in breast cancer but also to help patients that are carriers of <i>BRCA1</i> mutation to make informed clinical decisions.				
15. SUBJECT TERMS BRCA1, unclassified variants, genetic counseling, Breast cancer treatment				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 29
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U		
				19b. TELEPHONE NUMBER (include area code)

Table of Contents

	<u>Page</u>
Introduction.....	1
Body.....	1-3
Reportable Outcomes.....	3-4
Bulleted Accomplishments.....	5
Conclusion.....	6
Appendices.....	7-26

I. Introduction: Summary of project objectives and scope of research

Breast cancer is among the most frequent malignancies affecting women. Germline mutations in the breast and ovarian cancer predisposition gene 1 (*BRCA1*) are responsible for the majority of early-onset hereditary breast cancers arising in families with multiple cases. It is estimated that around 10% of all women undergoing testing and about 35-50% of women from minority populations receive non-informative results, due to the finding of a variant for which cancer association is not known. These are so called unclassified variants (UCVs). Considering that there are over 1500 alleles of *BRCA1*, one of the most challenging tasks for genetic counseling is to distinguish which are benign and which are cancer predisposing. Previous research has indicated that the likelihood of a variant being deleterious is higher when the variant is located in a structurally and functionally defined protein domain. Thus, the identification of other functional domains is critical to classifying variants. To approach this problem we hypothesize that poorly characterized, conserved domains in the central region of *BRCA1* (called motif 6 and coiled-coil domain) directly participate in tumor suppression functions of *BRCA1*.

This proposal aims to test our hypothesis and determine how specific domains and motifs of *BRCA1* act to promote tumor suppression. Importantly our research has much broader implications because gene products implicated in breast cancer seem to cluster around DNA damage response pathways. Thus, an understanding of the role of *BRCA1* will likely have an impact on other forms of breast cancer not attributable to germline mutations in *BRCA1*. Both radiation therapy and most of the drugs used for cancer treatment rely on introducing DNA damage in the cells. *BRCA1* is a main participant in the cellular response to DNA damage, which makes it very important factor determining the patient's response to therapy.

II. Key research accomplishments

We are on target to complete all tasks in the timeframe proposed.

Task 1. To determine the functional significance of two poorly characterized domains of BRCA1 (Months 1-24):

1a. Generating BRCA1 C61G in pLenti4 BRCA1 full length.

We subcloned BRCA1 C61G mutant into plenti4 BRCA1 vector. Thus, task 1a is completed.

1b. Generating BRCA1-null cell lines with reconstituted full-length BRCA1C61G.

We are currently testing BRCA1 C61G full-length expression in HCC1937 and SUM1315 cell lines. Thus, this task is going according to plan and should be completed in the next few months.

1c. Verifying the expression levels and subcellular localization of BRCA1 wt and mutants (C61G, M1775R, delta motif 6 and delta exon 12/13) in SUM1315 tet repressor, SUM149 tet repressor and HCC1937 tet repressor cell lines.

We initiated our experiments with two available BRCA1 negative cell lines: HCC1937 tet repressor and SUM1315 tet repressor that were developed in the lab. We infected the cells with lentivirus expressing full length BRCA1 wild type (pLentiBRCA1WT). Unfortunately we

were not able to achieve the inducible expression of BRCA1 after addition of tetracycline for neither of the cell lines (Fig.1).

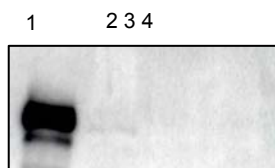


Fig.1 Testing BRCA1 expression in HCC1937 tet cell line. Lane 1-Hela cells were used as positive control; lane 2- HCC1937 tet parental as negative. Lane 3 and 4 HCC1937 tet infected with plentiBRCA1WT plasmid respectively before and after addition of tetracycline.

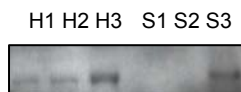


Fig.2 Three consecutive infections were necessary with plenti BRCA1WT to detect BRCA1 on WB. H1=HCC1937 first infection, H2= HCC1937 second infection, H3= HCC1937 third infection, S1= SUM1315 first infection, S2= SUM1315 second infection, S3= SUM1315 third infection

Next we repeated the infection with the same lentivirus using HCC1937 and SUM 1315 that do not express tet repressor. We needed three consecutive infections for both cell lines to achieve transient expression of BRCA1 (Fig. 2). The last approach required a high volume of lentiviruses that are not practical for routine use. Another problem was that the cells were expressing BRCA1 for very short window of time 24-36 hours. Thus, we could not obtain stable cell lines.

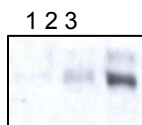


Fig. 3 Optimization of electroporation of plenti BRCA1WT plasmid with HCC 1937 cell line; lane 1-HCC1937 electroporated with pLenti lacZ plasmid served as a negative control. Lane 2 and 3 HCC1937 electroporated with plenti BRCA1WT plasmid 2 or 5 days after the procedure. WB for BRCA1 is shown.

Next we tested electroporation of the same BRCA1 construct (Fig.3) using HCC1937 and SUM1315 (not shown) cell lines. We optimized the procedure and achieved reproducible levels of expression of BRCA1 2-5 days after electroporation. We also tested different BRCA1 mutants and achieved similar results. We concluded that this will be the method of choice to analyze whether different mutants can restore BRCA1 checkpoint function.

1d. Colony forming assay after irradiation.

We performed colony forming assays with HCC1937 transfected with pLenti plasmids expressing either BRCA1 wt or mutant constructs: M1775R, a mutant lacking Motif 6 (delta motif 6) or a mutant lacking sequences in exons 12 and 13 that code for the coiled-coil domain (delta 12/13). We used HCC1937 cell line electroporated with pLenti lacZ plasmid as a control. Our initial results show that HCC 1937 expressing BRCA1 wt, delta motif6, or delta 12/13 constructs showed better survival after ionizing radiation than HCC1937 expressing lacZ or M1775R mutant. This suggests that these domains may not be critical for survival after irradiation.

Currently we are repeating the test with all the mutants mentioned above including BRCA1 C61G mutant.

1e. Early G2/M checkpoint assay.

In order to systematically evaluate the role of different BRCA1 domains in its checkpoint functions we started by analyzing the response of Hela cells (which we used as a positive control), SUM1315, and HCC1937 cells (which does not express functional BRCA1) one hour after ionizing radiation with 6 Gy (early G2/M checkpoint). We stained the cells with phospho

Ser-28 -histone H3 (mitotic marker) and analyzed them by flow cytometry. As expected HeLa cells presented 80% decrease in the mitotic cell population 1h after irradiation. For HCC1937 and SUM1315 cells the decrease in mitotic cells population was 30% and 40% respectively, showing that the cell lines that do not express BRCA1 (like HCC1937 and SUM1315) do not have intact G2/M checkpoint. We also tested HCC1937 expressing lacZ and BRCA1 WT or M1775R, delta Motif6 or delta 12/13 mutants. Our initial results show that the coil-coil domain (delta 12/13 construct) cannot reconstitute the BRCA1 wild type phenotype. This suggests that coil-coil domain of BRCA1 may be important for its function in G2/M checkpoint. We are currently repeating these experiments with large sample numbers and also adding BRCA1 C61G mutant.

1f. RDS (radioresistant DNA synthesis) assay.

We performed RDS assay using HeLa cells (as positive control) or HCC1937 cell lines. We also tried non-radioactive method to quantify the intra-S-phase checkpoint using BrdU incorporation followed by flow cytometry. We are prepared to use both methods if necessary. Within the next two months we are planning to start analyzing BRCA1 mutants proposed in the grant.

1g. Assay for intact spindle assembly.

We initially analyzed spindle assembly checkpoint using HeLa cells (as an example of cells that have intact spindle assembly checkpoint), HCC1937 and SUM1315 cell lines (the last two as an example of cells that does not have intact spindle assembly checkpoint). This was important as initial optimization of the assay (time points, duration, sensitivity). Next we plan to use HCC1937 and SUM1315 reconstituted with BRCA1 mutants proposed in the grant and to analyze spindle assembly checkpoint for each case.

In conclusion, we are on track to complete the tasks in the time proposed. Our expectations are that within next year we will be able to finish specific aim 1 as it is planned in the grant.

III. Reportable outcomes

Publications

The DOD pre-doctoral fellowship gave me an opportunity to collaborate with other lab members and to participate as a co-author in two papers, which are attached. We are also preparing a manuscript for publication with some of the work that has been described in this report. My fellowship BC083181 was credited in both papers.

1. De Ligio, J. T., A. Velkova, et al. (2009). "Can the status of the breast and ovarian cancer susceptibility gene 1 product (BRCA1) predict response to taxane-based cancer therapy?" *Anticancer Agents Med Chem* 9(5): 543-9.

2. Rios-Doria, J., A. Velkova, et al. (2009). "Ectopic expression of histone H2AX mutants reveals a role for its post-translational modifications." *Cancer Biol Ther* 8(5): 422-34.

Meetings

As part of my training I participated in Gordon Research Conference "Mammalian DNA repair"-February 8-13 2009 in Ventura, California. This conference had a significant impact on improving my knowledge not only in DNA repair but also in Breast cancer treatment.

Reportable outcomes**Papers/References: (Also attached in appendices section)**

1. De Ligio, J. T., **A. Velkova**, et al. (2009). "Can the status of the breast and ovarian cancer susceptibility gene 1 product (BRCA1) predict response to taxane-based cancer therapy?" Anticancer Agents Med Chem **9**(5): 543-9.
2. Rios-Doria, J., **A. Velkova**, et al. (2009). "Ectopic expression of histone H2AX mutants reveals a role for its post-translational modifications." Cancer Biol Ther **8**(5): 422-34.

Conference attended

Gordon Research Conference "Mammalian DNA repair"-February 8-13 2009 in Ventura, California

Bulleted list of key research and training accomplishments:

Cloning and expression of full length BRCA1 C61G mutant (tasks 1a and 1b)
Optimization of BRCA1 full-length expression (WT or mutants) in two cell lines (task1c)
Optimization of colony forming assay after irradiation (task1d)
Optimization of early G2/M checkpoint assay (task 1e)
Optimization of Radio-Resistant DNA synthesis assay (task 1f)
Optimization of spindle assembly checkpoint assay (task 1g)

Collaboration with other lab members

Projects-Role of BRCA1 in cancer treatment and the role of histone H2AX in chromosomal instability.

Two papers published:(my fellowship BC083181 was credited in both papers)

1. De Ligio, J. T., **A. Velkova**, et al. (2009). "Can the status of the breast and ovarian cancer susceptibility gene 1 product (BRCA1) predict response to taxane-based cancer therapy?" Anticancer Agents Med Chem **9**(5): 543-9.
2. Rios-Doria, J., **A. Velkova**, et al. (2009). "Ectopic expression of histone H2AX mutants reveals a role for its post-translational modifications." Cancer Biol Ther **8**(5): 422-34.

Reportable outcomes

Papers:

1. De Ligio, J. T., **A. Velkova**, et al. (2009). "Can the status of the breast and ovarian cancer susceptibility gene 1 product (BRCA1) predict response to taxane-based cancer therapy?" Anticancer Agents Med Chem **9**(5): 543-9.
2. Rios-Doria, J., **A. Velkova**, et al. (2009). "Ectopic expression of histone H2AX mutants reveals a role for its post-translational modifications." Cancer Biol Ther **8**(5): 422-34.

Conference attended

Gordon Research Conference "Mammalian DNA repair"-February 8-13 2009 in Ventura, California

Conclusion:

The purpose of this research is to classify *BRCA1* variants for which cancer association is not known (unclassified variants UCV). To approach this problem we hypothesized that poorly characterized but conserved domains in *BRCA1* directly participate in its tumor suppression function. To test this hypothesis we choose a global approach analyzing several *BRCA1* domains and point mutants in functions that have previously been attributed to *BRCA1*: long term survival after irradiation, early G2/M checkpoint, intra S phase checkpoint, and spindle assembly checkpoint. We successfully optimized conditions for expression of full-length *BRCA1* mutants in two different cell lines by electroporation. We also optimized all the checkpoints assays in our laboratory and are now ready to analyze *BRCA1* mutants proposed in this grant. This will have a significant impact not only to understand *BRCA1* role as a tumor suppressor in breast cancer but also to help patients that are carriers of *BRCA1* mutation to make informed clinical decisions.

Research Paper

Ectopic expression of histone H2AX mutants reveals a role for its post-translational modifications

Jonathan Rios-Doria,¹ Aneliya Velkova,^{1,2} Virna Dapic,¹ José M. Galán-Caridad,^{3,†} Vesna Dapic,³ Marcelo A. Carvalho,^{1,‡} Johana Melendez⁴ and Alvaro N.A. Monteiro^{1,*}

¹Risk Assessment, Detection and Intervention Program; H. Lee Moffitt Cancer Center & Research Institute; Tampa, FL USA; ²University of South Florida Cancer Biology Ph.D. Program; Tampa, FL USA; ³Strang Cancer Prevention Center; New York, NY USA; ⁴Flow Cytometry Core; H. Lee Moffitt Cancer Center & Research Institute; Tampa, FL USA

[†]Present address: Integrated Program in Cell; Molecular and Biophysical Studies; Columbia University Medical Center; New York, NY USA; [‡]Present address: Centro Federal de Educação Tecnológica de Química; Rio de Janeiro, Brazil

Abbreviations: ATM, ataxia-telangiectasia mutated; ATR, ATM and Rad3-related; BME, β -mercaptoethanol; BSA, bovine serum albumin; DBD, DNA binding domain; DNA-PK, DNA protein kinase; DSB, double strand breaks; EDTA, ethylene-diamine-tetra-acetic acid; γ -H2AX, histone H2AX phosphorylated at serine 139; GFP, green fluorescent protein; HEPES, 4-(2-hydroxyethyl)-1-piperazineethane-sulfonic acid; IR, ionizing radiation; MMS, methyl-methane sulfonate; PBS, phosphate buffered saline; PI, proteasome inhibitors; PI3K, phosphoinositide-3-kinase

Key words: histone, H2ax, ubiquitination, phosphorylation, half-life, DNA damage, apoptosis, cell cycle checkpoints

Recent evidence from a wide variety of biological systems has indicated important regulatory roles for post-translation histone modifications in cellular processes such as regulation of gene expression, DNA damage response and recombination. Phosphorylation of histone H2AX at serine 139 is a critical event in the response to DNA damage, but the functional implications of this modification are not yet clear. To investigate the role of H2AX phosphorylation we ectopically expressed epitope-tagged H2AX or mutants at the phosphorylation site. GFP-tagged wild type H2AX, H2AX Ser139Ala or H2AX Ser139Glu proteins were efficiently expressed, localizing exclusively to the interphase nucleus and to condensed chromosomes during mitosis. Biochemical fractionation indicated that epitope-tagged H2AX proteins are incorporated into nucleosomes. Expression of H2AX Ser139Ala, which disrupts the phosphorylation site partially suppressed early G₂/M arrest following ionizing radiation, and cells expressing this mutant were more sensitive to DNA damage. Conversely, expression of H2AX Ser139Glu, designed as phosphorylation mimic, induced a decrease in the number of cells in mitosis in the absence of DNA damage. Interestingly, this decrease induced by H2AX Ser139Glu was independent of the formation of 53BP1-containing foci and was partially suppressed in *CHK2*-deficient cells, suggesting a role for *CHK2* in this process. Further analyses revealed that expression of either mutant lead to apoptosis and induced higher caspase-3/7 activity compared to expression of wild type H2AX. In addition,

we also identified Lys119 as a site for ubiquitination that controls H2AX half-life. Phosphorylation of Ser139 and ubiquitination of K119 are not interdependent. Taken together these results demonstrate a role for H2AX Serine 139 phosphorylation in cell cycle regulation and apoptosis, and for Lysine 119 in the control of H2AX turnover.

Introduction

The response to DNA damage relies on a coordinated signaling network¹ and one of the earliest responses is phosphorylation of histone H2AX at Serine 139.² H2AX (*H2AFX*; OMIM 601772) is a minor variant of the highly conserved histone H2A that is part of the histone octamer in the core of the nucleosome in eukaryotic genomes.^{3,4} H2AX differs from H2A and the other human H2A variants by having a longer C-terminal tail that contains an SQE motif, a consensus site for phosphorylation by PI3K-related kinases.⁵ The kinases responsible for H2AX phosphorylation are the PI3K-like kinases ATM (Ataxia-Mutated), ATR (Ataxia and Rad3-related) and DNA-PK with each kinase thought to respond to different types of damage.⁶⁻⁸

After the induction of double strand breaks (DSB), phosphorylation of Ser 139 of H2AX radiates from the approximate site of damage to neighboring megabase regions of chromatin, although it seems not to be present in the immediate vicinity of the break.^{9,10} Proteins implicated in the DNA damage response such as BRCA1, NBS1 and 53BP1 were found to form discrete foci that colocalized with H2AX phosphorylated at Serine 139, also called γ -H2AX.¹¹ The role of γ -H2AX in the recruitment of these factors is still under investigation, but experiments suggest that γ -H2AX is required for the retention, but not initial recruitment, of these factors to sites of DSB.¹² In addition, cells from mice with homozygous disruption of *H2ax* are hypersensitive to ionizing radiation (IR) and develop

*Correspondence to: Alvaro N.A. Monteiro; H. Lee Moffitt Cancer Center; 12902 Magnolia Drive; Tampa, FL 33612 USA; Tel.: 813.7456321; Fax: 813.9036847; Email: alvaro.monteiro@moffitt.org

Submitted: 10/27/08; Revised: 12/03/08; Accepted: 12/09/08

Previously published online as a *Cancer Biology & Therapy* E-publication: <http://www.landesbioscience.com/journals/cbt/article/7592>

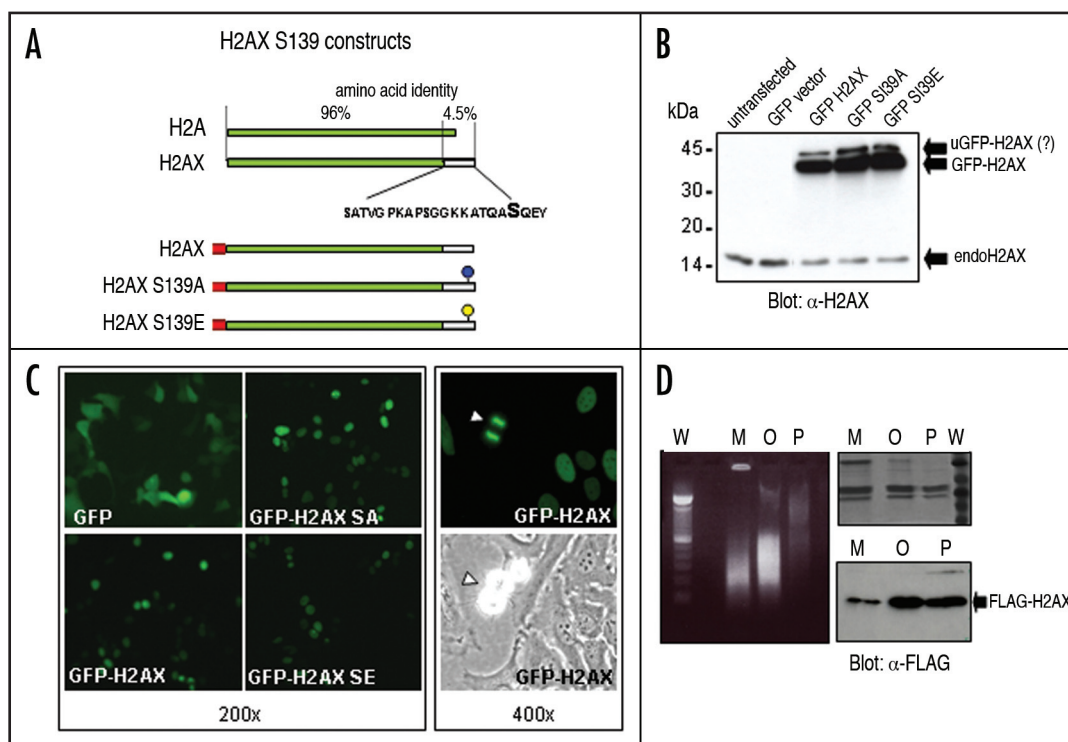


Figure 1. Expression of wild type H2AX and mutants. (A) Top diagram shows a comparison of H2A and H2AX indicating the percentage of amino acid similarity between the conserved part and the divergent tail. The amino acid sequence in the H2AX carboxy-terminal tail is depicted highlighting Serine 139. The bottom diagram shown wild-type H2AX, a mutant with a Serine139Alanine (S139A) mutation and a mutant with a Serine139Glutamic acid (S139E) mutation containing an N-terminal epitope (GFP or FLAG) tag. (B) Whole cell extracts of 293T cells transiently transfected with GFP Vector, GFP-H2AX, GFP-S139A and GFP-S139E were resolved by 12% SDS-PAGE and immunoblotted with α -H2AX antibody. Arrows indicate endogenous H2AX (endoH2AX), GFP-H2AX and slow migrating form of GFP-H2AX (uGFP-H2AX). (C) Left: Localization of ectopically expressed proteins in HeLa cells: GFP, note localization in nucleus and cytoplasm; GFP-H2AX, GFP-H2AX S139A and GFP-H2AX S139E localize exclusively to the nucleus; Right: HeLa cells in mitosis expressing GFP-H2AX (top) and phase contrast image of the same field (bottom), note localization in mitotic chromosomes. Magnification is 200x (left) and 400x (right). (D) Fractionation of nucleosomes in sucrose gradient. Ethidium bromide gel showing mono (M), oligo (O) and polynucleosome (P) fractions as indicated by a 100 bp marker (W), left; Coomassie-stained gel showing major histone components of all three fractions, top right; western blot with α -FLAG of all three fractions, bottom right.

genomic instability.^{13,14} These data demonstrate that H2AX plays a key role in the DNA damage response.

After DNA damage, levels of γ -H2AX rise rapidly then decreased over several hours to return to pre-damage levels.² Removal of γ -H2AX is a necessary step to proceeding with the cell cycle.^{15,16} This removal could happen by dephosphorylation of S139 residue and maintenance of nucleosome structure or, alternatively by degradation of γ -H2AX and subsequently nucleosome remodeling. However, it is still unclear what controls H2AX half-life.

Recently, it has been shown that *H2aX* may function as a haplo-insufficient tumor suppressor in the context of *Tp53* deletion.^{17,18} Absence of H2aX seems to shift DNA repair towards an error-prone mode.¹⁹ It is still not clear how disruption or decreased dosage of *H2aX* leads to cancer but induction of genomic instability in conjunction with defective DNA damage checkpoints seem to set the stage to cancer initiation. Fibroblasts from *H2aX* nullizygous mice display a functional G₂/M checkpoint at high doses of IR but defective at lower doses.^{13,20} Conceivably, lower doses are a better model to study physiological responses to DNA damage as higher doses may trigger a series of redundant responses that may not be normally observed in living cells. Thus, these experiments suggest a role for H2AX in control of cell cycle.²⁰ However, information is

still lacking on whether phosphorylation of serine 139 is required for the activation of the early G₂/M checkpoint in mammalian systems. Experiments in *S. cerevisiae* and *Schizosaccharomyces pombe* in which there was replacement of γ H2A with mutants of Serine 129 (the corresponding residue to Serine 139 in H2AX) did not reveal any abnormal checkpoint response.^{14,21,22} However, it is not surprising that there are intrinsic differences in the role of *H2AX* between the yeast and mammalian systems because γ H2A, the ortholog of mammalian H2AX, makes up virtually all the H2A component in the yeast cell. Thus, in order to systematically address the role of H2AX post-translational modifications we characterized an experimental model of transient and stable expression of wild type H2AX as well as a series of Serine and Lysine mutants in its C-terminal tail.

Results

Epitope-tagged H2AX is correctly localized to nucleosomes. To investigate the role of H2AX Serine 139 phosphorylation, we engineered plasmids which contain GFP- or FLAG-tagged wild type (wt) H2AX, and mutants which harbor Serine to Alanine (S139A) or Serine to Glutamic Acid (S139E) substitutions (Fig. 1A). The S139E mutant was designed as a phospho-mimetic, whereas the S139A mutant cannot be phosphorylated at position 139. Western

blot analysis demonstrated roughly equivalent expression levels of wt and mutant GFP-H2AX forms and significant overexpression when compared to endogenous H2AX (Fig. 1B). Wt and mutant H2AX ectopically expressed in 293T cells localized exclusively to the nucleus and during mitosis GFP-H2AX was associated with chromosomes (Fig. 1C). Expression was also comparable among FLAG-H2AX forms with a slight difference in levels at 12 h and 24 h after transfection but reaching similar levels at 36 h (Suppl. Fig. 1A).

To rule out the possibility that the ectopically expressed H2AX forms were not incorporated in nucleosomes but loosely associated with chromatin we performed nucleosome fractionation studies (Fig. 1D). Using a sucrose gradient we obtained three fractions corresponding to mononucleosomes, oligonucleosomes and polynucleosomes as determined by ethidium bromide staining of the agarose gel (Fig. 1D; left). A parallel Coomassie staining of the SDS-PAGE confirmed the presence of major histone components in all three fractions (Fig. 1D; right, top). A western blot for the FLAG epitope confirmed the presence of the ectopically expressed H2AX even in the mononucleosome fraction (Fig. 1D, right, bottom). In summary, epitope-tagged H2AX forms are efficiently expressed by transient transfection, are localized in the nucleus and are incorporated into nucleosomes.

Because transient expression of GFP- or FLAG-H2AX forms resulted in levels of expression significantly higher than the endogenous H2AX protein, we tested whether this would lead to large scale changes in chromatin. Micrococcal nuclease digestion of DNA from cells expressing FLAG-H2AX proteins did not reveal any difference when compared to untransfected cells (not shown). We also generated stable clones of 293T cells containing an integrated copy of a luciferase reporter gene driven by a GAL4 responsive promoter. Two independent clones were cotransfected with a FLAG-H2AX form and a GAL4 DNA binding domain (DBD) fusion to the transcription activating region of BRCA1.²³ Expression of H2AX forms did not significantly affect transcription of the reporter gene with the exception of wt H2AX in one of the clones (Suppl. Fig. 1B). In summary, epitope-tagged H2AX forms are efficiently expressed by transient transfection, are localized in the nucleus, and are incorporated into nucleosomes without causing major structural changes.

To confirm that the ectopically expressed H2AX could be phosphorylated after DNA damage, 293T cells expressing FLAG-H2AX and S139 mutants were irradiated with ten and 40 Gy and allowed 30 min for recovery. Ectopic wt H2AX was phosphorylated after DNA damage in a dose-dependent manner whereas the S139A and the S139E mutants fail to be phosphorylated (Suppl. Fig. 1C).

Stability of epitope-tagged H2AX depends on chromatin association. In order to determine whether the stability of different epitope-tagged forms varied in different compartments we transfected the wt, S139A and S139E mutants into 293T cells and incubated them for 36 hrs. This time point was chosen because all constructs showed their highest level and comparable expression (Suppl. Fig. 1A). Cells were then treated with cycloheximide to assess the stability of the ectopic proteins, irradiated or mock-treated, harvested at several time points following treatment and fractionated into cytosolic, nucleoplasm and chromatin fractions (Fig. 2A). While FLAG-H2AX forms were not detected in the cytoplasm (not shown), we detected two separate pools, one in the nucleoplasm and the other in the chromatin fraction (Fig. 2B). Levels of FLAG-H2AX

forms rapidly decreased in the nucleoplasm fraction, in the presence and in the absence of IR. Multiple experiments failed to show any reproducible difference in the half-life (~3.5 h) of FLAG-H2AX between irradiated and non-irradiated cells, and among the wt, S139A and S139E forms (Fig. 2B, compare top two rows).

Addition of proteasome inhibitors (PI) dramatically affected the steady state levels of the H2AX forms and indicated that their degradation is mediated by the proteasome (Fig. 2B; third row). Irradiated cells treated with PI were identical to non-irradiated ones (not shown). H2AX in the chromatin fraction was markedly more stable than the nucleoplasm fraction (Fig. 2B). We were unable to estimate the half-lives of the ectopic proteins in the nucleoplasm fraction in the presence of PI, or of proteins in the chromatin fraction because their increased stability called for longer incubation times with cycloheximide which lead to high toxicity.

While H2AX in the nucleoplasm was present as a single band of approximately ~16–18 kDa corresponding to the predicted molecular weight of FLAG-tagged H2AX (even in longer exposures), chromatin-associated H2AX presented at least two major bands, of ~16–18 kDa and ~25–27 kDa (Fig. 2B). Slight variations in molecular weight were due to different buffer conditions for fractionation. The ~9 kDa difference is suggestive of addition of one ubiquitin moiety. No consistent changes were seen upon irradiation (Fig. 2B, compare fourth and fifth rows). While a number of post-translationally modified forms of H2AX could be seen in the chromatin fraction, addition of proteasome inhibitor revealed additional post-translationally modified forms of H2AX. Their appearance following treatment with PI suggests that these are less stable forms that are stabilized by proteasome inhibition. While no other form was detectable in the nucleoplasm, we identified a large number of H2AX forms in the chromatin (Fig. 2B, sixth and seventh rows). To facilitate analysis we depicted in Figure 2C (right) all major and minor forms of H2AX encountered in different conditions after examining western blots results. The left panel in Figure 2C represents a long exposure of proteasome-treated chromatin fraction of wt H2AX. As the ladder pattern was indicative of ubiquitination we immunoprecipitated FLAG-tagged proteins from the cell lysate and probed the blot with anti-ubiquitin. A similar banding pattern emerged indicating that the major post-translationally modified H2AX forms were ubiquitinated (Fig. 2D).

Proteasome-dependent degradation is mediated by a modification of K119. Degradation by the proteasome has been shown to be mediated by ubiquitination of lysine residues in the target protein. To determine which lysine residue was the mediator of the degradation signal we constructed several mutants changing lysine residues present in the H2AX-specific tail (not present in H2A) for arginine as well as two lysines conserved in H2A (Fig. 3A). We treated cells with cycloheximide, harvested them at different time points, and analyzed the nucleoplasm fraction (Fig. 3A). Degradation was monitored by the disappearance of the signal and densitometric measurements were used to calculate the slope of the curves (Fig. 3B). The wild type K127R and K118R had similar slopes indicating that K118 and K127 play no significant role in the stability of H2AX (Fig. 3B). Mutants K134R and K133R displayed a slightly steeper slope suggesting that substitution of these residues slightly decreases the stability of H2AX, perhaps by shifting ubiquitination towards other sites. Mutant K119R is significantly more stable than other

forms indicating that K119 is the site targeted by a post-translational modification that controls H2AX stability (Fig. 3A and B).

In order to investigate whether the stabilization of H2AX by post-translational modification was dependent on the status of S139 we generated a series of double mutants, combining the mutants in S139 with the mutants with the K mutants. Mutation K119R conferred stability to all forms of H2AX independent of S139 (Fig. 3C). In addition, no other K mutant was able to significantly alter the stability of the other S139 forms of H2AX.

K119 is modified by ubiquitination and is not required for phosphorylation of S139. To determine whether K119 was post-translationally modified by ubiquitination we co-transfected cells with FLAG-H2AX or its S139 mutants and His-tagged ubiquitin. The chromatin fraction was used for pull-down assays with Nickel beads and blots were probed with α -H2AX antibody revealing that all forms of H2AX S139 mutants are ubiquitinated (Fig. 4A). However, there is a significant decrease in the precipitated band in cells transfected with K119R when compared with other forms (Fig. 4A). Note that input is comparable for all forms of H2AX. To verify whether this modification was also found in the endogenous H2AX we transfected cells with His-tagged ubiquitin only and increased the amount of protein loaded in the gel (Fig. 4B). A ubiquitinated endogenous H2AX form is present in cells in the presence and absence of irradiation (Fig. 4B). We noticed a slight increase in the ubiquitinated form after irradiation but this increase was not consistent over different experiments. Pull-down with Nickel beads and probing with α -FLAG antibody confirmed that H2AX K119R fails to be efficiently ubiquitinated (Fig. 4C). Also, mutant K119R can be phosphorylated at S139 (Fig. 4D arrow) when cells are subjected to DNA damage indicating that ubiquitination of K119 was not required for efficient phosphorylation of S139.

Mutation of S139 to alanine leads to chromosomal aberrations. We generated a series of HCT116 cell line derivatives expressing the wt, S139A and S139E forms under the control of a Tet-Off system (Fig. 5). The S139E mutant was not efficiently repressed by the presence of doxycyclin and induction by removal of doxycyclin did not increase S139E beyond non-induced levels (Fig. 5A). We also observed some leakage of the wild type H2AX in the presence of doxycyclin but levels were significantly increased upon induction (Fig. 5A). The S139A mutant showed a tight regulation with very low levels of ectopic expression in non-induced conditions and a significant

inducibility upon removal of doxycyclin (Fig. 5A). Cell lines were induced for seven days and their karyotype was analyzed. There was no significant difference in modal number of chromosomes in

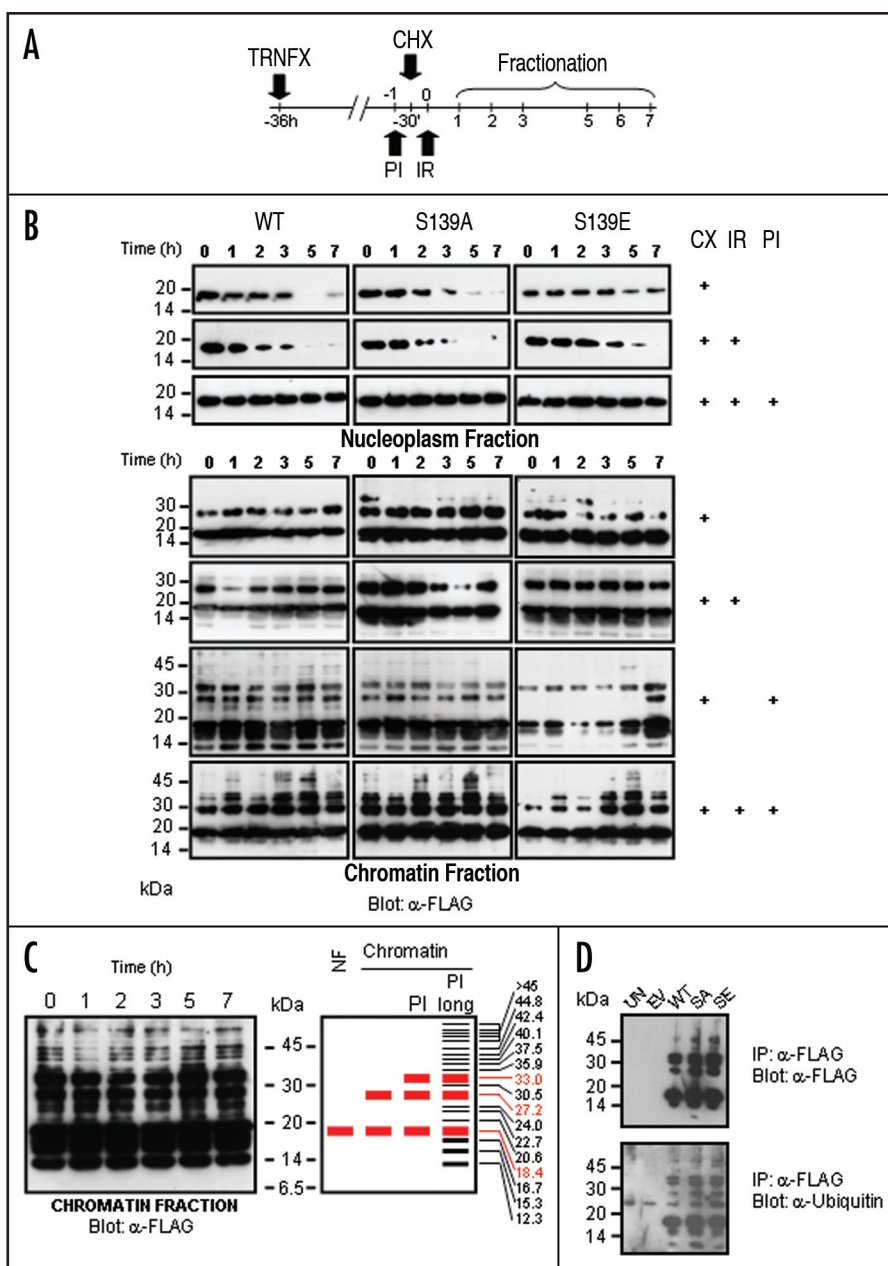


Figure 2. Post-translational modifications of ectopically expressed proteins. (A) Diagram illustrating the time course of treatment with proteasome inhibitors (PI), cycloheximide (CHX) and irradiation (IR). (B) Subcellular fractionation. Top three rows show nucleoplasm fraction levels of FLAG-H2AX forms after treatment with cycloheximide (first row), cycloheximide and irradiation (second row), and cycloheximide, irradiation and proteasome inhibitors (third row). Bottom four rows show chromatin fraction levels after treatment with cycloheximide (fourth row), cycloheximide and irradiation (fifth row), cycloheximide and proteasome inhibitors (sixth row) and cycloheximide, irradiation and proteasome inhibitors (seventh row). (C) A typical long exposure blot of chromatin fraction of FLAG-H2AX treated with cycloheximide, irradiation and proteasome inhibitors (left). A diagram detailing the major forms present after different treatments was derived (right). NF, nuclear fraction; PI, treated with proteasome inhibitors; PI Long, long exposure. (D) Lysates from cells transfected with empty vector (EV), FLAG-H2AX wild type (WT), FLAG-H2AX S139E (SE), FLAG-H2AX S139A (SA) and untransfected (UN) were immunoprecipitated with anti-FLAG antibody. Top panel is probed with anti-FLAG antibody to demonstrate expression. Bottom panel is probed with anti-ubiquitin.

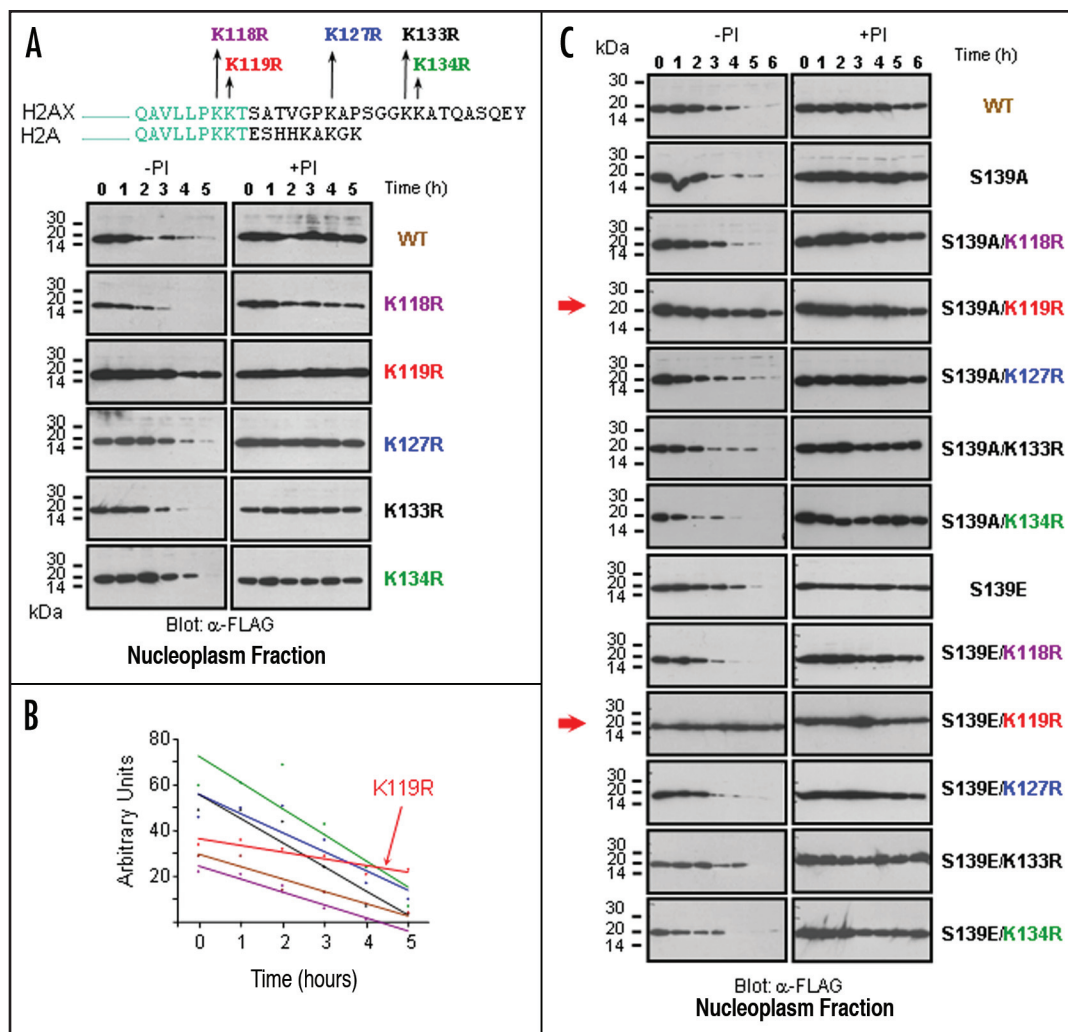


Figure 3. Mutation of Lysine 119 stabilizes H2AX protein levels. (A) Diagram showing amino acid sequence of H2AX and H2A C-terminal tail and sites of substitutions of Lysine residues to Arginine (top). Cells were transfected with different mutants and treated with cycloheximide in the presence (right) or absence (left) of proteasome inhibitors (PI). Cells were harvested and lysates were examined for the levels of FLAG-tag H2AX and its mutants at different time points. Note that K119R mutant is significantly more stable than all other constructs. (B) Densitometric measurements from the blots shown in (A) were used to plot the disappearance of H2AX mutants. Line colors correspond to different mutants as shown in (A). Note that the curve representing H2AX K119R has a clearly different slope from the wt or from the other mutants. (C) Double mutants of S139 and several K residues. Cells were transfected with different mutants and treated with cycloheximide in the presence (right) or absence (left) of proteasome inhibitors (PI). Cells were harvested and lysates were examined for the levels of FLAG-tag H2AX and its mutants at different time points. Note that K119R mutant is significantly more stable than all other constructs in the context of S139A or S139E (red arrows).

any of the cell lines (Suppl. Fig. 2). However, induced S139A cells displayed 11% of mitosis with chromosome abnormalities such as triradials and quadriradials (Fig. 5B). No gross abnormalities were found in non-induced S139A, or in induced or non-induced S139E or wild type.

H2AX mutants induce apoptosis and perturbation of G_2/M cell cycle checkpoint. During the course of our studies, we noticed that the S139A or S139E mutant appeared induce moderate cell death following transient transfection. Thus, we transiently transfected the GFP-H2AX forms into HeLa cells and quantified apoptosis by Annexin-V binding. This assay revealed a higher percentage of Annexin-V positive cells in both the S139E and the S139A transfected cells compared to wt H2AX (Fig. 6A). Increased apoptosis was confirmed by higher caspase-3/7 activity which was detected following expression of both mutants compared to wt H2AX

(Fig. 6B). These results demonstrate that ectopic expression of H2AX S139A or S139E mutants induce apoptosis.

Recent studies have shown that one of the first detectable physiological events after IR is phosphorylation of histone H2AX at Serine 139.² Therefore we tested whether transfection of the H2AX S139E mutant would trigger the G_2/M checkpoints by assessing early G_2/M arrest (also called transient G_2/M checkpoint) as well as G_2 accumulation, which have been described as two different mechanisms for G_2/M arrest.²⁴ The early G_2/M checkpoint was assessed using histone H3 phosphorylated at Serine 10 (pH3), as marker for mitosis in a flow cytometric assay.^{24,25} Analysis of the GFP-positive cell populations that stained for pH3 revealed that expression of the S139E mutant caused a significant reduction in the percentage of cells in mitosis, compared to the GFP negative cells (Fig. 6C). We also observed a modest reduction of cells in mitosis in GFP positive cells

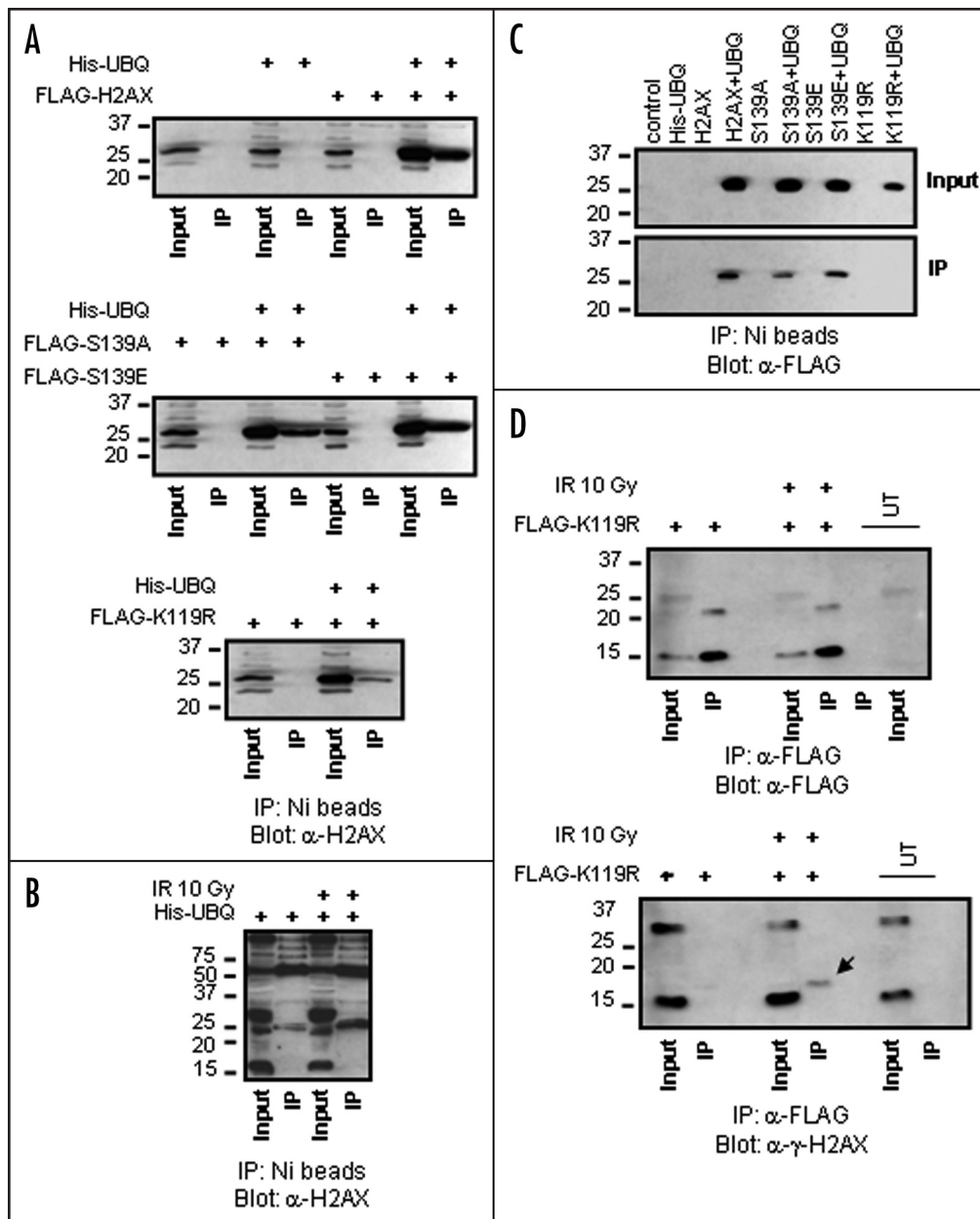


Figure 4. Ubiquitination of H2AX on K119. (A) Cells were co-transfected with constructs expressing His-tagged ubiquitin and FLAG-H2AX (top), FLAG-S139A, FLAG-S139E (middle), or FLAG-K119R (bottom). Lysates were precipitated (IP) with Ni-beads and blots were probed with α -H2AX. Note band corresponding to ubiquitinated H2AX in wt, S139A and S139E mutants but significantly reduced band in K119R mutant (bottom). (B) Cells were transfected with His-tagged ubiquitin and irradiated with 10 Gy after 24 hr post-transfection. Lysates were precipitated (IP) with Ni-beads and blots were probed with α -H2AX. (C) Cells were co-transfected as in (A). Lysates were precipitated (IP) with Ni-beads and blots were probed with α -FLAG. Note band corresponding to ubiquitinated H2AX in wt, S139A and S139E mutants but absent in K119R mutant (bottom). (D) Mutation of K119 does not prevent phosphorylation of S139. Cells were transfected with FLAG-K119R and irradiated (IR) or mock-treated. Note band corresponding to phosphorylated S139 H2AX in α -FLAG immunoprecipitate only in presence of irradiation (black arrow). UT, untransfected.

transfected with the S139A mutant and wt H2AX. To assess G_2 accumulation, 293T cells were transfected with the GFP-S139E mutant for 48 h and stained with propidium iodide. Analysis of cell cycle histograms of the GFP negative and positive populations revealed no significant changes in cell cycle phase distribution following transfection of the S139E mutant (Suppl. Fig. 3A). This indicates that the S139E mutant has no effect on G_2 /M accumulation.²⁴ While these data suggest that the S139E causes an early G_2 /M arrest it is possible that this mutant exerts its effects in other cell cycle compartments that lead to a decrease in the percentage of cells in mitosis.

We next tested whether phosphorylation of S139 was necessary for IR-induced early G_2 /M arrest. 293T cells were transfected with either the S139A mutant or wt H2AX and treated with 6 Gy of γ -radiation. Analysis of the GFP positive cells demonstrated that the S139A mutant partially suppressed early G_2 /M arrest following IR (Fig. 6D).

Based on data in the transient experiments showing that the H2AX mutants partially suppressed early G_2 /M arrest by IR (S139A), or triggered G_2 /M arrest in the absence of IR (S139E) we set out to determine the effects of these perturbations on the sensitivity to DNA

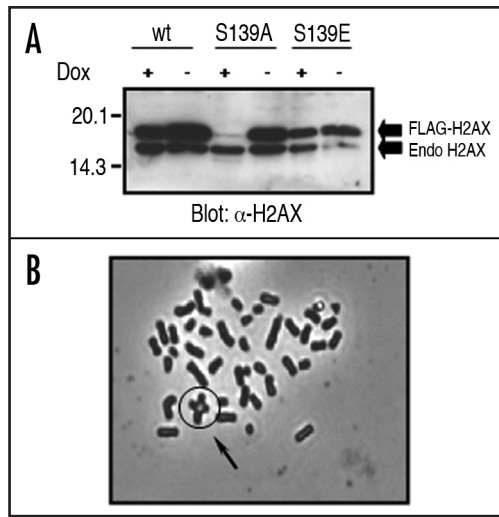


Figure 5. Induction of chromosome abnormalities in cells expressing H2AX S139A. (A) HCT116 Tet-off clones of cells expressing inducible FLAG-H2AX or mutants in the presence or absence of doxycycline (Dox). (B) Chromosome spreads showing a chromosomal aberration (red circle, black arrow), a quadriradial, found in cells expressing H2AX S139A.

damage. To achieve that, we generated stable cells lines expressing GFP, GFP-H2AX, GFP-H2AX S139A or GFP-H2AX S139E (Suppl. Fig. 3B) and treated them with increasing doses of the radiomimetic drug MMS (Fig. 6E). While expression of wild type H2AX or the S139E mutant did not affect sensitivity to MMS, cells stably over-expressing GFP-S139A displayed a markedly increased sensitivity (Fig. 6E). These results suggest that the S139A mutant impairs, directly or indirectly, DNA damage repair in these cells.

γ -H2AX has been shown to colocalize with several DNA damage response factors, including 53BP1, after DNA damage.²⁶ Thus, we hypothesized that expression of the S139A or S139E mutants might induce IR-induced focus formation and colocalize with 53BP1. HeLa cells were mock transfected, or transfected with GFP-H2AX, GFP-S139A or GFP-S139E mutants, followed by immunostaining for 53BP1. 53BP1 staining of undamaged cells revealed a faint background punctate staining in every cell in the population with a few large 53BP1 foci (Fig. 7A, first row, first column, arrow). Once irradiated cells presented with several large IR-induced 53BP1 foci (Fig. 7A, first column, second row). The number of these large IR-induced foci was determined in the following manner. The average number of 53BP1 foci per GFP-positive cell was determined

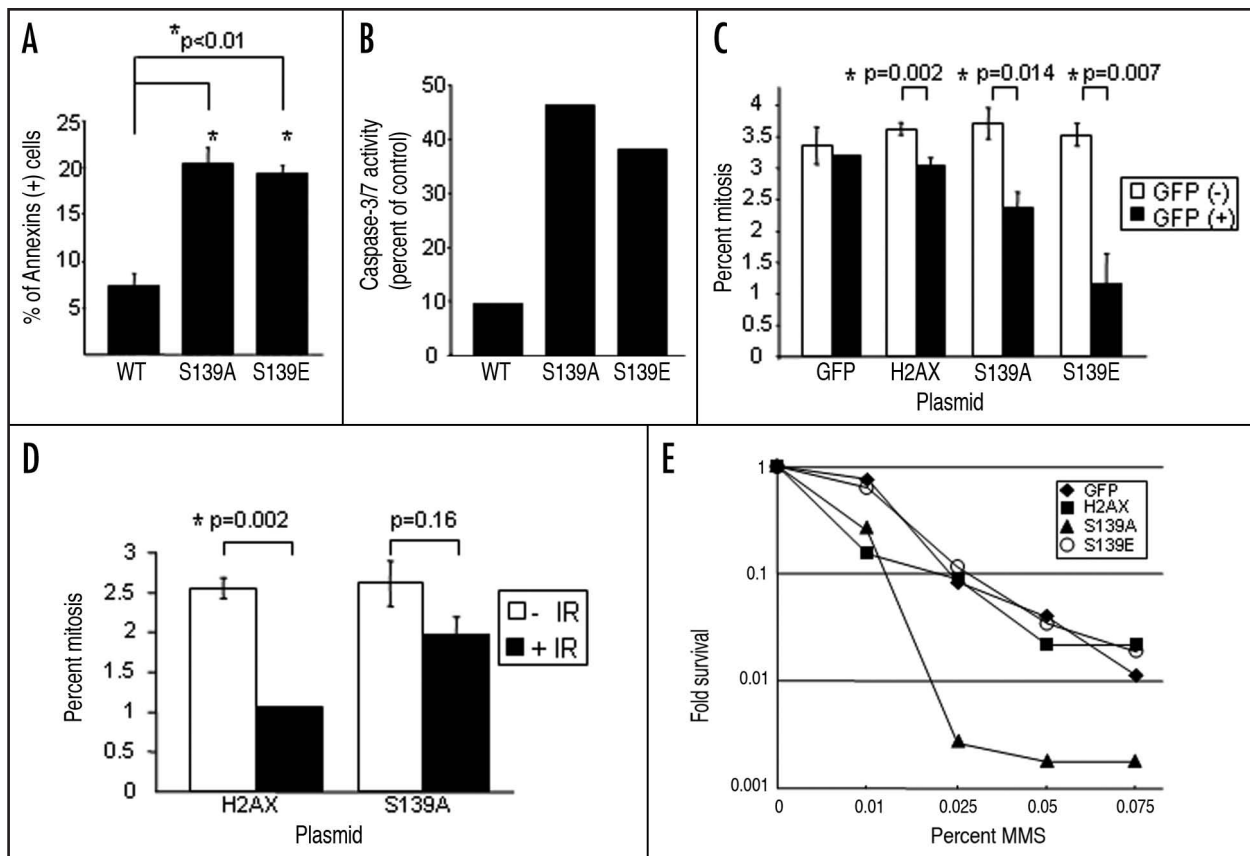


Figure 6. Effects of H2AX mutants on apoptosis and cell cycle checkpoints. (A) HeLa cells were transfected with GFP-H2AX, S139A or S139E and the percent increase of Annexin-V positive cells in the GFP positive cell population compared to the GFP negative cells in each sample was calculated. (B) HeLa cells were analyzed for caspase-3/7 activity 24 hours after transfection of H2AX, S139A, or the S139E constructs. Activity is relative to mock-transfected control cells. (C) Expression of S139E mutant triggers G₂/M arrest in the absence of DNA damage. 293T cells were transfected with GFP, the GFP Vector, GFP-H2AX, S139A or S139E for 48 hours, and the percentage of cells in mitosis was quantified by phosphorylated histone H3 (Serine 10) by flow cytometry. Comparisons of the percentage of mitotic cells between GFP Negative and GFP Positive cells were made. (D) Expression of S139A mutant abrogates the ionizing radiation-induced G₂/M arrest. 293T cells were transfected with the indicated constructs, irradiated with 6 Gy and analyzed one hour post-irradiation for phosphorylated histone H3. (E) Stable cell lines were treated with increasing doses of MMS for 50 minutes. Viability after 48 hours was measured by trypan blue exclusion.

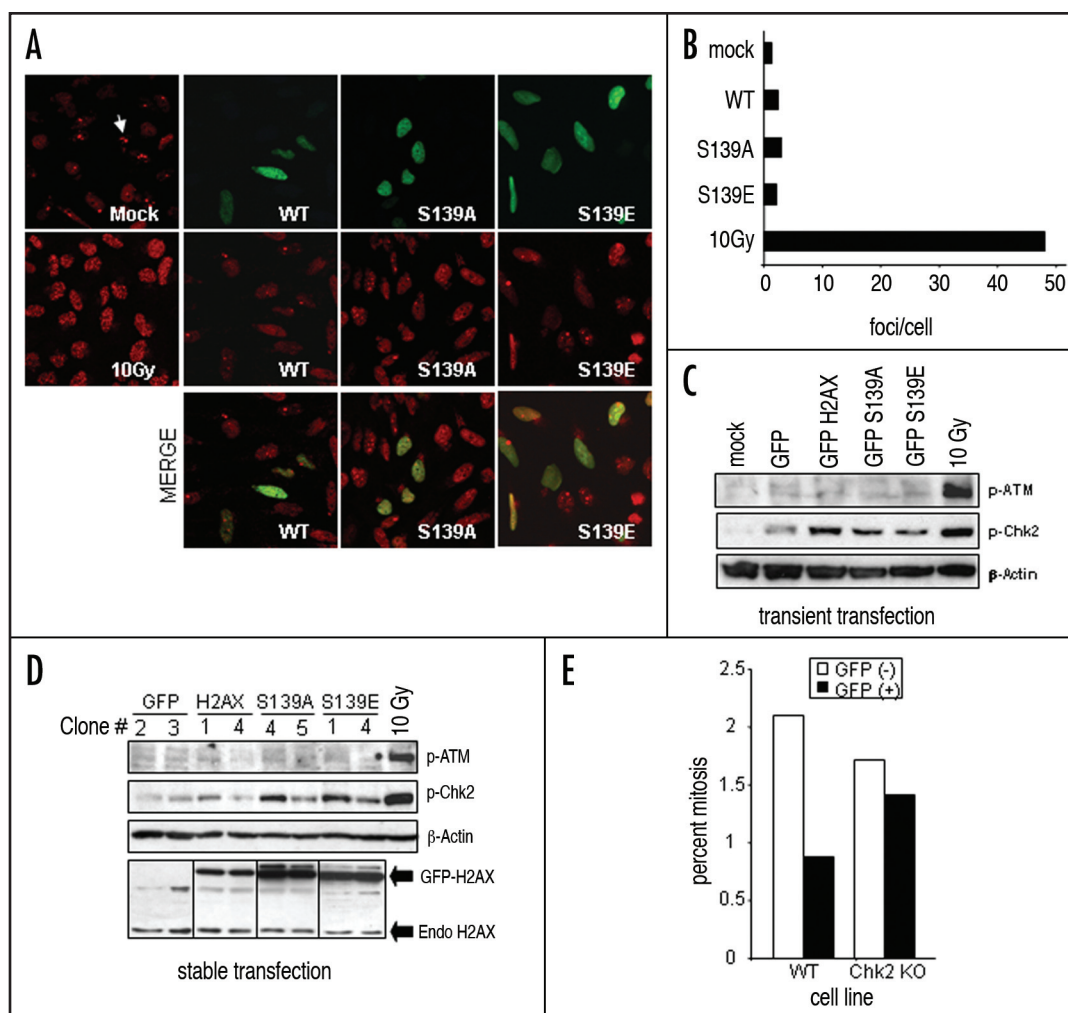


Figure 7. H2AX S139E does not induce 53BP1 foci. (A) HeLa cells were transfected with the indicated GFP-tagged constructs (green) and immunostained with 53BP1 antibody (red). Mock transfected and cells irradiated with 10 Gy are also shown (left columns). Images are at 630X magnification. The last row represents the merged images. (B) For mock-transfected cells, the number of foci per cell was quantitated automatically. For GFP-histone transfected cells, the number of foci per green cell was counted. (A) Expression of S139A or S139E activate Chk2. Whole cell lysates of 293T cells transiently transfected with the indicated constructs were immunoblotted with anti phospho-ATM Ser 1981 (top), Phospho Chk2 Thr 68 (middle) and β -Actin antibodies (bottom). An untransfected sample irradiated with 10 Gy is also shown. (D) Immunoblot analysis for phospho-ATM, phospho-Chk2, β -Actin and H2AX in HeLa clones stably expressing GFP, GFP-H2AX, GFP S139A and GFP S139E. (E) Chk2 is required for efficient early G_2 /m arrest by GFP-S139E. HCT116 wild-type or Chk2^{-/-} cells were transfected with GFP-S139E for 48 hours, and the percentage of GFP positive and negative cells in mitosis was calculated by phospho-H3 reactivity.

for the transfectants, whereas the number of foci per total number of cells was calculated for the mock transfected sample. This analysis demonstrated no significant induction of 53BP1 foci by any of the GFP-H2AX forms (Fig. 7A and B, compare with irradiated sample). Also, no difference was seen in number of foci between GFP-positive and GFP-negative cells in the same sample (Fig. 7A). In contrast, irradiating HeLa cells with 10 Gy induced ~48 foci per cell. These results demonstrate that the S139A or S139E mutants are not sufficient to induce foci that colocalize with 53BP1 and suggest that the observed effects on cell cycle checkpoint and apoptosis are independent of IR-induced foci formation.

To determine whether the H2AX forms activated other proteins involved in the DNA damage pathway, whole cell lysates of 293T cells transfected with the various H2AX forms were subjected to western blot analysis for phosphorylation of Ser1981 in ATM, Thr68 in CHK2 and Ser343 in NBS1. We barely detected any activation

of ATM in transiently or stably transfected cells as judged by phosphorylation of Ser1981 (Fig. 7C and D, Top). Similarly, we did not detect any activation of NBS1 after transient or stable transfection of the various H2AX forms (not shown). However, we observed an increase in phosphorylation of Thr68 of CHK2 in both stable clones and transiently transfected cells (Fig. 7C and D). A small but significant activation was also seen in cells expressing GFP alone (Fig. 7C). We also observed similar activation of CHK2 upon transfection of FLAG-H2AX forms ruling out that the activation was due to the GFP moiety (data not shown). In stable clones, expression of the mutant forms induced a higher level of activation of CHK2 than the expression of the wt but that could be due to difference in expression levels in the stable clones (Fig. 7D). Importantly, H2AX expression levels in early passage clones were roughly equivalent for all GFP-H2AX forms but levels of wt GFP-H2AX decreased with passage (not shown). These data show that the effect on cell cycle

regulation and apoptosis described here seem to be independent of NBS1 activation and also independent of 53BP1 foci formation.

To determine whether CHK2 played a role in the effects of the H2AX mutants on the cell cycle, the ability of the GFP-S139E mutant to decrease the number of cells in mitosis in HCT116 wild-type and *CHK2* deficient cells was determined. Our data show that the S139E mutant induced a decrease in mitotic cells in the parental HCT116 cells, but failed to induce arrest in *CHK2*-deficient cells to the same extent (Fig. 7E). However, transfection of the S139A mutant into *CHK2*-deficient cells displayed the partial suppression of IR-induced G₂/M arrest seen in parental HCT116 (data not shown). These data suggest that CHK2 plays a role downstream of S139E, but does not appear to play a role in partial suppression of arrest by the S139A mutant after IR.

Discussion

Ectopic expression of H2AX as a model to study its function. We developed and characterized a series of reagents to study the biology of histone H2AX. The first series used an N-terminal FLAG tag fused in frame to the wild type H2AX, to H2AX with Ser139 mutated to Glutamic acid (S139E), or to H2AX with Ser139 mutated to Alanine (S139A). The S139E substitution was designed to behave as a phosphorylation mimic as this strategy has been successful in a number of different approaches.^{27,28} Conversely, the S139A substitution was designed to represent an unphosphorylatable form of H2AX.

To monitor the association of the ectopic H2AX with chromatin we also generated a series of N-terminal GFP-tagged constructs. Other groups, studying histones have used GFP-histones successfully.^{29–31} The GFP-histones were exclusively nuclear showing that the N-terminal fusion did not impair its nuclear localization. In addition, in mitotic cells GFP-H2AX was exclusively localized to the metaphase chromosomes. Similar results were obtained by another laboratory.³² Tagged histones were present in fractions of purified mono and oligonucleosomes confirming that they are included into nucleosomes in vivo, and not just loosely associated with chromatin. In addition, ectopically expressed wt H2AX behaved similarly to endogenous H2AX as it was efficiently phosphorylated upon DNA damage.

Micrococcal nuclease digestion and transcriptional assays in cells expressing wt or mutant H2AX did not reveal large scale differences in chromatin structure when compared to untransfected cells. These results suggest that addition of epitope tags do not distort chromatin structure, in agreement with previous observations that incorporation of even a relatively large ubiquitin moiety in H2A has little effect on nucleosome structure.³³ It also suggests that absence (S139A mutant) or constitutive presence of a phosphorylation mimic (S139E mutant) does not lead to large scale changes in chromatin structure. Interestingly, expression of yH2A S129E (corresponds to H2AX S139E in humans) mutant in yeast led to a more relaxed chromatin suggesting that phosphorylation of yH2A could be acting to make the damaged sites more accessible to repair factors.²¹ This discrepancy can be explained by taking into account the difference in relative composition of H2AX between yeast and mammalian cells. In the yeast experiment expression of yH2A S129E was obtained in a background lacking wt yH2A, thus it is expected that the mutant will make up close to 100% of the H2A

pool in the cell. In mammalian cells H2AX make up from 5–20% of the total H2A component.² In our experiments mutants were expressed in addition to the endogenous H2A and its variants so that the levels of mutant H2AX incorporated in chromatin may not be enough to lead to large scale changes, although it is possible that more subtle changes occur.

Our system has several advantages but it also has inherent caveats. First, it is difficult to control or estimate the amount of H2AX as a fraction of the H2A component in the cell. Second, some results obtained after transient transfection could be due to an acute response to a change in the balance of H2A component. Likewise, cells expressing H2AX in a stable or inducible manner may undergo adaptation. The use of a combination of expression strategies should help in the interpretation of the results. Lastly, the S139E mutant which mimics DNA damage-induced phosphorylation of H2AX is expected to be homogeneously distributed on the chromosome, different from the localized phosphorylation associated with DSB. In this sense, our model may better reflect diffuse H2AX phosphorylation caused by UV exposure.³⁴

A role for K119 in H2AX turnover. Here we demonstrate that ectopically expressed H2AX was present in two cellular pools: chromatin and nucleoplasm. H2AX in the chromatin pool presented a much longer half-life than in the nucleoplasm. H2AX underwent post-translational modification by the addition of ubiquitin. The pattern of ubiquitination found in our experiments suggests that monoubiquitination is the major ubiquitinated form of H2AX. Upon stabilization by proteasome inhibitors a multiple ubiquitin conjugated form appeared. Mutation of K119 abolished ubiquitination and resulted in a stabilization of H2AX indicating that that ubiquitination of K119 is required for proteasome-dependent degradation. Interestingly, K119 is also the site of ubiquitination in H2A.³⁵ Proteasome inhibitors increased H2AX half-life suggesting that its turnover is mediated by the proteasome. This scenario is similar to that of H2A in HeLa cells in which ubiquitinated H2A turned over at a faster rate than non-modified H2A.³⁶

A limitation of our studies is that half-life experiments were conducted in the nucleoplasmic pool and not on the chromatin pool. Histone proteins in chromatin are known to be extremely stable varying from ~100 h for H1 microinjected in HeLa nuclei to several days for other histones in mammalian cells in vitro and in vivo.^{37–39} Longer incubation with cycloheximide induced severe toxicity which precluded experiments with the chromatin fraction.

In contrast to previously published data,⁴⁰ we found that ubiquitination of FLAG-H2AX was not dependent on DNA damage. Moreover, in our experiments phosphorylation of S139 was not required for ubiquitination of K119. One possible explanation for this discrepancy might be that the difference is quantitative rather than qualitative. Thus, experiments performed at the threshold of detection where ubiquitination is not detected under undamaged conditions but detected when cells are subjected to DNA damage, might be interpreted as ubiquitination been dependent on DNA damage. On the other hand experiments that are performed with more material might not reveal small changes. The modest enhancement of ubiquitination of H2A by RNF80 upon irradiation⁴¹ suggests that changes may be small.

A role for S139 in cell cycle control and apoptosis. Our results demonstrate that ablation of the phosphorylation site by a

substitution to Alanine attenuated the IR-induced early G₂/M arrest. Similar results suggesting that phosphorylation of H2AX is required for early G₂/M arrest at low doses of IR were obtained in mouse cells nullizygous for *H2AX*.²⁰ Cells overexpressing the S139A mutant were also more sensitive to DNA damage, consistent with previously published results with yeast expressing a S129A mutant²² and with H2AX-deficient cells.^{13,14} Taken together these data indicate that overexpression of the S139A mutant results in a phenotype comparable to *H2AX*^{-/-} cells and lends support to the notion that H2AX phosphorylation is required for checkpoint activation in mammalian cells.

Also, expression of H2AX S139E mutant leads to a significant decrease in the number of cells in mitosis. Irradiating cells expressing S139E with high doses of IR further reduced the fraction of cells in mitosis (data not shown) suggesting that this is a partial effect. There are several scenarios that can explain these observations. Because the effects of this mutant can be felt independent of external stimuli they could start after the expression levels reach a minimal threshold. Thus, a decrease in mitotic cells could be due to longer retention times of cells in other compartments due to G₁ arrest, S-phase delay, G₂ accumulation, or activation of early G₂/M checkpoint. It could also be due to shorter retention times in the mitotic compartment due to an accelerated mitotic exit. Flow cytometry analysis of propidium iodide-stained cells did not show increased accumulation of cells in G₁ or in G₂, which would indicate G₁ arrest or G₂ accumulation, respectively. However, it is still possible that S139E mutant causes S-phase delay, activation of G₂/M checkpoint or accelerated mitotic exit. Further research will be needed to clarify this issue.

Interestingly, expression of this mutant did not induce formation of 53BP1-containing foci in agreement with previous studies in mouse cells.¹⁸ While transfection of either wt H2AX or the S139A mutant also resulted in a decrease in the percentage of cells in mitosis, these effects were very modest when compared to expression of the S139E mutant. It is possible that levels of H2A variants are tightly controlled and perturbations may result in small effects on cell cycle regulation.

H2AX is phosphorylated by ATM, ATR or DNA-PK in response to different stimuli with partially overlapping specificity.^{7,8} Change in the overall tension and compaction of chromosomes have also been suggested as sufficient to trigger the DNA damage response.^{42,43} We did not detect large scale changes but Heo et al. have shown that in experiments done in vitro, H2AX phosphorylation alters nucleosome structure.⁴⁴ Importantly, although we were unable to detect significant ATM activation upon transient or stable transfection of any of the H2AX forms, we did detect phosphorylated CHK2 in stable cell lines overexpressing H2AX, S139A and S139E. It is possible that CHK2 activation observed is a result of subtle changes in chromatin structure due to expression of the ectopic H2AX forms that trigger a low level ATM activity that cannot be detected by the methods (and antibody) used.

To determine the role of CHK2 in the S139E-induced decrease in mitotic cells we transfected wild type and *CHK2*-deficient HCT116 cells with the S139E and the S139A mutants. These experiments showed that although all H2AX forms activated CHK2 to some degree, absence of CHK2 partially abrogated the decrease in the percentage of cells in mitosis induced by the S139E mutant and did not have any effect on the modest arrest induced

by the S139A mutant. We propose that there are additional factors involved that have not been identified that account for the molecular signals triggered by the H2AX mutants. Taken together, our data suggest that the effects of the S139E mutant on the cell cycle are at least partially dependent on CHK2 but are independent of 53BP1 focus formation.

Both the S139A and S139E mutant induce apoptosis to higher levels than wt H2AX. However, it is unclear if both mutants induce apoptosis through the same mechanism. It is conceivable that continuous presence of a damage signal over long periods of time, as represented by the S139E mutant, may lead to cell death. Induction of death by the S139A mutant might be due to accumulation of damage from replication errors in the context of a defective checkpoint. Alternatively, it has been shown that serine 139 is required for proper homologous recombination function¹⁹ and this may lead either mutant to trigger apoptosis using the same mechanism.

The data presented here support the notion that histone H2AX has a pleiotropic role in the DNA damage response with the ability to modulate cell cycle control responses and apoptosis. Our data also suggests a role for CHK2 in cell cycle control mediated by H2AX. A role for CHK2 in cell cycle control by H2AX is consistent with recent experiments in yeast.^{15,45} In yeast cells deficient for *PPH3*, the phosphatase that dephosphorylates γ -H2AX during damage repair,¹⁵ the sustained activation of Rad9 and Rad53 (the yeast CHK2 homolog) correlated with the maintenance of G₂/M arrest.¹⁵

Experiments using mice with disrupted *H2AX* gene have revealed that H2AX plays an important role in the DNA damage response in mammalian cells.^{13,14,17,18} However the mechanism by which H2AX exerts its effects has remained largely unknown. A tractable system to investigate the role of the Serine 139 phosphorylation has been established in the yeast *Saccharomyces cerevisiae* using replacement of yH2A gene (the ortholog of mammalian H2AX) with Serine 129 (the corresponding residue in yH2A) mutants.^{21,22} However, it is unclear whether results from yeast can be generalized to mammalian systems given the intrinsic differences in the DNA damage pathways in yeast and mammalian cells, particularly at the level of CHK1 and CHK2 kinases.^{46,47} For example, phosphorylation of serine 129 in yeast does not seem to affect cell cycle checkpoints.^{21,22}

In the present paper we established a mammalian system of ectopic expression of H2AX and its mutants and discussed its advantages and potential pitfalls. We believe that such a system may represent a useful tool to study the biological role of histone H2AX.

Material and Methods

Constructs. GAL4 DBD BRCA1 (aa 1396–1863) was previously described.⁴⁸ Human histone *H2AX* (OMIM 601772) cDNA was obtained by PCR from a human mammary gland cDNA library (Clontech, Mountain View, CA), using the following primers: H2AX-(S)-EcoR1 (5'-ATG AAT TCA TGT CGG GCC GCG GCA AGA C-3') and H2AX-(AS)-BamH1 (5'-TTG GAT CCT TAG TAC TCC TGG GAG GCC T-3'). The PCR product was cloned into pKS-Bluescript (Stratagene) and confirmed by sequencing. Mutants of Serine 139 to Alanine (S139A) and of Serine 139 to Glutamic acid (S139E) were generated by site-directed mutagenesis of the wild type construct using primers: for S139A (H2AX-(S)-EcoR1 and; H2AX S139A-(AS)-BamH1: 5'-TTG GAT CCT TAG TAC TCC TGG GCG GCC TGG GT-3'); for S139E (H2AX-(S)-EcoR1 and;

H2AX S139E-(AS)-BamHI: (5'-TTG GAT CCT TAG TAC TCC TGC TCG GCC TGG GT-3'). The wild type and mutant H2AX forms were then subcloned in frame to an N-terminal fusion of GFP in pEGP-C3 (Clontech) into pCMV FLAG2 (Sigma) in frame to an N-terminal fusion to FLAG epitope. To obtain pTRE-H2AX, pTRE-H2AX S139E and pTRE-H2AX S139A, we digested pKS-Bluescript containing the different H2AX forms with EcoRI and BamHI and ligated the inserts into similarly digested pTRE vectors (BD Biosciences).

Mutants of Lysine residues (K118R, K119R, K127R, K133R and K134R) were obtained through site-directed mutagenesis using the following primers: For K118R (K118R-S: 5'-CGT GCT GCT GCC CAG GAA GAC TAG TGC CAC CGT GGG GCC G-3'; K118R-AS: 5'-CGG CCC CAC GGT GGC ACT AGT CTT CCT GGG CAG CAG CAC G-3'); for K119R (K119R-S: 5'-CGT GCT GCT GCC CAA GAG GAC TAG TGC CAC CGT GGG GCC G-3'; K119R-AS: 5'-CGG CCC CAC GGT GGC ACT AGT CTT CCT GGG CAG CAG CAC G-3'); for K127R (K127R-S: 5'-GCC ACC GTG GGG CCG AGG GCA CCC TCG GGC GGC-3'; K127R-AS: 5'-GCC GCC CGA GGG TGC CCT CGG CCC CAC GGT GGC-3'); for K133R (K133R-S: 5'-CCC TCG GGC GGC AGG AAG GCA ACC CAG GCC TCC-3'; K133R-AS: 5'-GGA GGC CTG GGT TGC CTT CCT GCC CGG CGA GGG-3'); for K134R (K134R-S: 5'-CCC TCG GGC GGC AAG AGG GCA ACC CAG GCC TCC-3'; K134R-AS: 5'-GGA GGC CTG GGT TGC CCT CTT GCC GCC CGA GGG-3'). Site-directed mutagenesis for double mutants (containing a K mutation and an S139 mutation) were obtained using the same primers as above but with S139A or S139E mutant cDNAs as templates.

Cell lines and transfections. HeLa and human embryonic kidney (HEK) 293T cells were maintained in DMEM media supplemented with 7.5% FBS, 100 units/mL penicillin/streptomycin and 1.25 µg/mL amphotericin B (Sigma, St. Louis MO). HCT116 wild-type and *Chk2*^{-/-} cells (kind gift from Bert Vogelstein) were maintained in McCoy's 5A media supplemented with 10%FBS, 100 units/mL penicillin/streptomycin and 1.25 µg/mL amphotericin B. Transient transfections using Fugene 6 (Roche) were performed according to manufacturer's protocol.

Stable HeLa cell lines were created by the addition of 600 µg/mL G418 (Sigma) three days after transfection with GFP-H2AX constructs. Cells were kept under selection for two wk, after which they were subjected to fluorescence activated cell sorting using FACS Vantage SE with DIVA option. Sorted GFP positive cells were collected, replated and maintained with 200 µg/mL G418. Clones were generated from plating the stable pools at a 1:500 dilution in 150 mm tissue culture dishes and subsequently cloned with glass cylinders.

Stable HCT116 Tet-H2AX cell lines were created by initially transfecting HCT116 cells with pTet-Off (BD Biosciences) and adding 200 µg/mL G418. Clones were isolated using glass cylinders and tested for inducibility using a transient transfection of pTRE-luciferase in the presence and absence of doxycyclin. Transfections were performed in triplicate using Fugene 6 (Roche) and normalized with an internal control phGR-TK (Promega), which contains a Renilla luciferase gene under a constitutive TK basal promoter. Luciferase activity was measured using a dual luciferase assay system (Promega). A clone (HTO-23) was selected and subsequently

cotransfected with pHygro and pTRE-H2AX, pTRE-H2AX S139E or pTRE-H2AX S139A. Clones were isolated using glass cylinder in the presence double selection (G418 and hygromycin).

Stable 293T-G5-luc cells were obtained by transfection of 293T cells with pG5-luc, which contains a firefly luciferase gene under the control of five GAL4 binding sites, and clones were isolated by glass cylinders in the presence of 200 µg/mL G418.

Early G₂/M checkpoint assay. Briefly, cells were transfected with GFP-tagged histones for 48 h, harvested, washed in PBS and fixed in 0.5% methanol-free formaldehyde (Polysciences, Warrington, PA). After washing, cells were incubated in 70% EtOH overnight at -20°C. The next day cells were washed in PBS and permeabilized in PBS/0.25% Triton X-100 for 15 min on ice. Cells were then washed, and 0.75 µg of α-phospho-histone H3 (Phosphoserine 10) antibody (Upstate, Charlottesville, VA) was added to cells resuspended in 100 µl of PBS/1% BSA for 2.5 h at room temperature. Cells were washed in PBS and resuspended again in PBS/1%BSA to which Alexa Fluor 680-R-phycoerythrin goat anti-rabbit IgG was added at a 1:200 dilution (Molecular Probes, Eugene, OR). Cells were washed twice, and samples were run on a BDFacScan flow cytometer. The percentage of cells with phospho-H3 reactivity in the GFP positive and negative cell populations was calculated using FlowJo software (Treestar, Ashland, OR). For DNA content detection, cells were washed twice in PBS, and then resuspended in 40 µg/mL propidium iodide in PBS supplemented with 100 µg/mL RNase A and analyzed in the BDFacScan.

MMS sensitivity assay. The protocol was performed essentially as previously described.⁴⁹ Following treatment of HeLa stable cell lines with methyl methane sulfonate (MMS) for 50 min, they were washed with PBS, and fresh media was then added. Forty-eight hours later, attached and detached cells were harvested and viability was assessed using trypan blue exclusion (Invitrogen, Carlsbad, CA).

Apoptosis assays. For the Annexin-V assay, HeLa cells were transfected with the GFP-tagged H2AX, S139A or S139E constructs. Forty-eight hours after transfection, attached and detached cells were harvested and binding of Annexin-V was measured by flow cytometry according to the manufacturer's instructions (BD Biosciences, San Jose, CA). To measure caspase 3/7 activity, the Caspase-Glo kit was used (Promega, Madison, WI). Briefly, subconfluent HeLa cells were transfected with 50 ng/well of GFP-H2AX, S139A or S139E in 96-well plates. Caspase 3/7 activity was measured 24 h after transfection in a Victor 2 luminescent plate reader.

Subcellular fractionation, western blots and immunoprecipitations. Whole cell extracts were prepared by lysing cells in RIPA buffer [120 mM NaCl, 50 mM Tris pH 7.4, 0.5% NP-40, 1 mM EDTA]. For extraction of histones, transfected cells were harvested, washed with PBS, and lysed in Buffer A [20 mM Tris pH 7.4, 10 mM KCl, 1 µM EDTA, 0.2% NP40, 50% glycerol, 0.6 mM β-Mercaptoethanol (BME), 1 mM PMSF and 1X protease inhibitor cocktail (Roche)] for two min on ice. The pellet was resuspended in Buffer B [20 mM Tris pH 7.4, 10 mM KCl, 0.4 M NaCl, 1 µM EDTA, 50% glycerol, 0.6 mM BME, 1 mM PMSF, protease inhibitor cocktail] for 30 min on ice. After centrifugation, the pellet was resuspended in Acid Extraction Buffer (0.5 M HCl, 50% glycerol, 100 mM BME) for two min at room temperature. To the supernatant, Tris pH 7.4 (10 mM final concentration), NaOH (0.33 M final concentration) and protease inhibitors were added to 10 mM final concentration. Protein

concentrations were measured by the Bradford assay (Biorad). The following antibodies were used: α -H2AX, α - γ H2AX and α -phospho-Histone H3 Serine 10 (Upstate), α -GFP (Chemicon), α -phospho-CHK2 Threonine 68 (Cell Signaling), α -phospho ATM Serine 1981 (Upstate), α -Flag and β -Actin (Sigma). Beads were Protein A/G agarose (Santa Cruz) and Nickel-NTA-agarose (Qiagen).

Nucleosome fractionation. The procedure was carried out as previously described, with modifications.⁵⁰ 293T cells were transfected with wild-type Flag H2AX for 36 h, harvested, washed in PBS and resuspended in lysis buffer [20 mM HEPES pH 7.5, 0.25 M sucrose, 3 mM MgCl₂, 0.5% NP40, 3 mM BME, 0.4 M PMSF and protease inhibitors cocktail]. The cells were lysed in a dounce homogenizer and centrifuged for 15 min at 3,000 g. Pelleting was repeated twice with lysis buffer and once with fractionation buffer [20 mM HEPES, pH 7.5, 3 mM MgCl₂, 0.2 mM EGTA, 3 mM BME, 0.4 M PMSF and protease inhibitor cocktail]. This was followed by resuspension of the pellet in two volumes of fractionation buffer. To the suspension, one total volume of fractionation buffer/0.6 M KCL/10% glycerol was added. After stirring at 4°C for ten min the nuclei were pelleted by centrifugation at 17,500 g for 30 min at 4°C. The nuclear pellet was resuspended in 20 volumes of medium salt buffer [20 mM HEPES pH 7.5, 0.4 M NaCl, 1 mM EDTA, 5% glycerol, 1 mM BME, 0.5 M PMSF and protease inhibitors], followed by centrifugation at 10,000 g for ten min at 4°C. The pellet was then resuspended in four volumes high salt buffer [20 mM HEPES pH 7.5, 0.65 M NaCl, 1 mM EDTA, 0.34 M sucrose, 1 mM BME, 0.5 M PMSF], and homogenized with 40–50 strokes in a dounce homogenizer to release the oligonucleosome fragments. The nuclei were then centrifuged at 10,000 g for 20 min at 4°C. The supernatant was dialyzed overnight against low salt buffer [20 mM HEPES pH 7.5, 0.1 M NaCl, 1 mM EDTA, 1 mM BME, 0.5 M PMSF], followed by the addition of CaCl₂ to a 3 mM final concentration and ten units/ml micrococcal nuclease (Sigma). The reaction was incubated for ten min at 37°C, stopped with 0.1 volume 0.5 M EDTA, and subjected to a 10%–30% sucrose gradient, followed by ultracentrifugation for seven hrs. The 15 fractions were analyzed on a 1% agarose gel for the presence of nucleosome fragments. The positive fractions (which contained mono, oligo and poly-nucleosomes) were resolved by 12% SDS PAGE. Protein Bands were visualized by staining with Coomassie blue, and by immunoblotting with α -FLAG antibody.

Immunofluorescence. HeLa cells were plated onto chamber slides and transfected the next day with 0.5 μ g of GFP vector, GFP-H2AX, GFP-S139A or GFP-S139E. Forty eight hours after transfection, mock transfected cells were irradiated with 10 Gy. One hour after irradiation, samples were fixed with 4% formaldehyde for five min followed by five min incubation with cold 100% EtOH. Cells were permeabilized with PBS/0.25% Triton X-100 for ten min on ice, washed with PBS, and then blocked for 30 min with PBS/5% BSA at room temperature. After blocking, 53BP1 antibody (Upstate) was added at a 1:1000 dilution to PBS/1% BSA for one hour at room temperature. Cells were washed and goat α -mouse AlexaFluor 555 (Molecular Probes) was added at 1:5,000 dilution in PBS/1% BSA for one hour at room temperature. Cells were washed four times and mounted with Prolong Gold medium (Molecular Probes). Quantitation of foci was performed using ImagePro software (MediaCybernetics, Silver Spring, MD).

Acknowledgements

The authors are indebted to members of the Monteiro Lab for helpful discussions. This work was supported by a DoD postdoctoral fellowship DAMD17-01-1-0403 (V.D.), a DoD predoctoral fellowship BC083181 (A.V.), by the Julia Murtha Fund (A.M.), NIH grant CA92309 (A.M.) and supplement CA92309-04S1 (J.R.D) and supported in part by the Molecular Imaging, Flow Cytometry, Analytic Microscopy and the Molecular Biology cores at the H.L. Moffitt Cancer Center & Research Institute.

Note

Supplementary materials can be found at:
www.landesbioscience.com/supplement/RiosDoriaCBT8-5-Sup.pdf

References

1. Zhou BB, Elledge SJ. The DNA damage response: Putting checkpoints in perspective. *Nature* 2000; 408:433-9.
2. Rogakou EP, Pilch DR, Orr AH, Ivanova VS, Bonner WM. DNA double-stranded breaks induce histone H2AX phosphorylation on serine 139. *J Biol Chem* 1998; 273:5858-68.
3. Redon C, Pilch D, Rogakou E, Sedelnikova O, Newrock K, Bonner W. Histone H2A variants H2AX and H2AZ. *Curr Opin Genet Dev* 2002; 12:162-9.
4. Hatch CL, Bonner WM, Moudrianakis EN. Minor histone 2A variants and ubiquitinated forms in the native H2A:H2B dimer. *Science* 1983; 221:468-70.
5. Ivanova VS, Zimonjic D, Popescu N, Bonner WM. Chromosomal localization of the human histone H2A.X gene to 11q23.2-q23.3 by fluorescence in situ hybridization. *Hum Genet* 1994; 94:303-6.
6. Burma S, Chen BP, Murphy M, Kurimasa A, Chen DJ. ATM phosphorylates histone H2AX in response to DNA double-strand breaks. *J Biol Chem* 2001; 276:42462-7.
7. Ward IM, Chen J. Histone H2AX is phosphorylated in an ATR-dependent manner in response to replicational stress. *J Biol Chem* 2001; 276:47759-62.
8. Stiff T, O'Driscoll M, Rief N, Iwabuchi K, Lobrich M, Jeggo PA. ATM and DNA-PK function redundantly to phosphorylate H2AX after exposure to ionizing radiation. *Cancer Res* 2004; 64:2390-6.
9. Rogakou EP, Boon C, Redon C, Bonner WM. Megabase chromatin domains involved in DNA double-strand breaks in vivo. *J Cell Biol* 1999; 146:905-16.
10. Shroff R, Arbel-Eden A, Pilch D, Ira G, Bonner WM, Petrini JH, et al. Distribution and dynamics of chromatin modification induced by a defined DNA double-strand break. *Curr Biol* 2004; 14:1703-11.
11. Paull TT, Rogakou EP, Yamazaki V, Kirchgesner CU, Gellert M, Bonner WM. A critical role for histone H2AX in recruitment of repair factors to nuclear foci after DNA damage. *Curr Biol* 2000; 10:886-95.
12. Celeste A, Fernandez-Capetillo O, Kruhlak MJ, Pilch DR, Staudt DW, Lee A, et al. Histone H2AX phosphorylation is dispensable for the initial recognition of DNA breaks. *Nat Cell Biol* 2003; 5:675-9.
13. Celeste A, Petersen S, Romanienko PJ, Fernandez-Capetillo O, Chen HT, Sedelnikova OA, et al. Genomic instability in mice lacking histone H2AX. *Science* 2002; 296:922-7.
14. Bassing CH, Chua KE, Sekiguchi J, Suh H, Whitlow SR, Fleming JC, et al. Increased ionizing radiation sensitivity and genomic instability in the absence of histone H2AX. *Proc Natl Acad Sci USA* 2002; 99:8173-8.
15. Keogh MC, Kim JA, Downey M, Fillingham J, Chowdhury D, Harrison JC, et al. A phosphatase complex that dephosphorylates gammaH2AX regulates DNA damage checkpoint recovery. *Nature* 2005; 439:406-7.
16. Chowdhury D, Keogh MC, Ishii H, Peterson CL, Buratowski S, Lieberman J. Gamma-H2AX dephosphorylation by protein phosphatase 2A facilitates DNA double-strand break repair. *Mol Cell* 2005; 20:801-9.
17. Bassing CH, Suh H, Ferguson DO, Chua KE, Manis J, Eckersdorff M, et al. Histone H2AX: A dosage-dependent suppressor of oncogenic translocations and tumors. *Cell* 2003; 114:359-70.
18. Celeste A, Difilippantonio S, Difilippantonio MJ, Fernandez-Capetillo O, Pilch DR, Sedelnikova OA, et al. H2AX haploinsufficiency modifies genomic stability and tumor susceptibility. *Cell* 2003; 114:371-83.
19. Xie A, Puget N, Shim I, Odate S, Jarzyna I, Bassing CH, et al. Control of sister chromatid recombination by histone H2AX. *Mol Cell* 2004; 16:1017-25.
20. Fernandez-Capetillo O, Chen HT, Celeste A, Ward I, Romanienko PJ, Morales JC, et al. DNA damage-induced G₂-M checkpoint activation by histone H2AX and 53BP1. *Nat Cell Biol* 2002; 4:993-7.
21. Downs JA, Lowndes NF, Jackson SP. A role for *Saccharomyces cerevisiae* histone H2A in DNA repair. *Nature* 2000; 408:1001-4.
22. Redon C, Pilch DR, Rogakou EP, Orr AH, Lowndes NF, Bonner WM. Yeast histone 2A serine 129 is essential for the efficient repair of checkpoint-blind DNA damage. *EMBO Rep* 2003; 4:678-84.

23. Monteiro AN, August A, Hanafusa H. Evidence for a transcriptional activation function of BRCA1 C-terminal region. *Proc Natl Acad Sci USA* 1996; 93:13595-9.
24. Xu B, Kim ST, Lim DS, Kastan MB. Two molecularly distinct G₂/M checkpoints are induced by ionizing irradiation. *Mol Cell Biol* 2002; 22:1049-59.
25. Xu B, Kim S, Kastan MB. Involvement of Brca1 in S-phase and G(2)-phase checkpoints after ionizing irradiation. *Mol Cell Biol* 2001; 21:3445-50.
26. Fernandez-Capetillo O, Lee A, Nussenzweig M, Nussenzweig A. H2AX: The histone guardian of the genome. *DNA Repair (Amst)* 2004; 3:959-67.
27. Ishida N, Kitagawa M, Hatakeyama S, Nakayama Ki. Phosphorylation at serine 10, a major phosphorylation site of p27^{Kip1}, increases its protein stability. *J Biol Chem* 2000; 275:25146-54.
28. Potter LR, Hunter T. A constitutively "phosphorylated" guanylyl cyclase-linked atrial natriuretic peptide receptor mutant is resistant to desensitization. *Mol Biol Cell* 1999; 10: 1811-20.
29. Misteli T, Gunjan A, Hock R, Bustin M, Brown DT. Dynamic binding of histone H1 to chromatin in living cells. *Nature* 2000; 408:877-81.
30. Kanda T, Sullivan KF, Wahl GM. Histone-GFP fusion protein enables sensitive analysis of chromosome dynamics in living mammalian cells. *Curr Biol* 1998; 8:377-85.
31. Gautier T, Abbott DW, Molla A, Verdel A, Ausio J, Dimitrov S. Histone variant H2ABbd confers lower stability to the nucleosome. *EMBO Rep* 2004; 5:715-20.
32. Siino JS, Nazarov IB, Svetlova MP, Solovjeva LV, Adamson RH, Zalenskaya IA, et al. Photobleaching of GFP-labeled H2AX in chromatin: H2AX has low diffusional mobility in the nucleus. *Biochem Biophys Res Commun* 2002; 297:1318-23.
33. Kleinschmidt AM, Martinson HG. Structure of nucleosome core particles containing uH2A (A24). *Nucleic Acids Res* 1981; 9:2423-31.
34. Marti TM, Hefner E, Feeney L, Natale V, Cleaver JE. H2AX phosphorylation within the G₁ phase after UV irradiation depends on nucleotide excision repair and not DNA double-strand breaks. *PNAS* 2006; 103:9891-6.
35. Goldknopf IL, Busch H. Isopeptide linkage between nonhistone and histone 2A polypeptides of chromosomal conjugate-protein A24. *Proc Natl Acad Sci USA* 1977; 74:864-8.
36. Seale RL. Rapid turnover of the histone-ubiquitin conjugate, protein A24. *Nucleic Acids Res* 1981; 9:3151-8.
37. Wu LH, Kuehl L, Rechsteiner M. Dynamic behavior of histone H1 microinjected into HeLa cells. *J Cell Biol* 1986; 103:465-74.
38. Pina B, Suau P. Changes in histones H2A and H3 variant composition in differentiating and mature rat brain cortical neurons. *Dev Biol* 1987; 123:51-8.
39. Tsvetkov S, Ivanova E, Djondjurov L. Metabolic behaviors of the core histones in proliferating friend cells. *Exp Cell Res* 1989; 180:94-105.
40. Huen MS, Grant R, Manke I, Minn K, Yu X, Yaffe MB, et al. RNF8 transduces the DNA-damage signal via histone ubiquitylation and checkpoint protein assembly. *Cell* 2007; 131:901-14.
41. Mailand N, Bekker-Jensen S, Fastrup H, Melander F, Bartek J, Lukas C, et al. RNF8 ubiquitylates histones at DNA double-strand breaks and promotes assembly of repair proteins. *Cell* 2007; 131:887-900.
42. Kleckner N, Zickler D, Jones GH, Dekker J, Padmore R, Henle J, et al. A mechanical basis for chromosome function. *Proc Natl Acad Sci USA* 2004; 101:12592-7.
43. Bakkenist CJ, Kastan MB. DNA damage activates ATM through intermolecular autophosphorylation and dimer dissociation. *Nature* 2003; 421:499-506.
44. Heo K, Kim H, Choi SH, Choi J, Kim K, Gu J, et al. FACT-mediated exchange of histone variant H2AX regulated by phosphorylation of H2AX and ADP-ribosylation of Spt16. *Mol Cell* 2008; 30:86-97.
45. Rios-Doria J, Fay A, Velkova A, Monteiro AN. DNA damage response: Determining the fate of phosphorylated histone H2AX. *Cancer Biol Ther* 2006; 5:142-4.
46. McGowan CH, Russell P. The DNA damage response: Sensing and signaling. *Curr Opin Cell Biol* 2004; 16:629-33.
47. Bartek J, Falck J, Lukas J. CHK2 kinase—a busy messenger. *Nat Rev Mol Cell Biol* 2001; 2:877-86.
48. Phelan CM, Dapic V, Tice B, Favis R, Kwan E, Barany F, et al. Classification of BRCA1 missense variants of unknown clinical significance. *J Med Genet* 2005; 42:138-46.
49. Zhong Q, Chen CF, Li S, Chen Y, Wang CC, Xiao J, et al. Association of BRCA1 with the hRad50-hMre11-p95 complex and the DNA damage response. *Science* 1999; 285:747-50.
50. Zaret K. Chromatin assembly and analysis: Micrococcal nuclease analysis of chromatin structure. In: Ausubel FM, Brent R, Kingston R, Moore D, Seidman J, Smith JA, et al. *Curr Protoc Mol Biol*. New York: John Wiley & Sons, Inc 2005; 21:1-14.

Can the Status of the Breast and Ovarian Cancer Susceptibility Gene 1 Product (BRCA1) Predict Response to Taxane-Based Cancer Therapy?

J. Thomas DeLigio^{1,#}, Aneliya Velkova^{2,3}, Diego A.R. Zorio^{1,#} and Alvaro N.A. Monteiro^{2,*}

¹Taxolog, Inc., Tallahassee, FL 32303, USA; ²Risk Assessment, Detection, and Intervention Program, H. Lee Moffitt Cancer Center & Research Institute, Tampa, FL 33612, USA; ³University of South Florida Cancer Biology PhD Program, Tampa, FL 33612, USA and [#]Present Address: Florida State University, Dept. Chemistry, 740 DLC, Tallahassee, FL 32306, USA

Abstract: Taxanes (paclitaxel and docetaxel) are currently used to treat ovarian, breast, lung, and head and neck cancers. Despite its clinical success taxane-based treatment could be significantly improved by identifying those patients whose tumors are more likely to present a clinical response. In this mini-review we discuss the accumulating evidence indicating that the breast and ovarian cancer susceptibility gene product BRCA1 mediates cellular response to taxanes. We review data from *in vitro*, animal, and clinical studies, and discuss them in context of response to therapy. We argue that levels of BRCA1 in tumors may provide a predictive marker for the response to treatment with taxanes. In addition, the study of the role of BRCA1 in the mechanism of action of taxanes might reveal alternative approaches to avoid resistance.

Key Words: Taxol, taxane, BRCA1, cancer, biomarker, microtubule, tubulin, chemotherapy.

ISOLATION AND CHARACTERIZATION OF TAXOL

Isolation of Taxol from the bark of the pacific yew tree, *Taxus brevifolia*, permanently changed the map of cancer treatment and research. Enthusiasm surrounding this finding ran high in both chemical and biological circles as the taxane ring proved to be a novel structure with anti-cancer properties (Fig. (1)) [1]. Because of Taxol's wide spectrum of anti-tumor activity, the need to understand how this compound worked became a priority. It was not until the early 1970's when Susan Horwitz and colleagues reported that Taxol inhibited cell division of exponentially growing HeLa cells at low concentrations with no secondary effects in nucleic acid metabolism or protein synthesis [2]. Using *in vitro* microtubule assembly assays, they showed that, contrary to previous plant-derived compounds, such as colchicines which inhibit microtubule assembly, Taxol promoted and stabilized microtubule assembly (rendering cells into late G2/M blockage) [2]. Taxol was also shown to be effective in blocking cell replication in mouse fibroblasts and inhibiting 3T3 fibroblasts migration, indicating that the Taxol-microtubule interaction could have an impact in several morphological and physiological processes critical for cell survival, migration, and replication [3].

Microtubules, considered to be the main component of the cellular skeleton, are composed of heterodimers of α and β -tubulin which are ~40% homologous. An abundance of isotype forms for both α and β co-exist in the cell, which undergo several post-translational modifications [4]. Each subunit has a guanine triphosphate (GTP) nucleotide binding site and hydrolysis only occurs on GTP bound to the β -subunit during microtubule assembly [4]. The precise mechanism by which Taxol interacts with microtubules was characterized in detail using photoaffinity Taxol analogues. This approach mapped the region to the β -tubulin subunit in which Taxol binding occurs [5-7]. The predicted region was later demonstrated to be in agreement with the crystal structure of the $\alpha\beta$ -tubulin dimer at 3.7 Å resolution [8]. This was further corroborated by functional studies that demonstrated Taxol-resistant human ovarian cancer cells and Chinese hamster ovarian cells had β -tubulin mutations effectively compromising Taxol driven polymerization [9,10].

CLINICAL SUCCESS OF TAXANES

Taxanes have been well incorporated in adjuvant and neoadjuvant chemotherapeutic drug regimens given to patients with operable or metastatic breast cancer [11]. Several phase III trials have addressed the effects of using either paclitaxel or docetaxel (Fig. (1)) in combination with typical first line treatment protocols such as 5-fluorouracil (5-FU), doxorubicin, and cyclophosphamide. In cases of paclitaxel treatment used in adjuvant therapy, significant increases in disease-free survival (DFS) were recorded for up to six years post treatment [12-14]. Docetaxel given in combination with doxorubicin and cyclophosphamide as adjuvant therapy showed marked decreases in DFS as compared to 5-FU/doxorubicin/cyclophosphamide in the Breast Cancer International Research Group phase III study [15]. However, using docetaxel as a neoadjuvant to surgery following treatment with doxorubicin/cyclophosphamide showed improved clinical and pathological complete response rates, as well as increased overall clinical response rates [16]. A similar result was also observed in a University of Aberdeen phase II trial that looked at neoadjuvant treatment of locally advanced breast cancer with anthracycline therapy in combination with docetaxel; significant results were accomplished establishing a basis for using docetaxel as standard neoadjuvant therapy [17].

Retrospective evaluation of HER2 status in patients was undertaken by The Cancer and Leukemia Group B (CALGB) trial, and their findings indicated increased benefits from treatment when patients were found to have HER2-positive tumor cells versus HER2-negative patients [18]. Further, specific molecular subtyping of HER2 has proven beneficial to predicting efficacy of treatment as shown in CALGB 9344 and CALGB 9741 trials [18]. Inasmuch as molecular subtyping of breast cancer cells by their HER2 or Estrogen Receptor (ER) status may provide useful diagnostic data to the clinician, the challenge to identify additional predictors of treatment response presents the next phase in realizing the goal of personalized medicine.

The use of taxanes in several additional types of cancers has also been studied, namely non-small cell lung cancer (NSCLC), ovarian cancer, and head and neck squamous cell carcinoma (HNSCC). Phase II studies have examined the use of docetaxel in combination with gemcitabine as a second line treatment in NSCLC with promising results [19]. In a randomized, open-label, phase III trial comparing treatment with the standard first line platinum containing regimen (paclitaxel plus carboplatin) versus a platinum-free

*Address correspondence to this author at the H. Lee Moffitt Cancer Center, 12902 Magnolia Drive, Tampa, FL 33612, USA; Tel: 813-7456321; Fax: 813-7451720; E-mail: alvaro.monteiro@moffitt.org

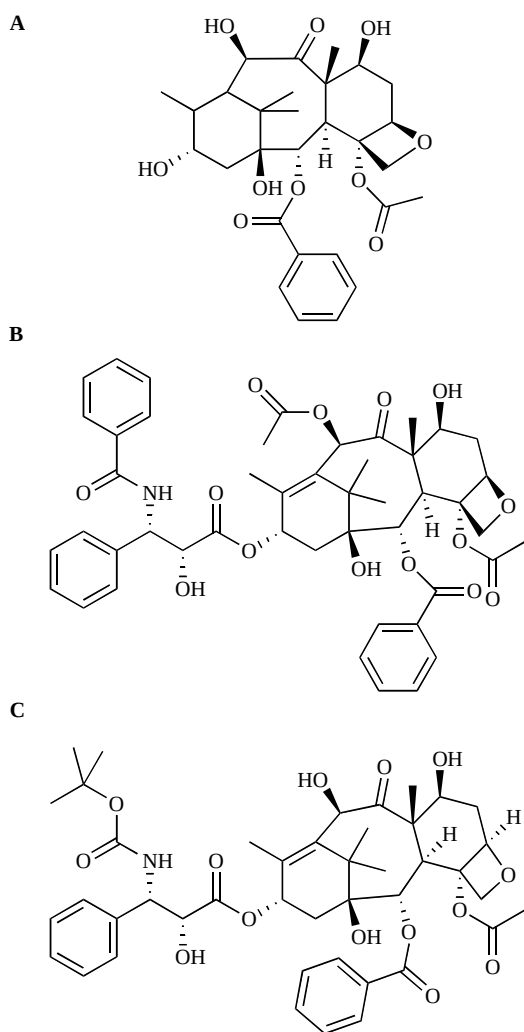


Fig. (1). Structural formulas for **A** (2*aR*,4*S*,4*aS*,6*R*,9*S*,11*S*,12*S*,12*aR*,12*bS*)-12b-(Acetyloxy)-12-(benzoyloxy)-1,2*a*,3,4,4*a*,6,9,10,11,12,12*a*,12*b*-dodecahydro-4,6,9,11-tetrahydroxy-4*a*,8,13,13-tetramethyl-7,11-methano-5*H*-cyclo-deca(3,4)benz(1,2-*b*) oxet-5-one, **10-deacetylbaccatin** (10-DAB), **B** (2*a*,4*a*,5*β*,7*β*,10*β*,13*α*)-4,10-bis(acetyloxy)-13-[[[(2*R*,3*S*)-3-(benzoylamino)-2-hydroxy-3-phenylpropanoyl]oxy]-1,7-dihydroxy-9-oxo-5,20-epoxytax-11-en-2-yl benzoate, **Taxol** (paclitaxel) and **C** (2*R*,3*S*)-*N*-carboxy-3-phenylisoserine, *N*-tert-butyl ester, 13-ester with 5,20-epoxy-1,2,4,7,10,13-hexahydroxytax-11-en-9-one 4-acetate 2-benzoate, trihydrate, **Taxotere** (docetaxel).

experimental regimen (triplet of vinorelbine, gemcitabine, and docetaxel), researchers found treatment efficacy to be equivalent with unique toxicity profiles [20]. No superiority over either treatment was recorded in this study thus allowing for greater options to patients [20,21]. Taxane-based chemotherapy has also become the first line treatment in ovarian cancer [22]. Studies have shown a marked improvement in progression-free survival rates of patients treated with a combination of taxane (paclitaxel or docetaxel) and cisplatin over cisplatin/cyclophosphamide [23,24]. These types of combination therapy approaches have become the cornerstone of treating cisplatin-resistant ovarian cancer [25].

The treatment of HNSCC with docetaxel as induction chemotherapy has also been established in clinical trials. Combinations of docetaxel and cisplatin have been shown to exhibit upwards of fifty-three percent overall response rates in these patients [26]. More recently a randomized phase III trial compared docetaxel, cisplatin, and 5-fluorouracil (5-FU) versus cisplatin and 5-FU alone (both groups receiving follow-up chemoradiotherapy). The results showed significantly higher overall response rates in the taxane

comprising treatment group versus cisplatin and 5-FU alone (72% versus 64%, respectively) [27]. Taken together, these data serve to illustrate the establishment of taxanes in treatment of many types of cancers as a standard chemotherapeutic option.

Although we continue to learn a great deal about taxane response in past and present clinical trials, continuous improvement in determining drug efficacy either as a single agent or as an adjuvant therapy exists. Chemoresistance determinants [11], new drug formulations and the search of derivatives with better therapeutic index [28] are good examples of areas in which improvements could be achieved. In addition, identifying markers in tumors prior to treatment could help researchers and clinicians in designing future clinical trials with higher predicted response rates. For example, it has been demonstrated that inhibition of Aurora Kinase A in conjunction with paclitaxel treatment synergistically enhanced apoptosis induction in HNSCC cells and xenografts [29]. Based on the current literature, we propose that the breast and ovarian cancer susceptibility gene 1 (BRCA1) protein could be a potential predictive marker for taxane treatment. Furthermore, understanding the role of BRCA1 in taxane response could aid in streamlining the clinical approach to improved chemotherapeutic therapy.

BRCA1

BRCA1 [OMIM #113705] was mapped to chromosome 17q21 and isolated by positional cloning in 1994 as a breast and ovarian cancer susceptibility gene [30-33]. *BRCA1* germline mutations have been attributed to a considerable increase in the risk of developing breast (56-80% versus 11% in the general population) and ovarian cancer (15-60% versus 1.4-2.5%) with early onset of the disease [33]. *BRCA1* is rarely mutated in sporadic breast cancers but epigenetic inactivation of *BRCA1* has been documented in high grade sporadic tumors suggesting that it also plays a role in non-familial cases [34,35]. The gene encodes a nuclear phosphoprotein that plays a role in a number of different biological processes such as DNA damage response, cell cycle control, and regulation of transcription, but it is not yet clear which molecular function(s) are major contributors to the gene's tumor suppressive activity (reviewed in refs. [36-40]).

BRCA1 AND RESISTANCE TO MICROTUBULE-DISRUPTING DRUGS

Cells lacking BRCA1 are prone to apoptosis and are more sensitive to DNA damaging agents [41,42]. Conversely, a series of experiments have suggested that low levels of BRCA1 in cell lines correlate with resistance to taxanes and vinca alkaloids (Table 1) [42-47]. While this proved true for breast cancer cell lines, it was not observed in one ovarian cancer cell line [48] and no clear sensitivity differences were found in lymphocytes from BRCA1 mutation carriers [49]. Thus, cell culture experiments suggest that BRCA1 is required for sensitivity to microtubule poisons but this may vary with gene dosage as well as with cell type.

The evidence highlighting the role of BRCA1 in taxane sensitivity is not limited to studies with cell lines. In a *K14cre; Brca1^{F/F}; p53^{F/F}* mouse (targeted deletion of *Brca1* and *p53* in the mammary gland) spontaneous tumors became invariably resistant to docetaxel but not to cisplatin [50]. Acquired resistance in this case might be due to increased drug elimination via upregulated transport proteins. But even if this is the case, one can imagine that by targeting tumors that are more sensitive (high BRCA1 levels) will preclude the accumulation of genetic or epigenetic changes needed to develop resistance. A different mouse model in which ovarian explants from *K5-TVA; Brca1^{lox/lox}; p53^{lox/lox}* (targeted deletion of *Brca1* and *p53* combined with the expression of the avian receptor TVA) [51] are cotransduced *ex vivo* with *Cre* and *Myc*, and injected subcutaneously in nude mice illustrate once again potential cell type differences. When treated *in vitro* with paclitaxel, *Brca1^{-/-}* or *Brca1^{+/-}* cell lines showed comparable sensitivity [52].

Table 1. Sensitivity to Microtubule-Interfering Drugs in Cell Lines

Cells	BRCA1 Status	IC ₅₀	Drug [Exposure Time] & Assay Used
Comparison across breast cancer cell lines			
HCC1937	ER ^{neg} , one deleted allele and one C-terminally truncated allele.	>2μM	Paclitaxel [48h] & MTT (Tassone <i>et al.</i> 2003; ref. [45])
MCF-7	ER ^{pos} , hemizygous for wild type BRCA1	0.1-0.2 μM	
MDA-MB231	Homozygous for wt BRCA1	10-20 nM	
Comparison across isogenic breast cancer cell lines			
HCCBR116	HCC1937 transfected with wt BRCA1	7.73 nM	Paclitaxel [72h] & MTT (Gilmore <i>et al.</i> 2004; ref. [43]).
HCCEV1	HCC1937 transfected with empty vector	6.21 μM	
MBR62-bcl2	MCF-7 derivative stably transfected with tet-inducible wt BRCA1 (induced)	7.7 nM	Paclitaxel [72h] & cell counting (Quinn <i>et al.</i> 2003; ref. [42]).
MBR62-bcl2	MCF-7 derivative stably transfected with tet-inducible wt BRCA1 (non-induced)	96.4 pM	
T47D	T47D (BRCA1 ^{+/+} and ER ^{pos}) transfected with a control siRNA	2.2 μM	Paclitaxel [72h] & cell counting (Quinn <i>et al.</i> 2003; ref. [42]).
T47D	T47D transfected with a BRCA1 siRNA	>0.1 mM	
HCCBR116	HCC1937 transfected with wt BRCA1	7.7 nM	Paclitaxel [72h] & cell counting (Quinn <i>et al.</i> 2003; ref. [42]).
HCCEV1	HCC1937 transfected with empty vector	6.2 μM	
HCCBR116		1.9 nM	Vinorelbine [72h] & cell counting (Quinn <i>et al.</i> 2003; ref. [42]).
HCCEV1		17 μM	
HCCBR18	HCC1937 transfected with wt BRCA1	0.3 nM	Paclitaxel [72h] & cell counting (Quinn <i>et al.</i> 2003; ref. [42]).
HCCEV2	HCC1937 transfected with empty vector	1.6 μM	
HCCBR mix	HCC1937 transfected with wt BRCA1	1.5 nM	Paclitaxel [72h] & cell counting (Quinn <i>et al.</i> 2003; ref. [42]).
HCCEV3	HCC1937 transfected with empty vector	10.7 μM	
MCF-7	MCF-7 transfected with a control siRNA	36 nM*	Paclitaxel [72h] & WST-1 cleavage (Chabalier <i>et al.</i> 2006; ref. [46]). *IC ₂₅ shown.
MCF-7	MCF-7 transfected with a BRCA1 siRNA	4.1 nM*	

THE MECHANISM OF BRCA1 RESPONSE

Although the mechanism by which cells require BRCA1 to respond to taxanes is largely unknown, three modes of action have been proposed and none of them are mutually exclusive. The first mechanism is a differential apoptotic response; the second confers a requirement in spindle-assembly checkpoint; and the third provides a role in centrosome-mediated microtubule stability.

It has been proposed that resistance of BRCA1-deficient cells to taxanes is correlated to a defective apoptotic response but it has not yet been formally demonstrated [42]. The induction of ectopic BRCA1 expression led to an increased sensitivity to paclitaxel in a derivative of the human mammary carcinoma cell line MDA435 when compared to a non-induced control. Treatment triggered cell cycle arrest in G2/M phase and a dramatic increase in apoptosis, with concomitant induction at the transcriptional level of GADD45 by BRCA1 [44]. Interestingly, treatment of A375 and DLD1 cells (melanoma and colon cancer, respectively) with paclitaxel and/or docetaxel also causes transcriptional induction of GADD45 (DeLigio and Zorio, unpublished data).

A ribozyme-based strategy to inhibit expression of BRCA1 in breast epithelial HBL100 cells caused decreased sensitivity to mitotic-spindle poisons Taxol and vincristine [47]. Upon treatment with Taxol there was a strong increase in JNK phosphorylation and subsequent apoptosis in BRCA1-expressing versus non-expressing cells. This observation was consistent with previous data showing that BRCA1 can enhance apoptosis through a pathway involving H-Ras, MEKK4, JNK, and activation of caspases 8 and 9 [53].

By stabilizing microtubules, paclitaxel disrupts mitotic spindle assembly and triggers the spindle checkpoint [54]. BRCA1 participation in spindle assembly checkpoint signaling is confirmed by the experiments that show targeted knockdown of BRCA1 in MCF7 cells increases resistance to paclitaxel. MCF7 cells exhibited premature sister chromatid separation after treatment with the drug

suggesting that the role of BRCA1 in the response to paclitaxel may need spindle assembly checkpoint signaling [46]. This hypothesis is supported by the fact that BRCA1 is important for transcriptional regulation of spindle assembly checkpoint proteins BUBR1 [46] and MAD2 [55]. These proteins (BUBR1, MAD2, and BRCA1) have a critical role in mitotic microtubule organization and spindle pole assembly in *Xenopus* egg extracts and cultured mammalian HeLa cells. The BRCA1/BARD1 heterodimer controls efficient transport to the spindle poles of microtubule associated protein TPX2 [56]. This function was partially dependent upon BRCA1/BARD1 ubiquitin ligase activity. Among the phenotypes observed in BRCA1-depleted cells were compromised mitotic exit, chromosome segregation defects, and micronucleus formation [56]. Defects in the spindle checkpoint have been associated with resistance to taxanes [57,58]. Thus, it is conceivable that BRCA1 also modulates taxane sensitivity through its effects on the spindle checkpoint. A completely inactive checkpoint seems to be lethal, while a weakened (signal produced but not sustained) checkpoint leads to chromosome instability [59]. Absent or low levels of BRCA1 may act as a hypomorphic mutation and allow for a defective or attenuated spindle assembly checkpoint.

In addition to its role in the spindle-assembly checkpoint, BRCA1 is also involved in the regulation of centrosome function [60]. The hypophosphorylated form of BRCA1 has been found associated with centrosomes during mitosis [61]. BRCA1 (amino acids 504-803) interacts with γ -tubulin, and over expression of this fragment causes accumulation of mitotic cells with multiple centrosomes and abnormal spindles; which in turn interferes with cell growth and induces apoptosis in COS7 cells [62].

Transient inhibition of BRCA1 in cells derived from mammary tissues also leads to amplification and fragmentation of centrosomes [63]. Important activity relationships have been divulged *in vitro* regarding ubiquitination of centrosomal proteins by BRCA1/

BARD1. Specifically, this protein complex monoubiquitinates γ -tubulin at lysine residues 48 and 344. Individually mutating γ -tubulin to abolish BRCA1 ubiquitination at these residues has shown BRCA1 controls both centrosome duplication and its microtubule nucleation properties in different stages of the cell cycle [64].

BRCA1 AS A MARKER FOR CLINICAL OUTCOME

Despite the evidence from *in vitro* studies showing a trend towards cells that have no BRCA1 (or express lower BRCA1 levels) being more resistant to taxanes, a positive correlation in clinical studies would prove noteworthy. In the few studies published so far focusing on breast, ovarian, and most recently, lung cancer, a case for this relationship is starting to emerge.

Absence of BRCA1 expression in primary tumors of metastatic breast cancer patients who were treated with taxanes was identified as an independent predictor of shorter time to progression, although there was no clear correlation with clinical tumor response [65]. On the other hand, a study in primary breast cancers failed to see a correlation between BRCA1 levels (grouped as either high or low expressers) and resistance to docetaxel [66]. However, in a study comparing *BRCA1* germ-line mutation carriers and non-carriers, response rates to neoadjuvant docetaxel treatment in the carrier group was limited while non-carriers showed a high number of complete or partial responses [67].

Patients with familial ovarian cancers (which included carriers and non-carriers of the 5382insC founder truncating mutation in *BRCA1*) responded less favorably to treatment with paclitaxel and cisplatin or carboplatin than patients with sporadic tumors [68]. In addition, a recent study in sporadic ovarian cancer patients provided evidence that *BRCA1* mRNA expression levels can be used as a predictive marker of survival. The overall median survival for high *BRCA1* expressing patients was increased after taxane-containing chemotherapy [69].

A detailed review of the clinical studies described in the previous paragraphs reveal important limitations in design and methodology. They all have small sample sizes which may lack sufficient power to detect effects. Many do not provide patient genotyping information and in many cases treatment combined several other classes of chemotherapy drugs with taxanes. More importantly, they vary widely in how BRCA1 status was determined (e.g. quantitative RT-PCR or immunohistochemistry) and how differences in levels were considered for (e.g. continuous or discrete). Nevertheless, those limitations are more likely to underestimate differences. Thus, the correlative clinical results, combined with the *in vitro* data, provide a solid starting point for the hypothesis that BRCA1 can be used as a marker of clinical outcome after treatment with taxanes.

Low BRCA1 protein expression, due to promoter methylation, was shown to be a common feature in NSCLC samples [70]. Researchers found that patients subjected to neoadjuvant therapy with gemcitabine/cisplatin whose tumors expressed low levels of *BRCA1* mRNA had a better outcome than those expressing high levels [71]. In conflict to these results, one study of NSCLC patients treated with gemcitabine/cisplatin or epirubicin/gemcitabine did not show any predictive value using comparisons of BRCA1 levels in the tumors as measured by immunohistochemistry [72]. However, analysis of mRNA expression levels in metastatic malignant effusions from NSCLC patients revealed *BRCA1* expression level as positively correlated to docetaxel sensitivity [73]. Finally, overexpression of *BRCA1* mRNA was strongly associated with poor survival (Hazard Ratio: 1.98; 95% confidence interval 1.11-6) in chemo-naïve NSCLC patients [74]. Thus, although these studies also suffer from limitations (e.g. using mRNA measurements without also analyzing protein levels), they provide preliminary evidence supporting the role of BRCA1 status as a marker for outcome in lung cancer. In light of this evidence, the Spanish Lung Cancer

Group has initiated a BRCA1 Expression Customization (BREC) study to test the usefulness of BRCA1 in current and future customized therapy of NSCLC [75]. This exploratory evaluation attempts to expose BRCA1 as a potential genetic marker given the hypothesis that low BRCA1 levels correlate with increased sensitivity to DNA damaging agents such as cisplatin. The results of the BREC study regarding time to progression of disease and BRCA1 levels will be highly anticipated in that its implications reach toward a targeted and efficient approach to chemotherapy with taxanes and/or DNA damaging agents in NSCLC.

CONCLUSION

BRCA1 plays an important role in the cell's response to chemotherapy. In the past few years several lines of evidence have indicated that the status of BRCA1 protein influences the ability of cells to respond to agents that cause DNA damage. Recently, data has emerged suggesting that the status of BRCA1 may also influence response to agents that do not cause direct DNA damage, such as microtubule inhibitors. If this role of BRCA1 is confirmed, BRCA1 may represent an ideal biomarker with the ability to predict response to a wide array of agents currently used in cancer therapy.

ACKNOWLEDGEMENTS

Work in the Monteiro Lab is supported by a DoD predoctoral fellowship BC083181 (A.V.), NIH award CA92309, a grant from the Florida Breast Cancer Coalition Foundation, and pilot funds from Lung SPORE P50-CA119997. The authors acknowledge Drs. Robert Holton and Mike Edler for critical review of this manuscript.

ABBREVIATIONS

5-FU	= 5-Fluorouracil
10-DAB	= 10-Deacetylbaecatin
BARD1	= BRCA1 associated RING domain 1
BRCA1	= Breast and ovarian cancer susceptibility gene 1
DFS	= Disease-free survival
ER	= Estrogen receptor
GTP	= Guanine tri-phosphate
HER2	= Human epidermal growth factor receptor 2
HNSCC	= Head and neck squamous cell carcinoma
JNK	= Jun N-terminal kinase
NSCLC	= Non-small cell lung cancer
RT-PCR	= Reverse transcriptase polymerase chain reaction

REFERENCES

- [1] Wani, M.C.; Taylor, H.L.; Wall, M.E.; Coggon, P.; McPhail, A.T. Plant antitumor agents. VI. The isolation and structure of taxol, a novel antileukemic and antitumor agent from *Taxus brevifolia*. *J. Am. Chem. Soc.* **1971**, 93(9), 2325-2327.
- [2] Schiff, P.B.; Fant, J.; Horwitz, S.B. Promotion of microtubule assembly *in vitro* by taxol. *Nature* **1979**, 277(5698), 665-667.
- [3] Schiff, P.B.; Horwitz, S.B. Taxol stabilizes microtubules in mouse fibroblast cells. *Proc. Natl. Acad. Sci. USA* **1980**, 77(3), 1561-1565.
- [4] Luduena, R.F. Multiple forms of tubulin: different gene products and covalent modifications. *Int. Rev. Cytol.* **1998**, 178, 207-275.
- [5] Rao, S.; Krauss, N.E.; Heering, J.M.; Swindell, C.S.; Ringel, I.; Orr, G.A.; Horwitz, S.B. 3'-(p-azidobenzamido)taxol photolabels the N-terminal 31 amino acids of beta-tubulin. *J. Biol. Chem.* **1994**, 269(5), 3132-3134.
- [6] Rao, S.; Orr, G.A.; Chaudhary, A.G.; Kingston, D.G.; Horwitz, S.B. Characterization of the taxol binding site on the microtubule. 2-(m-Azidobenzoyl)taxol photolabels a peptide (amino acids 217-231) of beta-tubulin. *J. Biol. Chem.* **1995**, 270(35), 20235-20238.

- [7] Rao, S.; He, L.; Chakravarty, S.; Ojima, I.; Orr, G.A.; Horwitz, S.B. Characterization of the Taxol binding site on the microtubule. Identification of Arg(282) in beta-tubulin as the site of photoincorporation of a 7-benzophenone analogue of Taxol. *J. Biol. Chem.* **1999**, 274(53), 37990-37994.
- [8] Nogales, E.; Wolf, S.G.; Downing, K.H. Structure of the alpha beta tubulin dimer by electron crystallography. *Nature* **1998**, 391(6663), 199-203.
- [9] Giannakakou, P.; Sackett, D.L.; Kang, Y.K.; Zhan, Z.; Buters, J.T.; Fojo, T.; Poruchynsky, M.S. Paclitaxel-resistant human ovarian cancer cells have mutant beta-tubulins that exhibit impaired paclitaxel-driven polymerization. *J. Biol. Chem.* **1997**, 272(27), 17118-17125.
- [10] Gonzalez-Garay, M.L.; Chang, L.; Blade, K.; Menick, D.R.; Cabral, F.A. beta-tubulin leucine cluster involved in microtubule assembly and paclitaxel resistance. *J. Biol. Chem.* **1999**, 274(34), 23875-23882.
- [11] McGrogan, B.T.; Gilmartin, B.; Carney, D.N.; McCann, A. Taxanes, microtubules and chemoresistant breast cancer. *Biochim. Biophys. Acta* **2008**, 1785(2), 96-132.
- [12] Henderson, I.C.; Berry, D.A.; Demetri, G.D.; Cirincione, C.T.; Goldstein, L.J.; Martino, S.; Ingle, J.N.; Cooper, M.R.; Hayes, D.F.; Tkaczuk, K.H.; Fleming, G.; Holland, J.F.; Duggan, D.B.; Carpenter, J.T.; Frei, E., III; Schilsky, R.L.; Wood, W.C.; Muss, H.B.; Norton, L. Improved outcomes from adding sequential Paclitaxel but not from escalating Doxorubicin dose in an adjuvant chemotherapy regimen for patients with node-positive primary breast cancer. *J. Clin. Oncol.* **2003**, 21(6), 976-983.
- [13] Citron, M.L.; Berry, D.A.; Cirincione, C.; Hudis, C.; Winer, E.P.; Gradishar, W.J.; Davidson, N.E.; Martino, S.; Livingston, R.; Ingle, J.N.; Perez, E.A.; Carpenter, J.; Hurd, D.; Holland, J.F.; Smith, B.L.; Sartor, C.I.; Leung, E.H.; Abrams, J.; Schilsky, R.L.; Muss, H.B.; Norton, L. Randomized trial of dose-dense versus conventionally scheduled and sequential versus concurrent combination chemotherapy as postoperative adjuvant treatment of node-positive primary breast cancer: first report of Intergroup Trial C9741/Cancer and Leukemia Group B Trial 9741. *J. Clin. Oncol.* **2003**, 21(8), 1431-1439.
- [14] Mamounas, E.P.; Bryant, J.; Lembersky, B.; Fehrenbacher, L.; Sedlacek, S.M.; Fisher, B.; Wickerham, D.L.; Yothers, G.; Soran, A.; Wolmark, N. Paclitaxel after doxorubicin plus cyclophosphamide as adjuvant chemotherapy for node-positive breast cancer: results from NSABP B-28. *J. Clin. Oncol.* **2005**, 23(16), 3686-3696.
- [15] Martin, M.; Pienkowski, T.; Mackey, J.; Pawlicki, M.; Guastalla, J.P.; Weaver, C.; Tomiak, E.; Al-Tweigeri, T.; Chap, L.; Juhos, E.; Guevin, R.; Howell, A.; Fornander, T.; Hainsworth, J.; Coleman, R.; Vinholes, J.; Modiano, M.; Pinter, T.; Tang, S.C.; Colwell, B.; Prady, C.; Provencher, L.; Walde, D.; Rodriguez-Lescure, A.; Hugh, J.; Loret, C.; Rupin, M.; Blitz, S.; Jacobs, P.; Murawsky, M.; Riva, A.; Vogel, C. Adjuvant docetaxel for node-positive breast cancer. *N. Engl. J. Med.* **2005**, 352(22), 2302-2313.
- [16] Bear, H.D.; Anderson, S.; Brown, A.; Smith, R.; Mamounas, E.P.; Fisher, B.; Margolese, R.; Theoret, H.; Soran, A.; Wickerham, D.L.; Wolmark, N. The effect on tumor response of adding sequential preoperative docetaxel to preoperative doxorubicin and cyclophosphamide: preliminary results from National Surgical Adjuvant Breast and Bowel Project Protocol B-27. *J. Clin. Oncol.* **2003**, 21(22), 4165-4174.
- [17] Smith, I.C.; Heys, S.D.; Hutcheon, A.W.; Miller, I.D.; Payne, S.; Gilbert, F.J.; Ah-See, A.K.; Eremin, O.; Walker, L.G.; Sarkar, T.K.; Eggleston, S.P.; Ogston, K.N. Neoadjuvant chemotherapy in breast cancer: significantly enhanced response with docetaxel. *J. Clin. Oncol.* **2002**, 20(6), 1456-1466.
- [18] Hayes, D.F.; Thor, A.D.; Dressler, L.G.; Weaver, D.; Edgerton, S.; Cowan, D.; Broadwater, G.; Goldstein, L.J.; Martino, S.; Ingle, J.N.; Henderson, I.C.; Norton, L.; Winer, E.P.; Hudis, C.A.; Ellis, M.J.; Berry, D.A.; the Cancer and Leukemia Group. HER2 and response to paclitaxel in node-positive breast cancer. *N. Engl. J. Med.* **2007**, 357(15), 1496-1506.
- [19] Huang, C.H.; Millenson, M.M.; Sherman, E.J.; Borghaei, H.; Mintzer, D.M.; Cohen, R.B.; Staddon, A.P.; Seldomridge, J.; Treat, O.J.; Tuttle, H.; Ruth, K.J.; Langer, C.J. Promising survival in patients with recurrent non-small cell lung cancer treated with docetaxel and gemcitabine in combination as second-line therapy. *J. Thorac. Oncol.* **2008**, 3(9), 1032-1038.
- [20] Kubota, K.; Kawahara, M.; Ogawara, M.; Nishiwaki, Y.; Komuta, K.; Minato, K.; Fujita, Y.; Teramukai, S.; Fukushima, M.; Furuse, K. Vinorelbine plus gemcitabine followed by docetaxel versus carboplatin plus paclitaxel in patients with advanced non-small-cell lung cancer: a randomised, open-label, phase III study. *Lancet Oncol.* **2008**, 9(12), 1135-1142.
- [21] Barlesi, F. Lung cancer: moving forward with tailored strategies. *Lancet Oncol.* **2008**, 9(12), 1116-1117.
- [22] Markman, M. Pharmaceutical management of ovarian cancer : current status. *Drugs* **2008**, 68(6), 771-789.
- [23] Piccart, M.J.; Bertelsen, K.; James, K.; Cassidy, J.; Mangioni, C.; Simonsen, E.; Stuart, G.; Kaye, S.; Vergote, I.; Blom, R.; Grimshaw, R.; Atkinson, R.J.; Swenerton, K.D.; Trope, C.; Nardi, M.; Kaern, J.; Tumolo, S.; Timmers, P.; Roy, J.A.; Lhoas, F.; Lindvall, B.; Bacon, M.; Birt, A.; Andersen, J.E.; Zee, B.; Paul, J.; Baron, B.; Pecorelli, S. Randomized intergroup trial of cisplatin-paclitaxel versus cisplatin-cyclophosphamide in women with advanced epithelial ovarian cancer: three-year results. *J. Natl. Cancer Inst.* **2000**, 92(9), 699-708.
- [24] Vasey, P.A.; Jayson, G.C.; Gordon, A.; Gabra, H.; Coleman, R.; Atkinson, R.; Parkin, D.; Paul, J.; Hay, A.; Kaye, S.B. Phase III randomized trial of docetaxel-carboplatin versus paclitaxel-carboplatin as first-line chemotherapy for ovarian carcinoma. *J. Natl. Cancer Inst.* **2004**, 96(22), 1682-1691.
- [25] Stordal, B.; Pavlakis, N.; Davey, R.A. A systematic review of platinum and taxane resistance from bench to clinic: an inverse relationship. *Cancer Treat. Rev.* **2007**, 33(8), 688-703.
- [26] Schoffski, P.; Catimel, G.; Planting, A.S.; Droz, J.P.; Verweij, J.; Schrijvers, D.; Gras, L.; Schrijvers, A.; Wanders, J.; Hanauske, A.R. Docetaxel and cisplatin: an active regimen in patients with locally advanced, recurrent or metastatic squamous cell carcinoma of the head and neck. Results of a phase II study of the EORTC Early Clinical Studies Group. *Ann. Oncol.* **1999**, 10(1), 119-122.
- [27] Posner, M.R.; Hershock, D.M.; Blajman, C.R.; Mickiewicz, E.; Winquist, E.; Gorbounova, V.; Tjulandina, S.; Shin, D.M.; Cullen, K.; Ervin, T.J.; Murphy, B.A.; Raez, L.E.; Cohen, R.B.; Spaulding, M.; Tishler, R.B.; Roth, B.; Viroglia, R.C.; Venkatesan, V.; Romanov, I.; Agarwala, S.; Harter, K.W.; Dugan, M.; Cmelak, A.; Markoe, A.M.; Read, P.W.; Steinbrenner, L.; Colevas, A.D.; Norris, C.M., Jr.; Haddad, R.I. Cisplatin and fluorouracil alone or with docetaxel in head and neck cancer. *N. Engl. J. Med.* **2007**, 357(17), 1705-1715.
- [28] Ferlini, C.; Gallo, D.; Scambia, G. New taxanes in development. *Expert. Opin. Investig. Drugs* **2008**, 17(3), 335-347.
- [29] Mazumdar, A.; Henderson, Y.C.; El-Naggar, A.K.; Sen, S.; Clayman, G.L. Aurora kinase A inhibition and paclitaxel as targeted combination therapy for head and neck squamous cell carcinoma. *Head Neck* **2008**, 31(5), 625-634.
- [30] Hall, J.M.; Lee, M.K.; Newman, B.; Morrow, J.E.; Anderson, L.A.; Huey, B.; King, M.C. Linkage of early-onset familial breast cancer to chromosome 17q21. *Science* **1990**, 250(4988), 1684-1689.
- [31] Narod, S.A.; Feunteun, J.; Lynch, H.T.; Watson, P.; Conway, T.; Lynch, J.; Lenoir, G.M. Familial breast-ovarian cancer locus on chromosome 17q12-q23. *Lancet* **1991**, 338(8759), 82-83.
- [32] Vogelstein, B.; Kinzler, K.W. Has the breast cancer gene been found? *Cell* **1994**, 79(1), 1-3.
- [33] Miki, Y.; Swensen, J.; Shattuck-Eidens, D.; Futreal, P.A.; Harshman, K.; Tavtigian, S.; Liu, Q.; Cochran, C.; Bennett, L.M.; Ding, W.A. A strong candidate for the breast and ovarian cancer susceptibility gene BRCA1. *Science* **1994**, 266(5182), 66-71.
- [34] Futreal, P.A.; Liu, Q.; Shattuck-Eidens, D.; Cochran, C.; Harshman, K.; Tavtigian, S.; Bennett, L.M.; Haugen-Strano, A.; Swensen, J.; Miki, Y. BRCA1 mutations in primary breast and ovarian carcinomas. *Science* **1994**, 266(5182), 120-122.
- [35] Wilson, C.A.; Ramos, L.; Villasenor, M.R.; Anders, K.H.; Press, M.F.; Clarke, K.; Karlan, B.; Chen, J.J.; Scully, R.; Livingston, D.; Zuch, R.H.; Kanter, M.H.; Cohen, S.; Calzone, F.J.; Slamon, D.J. Localization of human BRCA1 and its loss in high-grade, non-inherited breast carcinomas. *Nat. Genet.* **1999**, 21(2), 236-240.

- [36] Narod, S.A.; Foulkes, W.D. BRCA1 and BRCA2: 1994 and beyond. *Nat. Rev. Cancer* **2004**, *4*(9), 665-676.
- [37] Scully, R.; Livingston, D. In search of the tumour-suppressor functions of BRCA1 and BRCA2. *Nature* **2000**, *408*, 429-432.
- [38] Venkitaraman, A.R. Cancer susceptibility and the functions of BRCA1 and BRCA2. *Cell* **2002**, *108*(2), 171-182.
- [39] Scully, R.; Xie, A.; Nagaraju, G. Molecular functions of BRCA1 in the DNA damage response. *Cancer Biol. Ther.* **2004**, *3*(6), 521-527.
- [40] Lane, T.F. BRCA1 and transcription. *Cancer Biol. Ther.* **2004**, *3*(6), 528-533.
- [41] Kennedy, R.D.; Quinn, J.E.; Mullan, P.B.; Johnston, P.G.; Harkin, D.P. The role of BRCA1 in the cellular response to chemotherapy. *J. Natl. Cancer Inst.* **2004**, *96*(22), 1659-1668.
- [42] Quinn, J.E.; Kennedy, R.D.; Mullan, P.B.; Gilmore, P.M.; Carty, M.; Johnston, P.G.; Harkin, D.P. BRCA1 functions as a differential modulator of chemotherapy-induced apoptosis. *Cancer Res.* **2003**, *63*(19), 6221-6228.
- [43] Gilmore, P.M.; McCabe, N.; Quinn, J.E.; Kennedy, R.D.; Gorski, J.J.; Andrews, H.N.; McWilliams, S.; Carty, M.; Mullan, P.B.; Duprex, W.P.; Liu, E.T.; Johnston, P.G.; Harkin, D.P. BRCA1 interacts with and is required for paclitaxel-induced activation of mitogen-activated protein kinase kinase kinase 3. *Cancer Res.* **2004**, *64*(12), 4148-4154.
- [44] Mullan, P.B.; Quinn, J.E.; Gilmore, P.M.; McWilliams, S.; Andrews, H.; Gervin, C.; McCabe, N.; McKenna, S.; White, P.; Song, Y.H.; Maheswaran, S.; Liu, E.; Haber, D.A.; Johnston, P.G.; Harkin, D.P. BRCA1 and GADD45 mediated G2/M cell cycle arrest in response to antimicrotubule agents. *Oncogene* **2001**, *20*(43), 6123-6131.
- [45] Tassone, P.; Tagliaferri, P.; Perricelli, A.; Blotta, S.; Quaresima, B.; Martelli, M.L.; Goel, A.; Barbieri, V.; Costanzo, F.; Boland, C.R.; Venuta, S. BRCA1 expression modulates chemosensitivity of BRCA1-defective HCC1937 human breast cancer cells. *Br. J. Cancer* **2003**, *88*(8), 1285-1291.
- [46] Chabaliere, C.; Lamare, C.; Racca, C.; Privat, M.; Valette, A.; Larminat, F. BRCA1 downregulation leads to premature inactivation of spindle checkpoint and confers paclitaxel resistance. *Cell Cycle* **2006**, *5*(9), 1001-1007.
- [47] Lafarge, S.; Sylvain, V.; Ferrara, M.; Bignon, Y.J. Inhibition of BRCA1 leads to increased chemoresistance to microtubule-interfering agents, an effect that involves the JNK pathway. *Oncogene* **2001**, *20*(45), 6597-6606.
- [48] Zhou, C.; Smith, J.L.; Liu, J. Role of BRCA1 in cellular resistance to paclitaxel and ionizing radiation in an ovarian cancer cell line carrying a defective BRCA1. *Oncogene* **2003**, *22*(16), 2396-2404.
- [49] Trenz, K.; Lugowski, S.; Jahrsdorfer, U.; Jainta, S.; Vogel, W.; Speit, G. Enhanced sensitivity of peripheral blood lymphocytes from women carrying a BRCA1 mutation towards the mutagenic effects of various cytostatics. *Mutat. Res.* **2003**, *544*(2-3), 279-288.
- [50] Rottenberg, S.; Nygren, A.O. H.; Pajic, M.; van Leeuwen, F.W. B.; van der Heijden, I.; van de Wetering, K.; Liu, X.; de Visser, K.E.; Gilhuijs, K.G.; van Tellingen, O.; Schouten, J.P.; Jonkers, J.; Borst, P. Selective induction of chemotherapy resistance of mammary tumors in a conditional mouse model for hereditary breast cancer. *Proc. Natl. Acad. Sci. USA* **2007**, *0702955104*.
- [51] Orsulic, S.; Li, Y.; Soslow, R.A.; Vitale-Cross, L.A.; Gutkind, J.S.; Varmus, H.E. Induction of ovarian cancer by defined multiple genetic changes in a mouse model system. *Cancer Cell* **2002**, *1*(1), 53-62.
- [52] Xing, D.; Orsulic, S.A. Mouse model for the molecular characterization of brca1-associated ovarian carcinoma. *Cancer Res.* **2006**, *66*(18), 8949-8953.
- [53] Thangaraju, M.; Kaufmann, S.H.; Couch, F.J. BRCA1 facilitates stress-induced apoptosis in breast and ovarian cancer cell lines. *J. Biol. Chem.* **2000**, *275*(43), 33487-33496.
- [54] Wassmann, K.; Benezra, R. Mitotic checkpoints: from yeast to cancer. *Curr. Opin. Genet. Dev.* **2001**, *11*(1), 83-90.
- [55] Wang, R.H.; Yu, H.; Deng, C.X. A requirement for breast-cancer-associated gene 1 (BRCA1) in the spindle checkpoint. *Proc. Natl. Acad. Sci. USA* **2004**, *101*(49), 17108-17113.
- [56] Joukov, V.; Groen, A.C.; Prokhorova, T.; Gerson, R.; White, E.; Rodriguez, A.; Walter, J.C.; Livingston, D.M. The BRCA1/BARD1 heterodimer modulates ran-dependent mitotic spindle assembly. *Cell* **2006**, *127*(3), 539-552.
- [57] Sudo, T.; Nitta, M.; Saya, H.; Ueno, N.T. Dependence of paclitaxel sensitivity on a functional spindle assembly checkpoint. *Cancer Res.* **2004**, *64*(7), 2502-2508.
- [58] Anand, S.; Penrhyn-Lowe, S.; Venkitaraman, A.R. AURORA-A amplification overrides the mitotic spindle assembly checkpoint, inducing resistance to Taxol. *Cancer Cell* **2003**, *3*(1), 51-62.
- [59] Weaver, B.A.; Cleveland, D.W. Decoding the links between mitosis, cancer, and chemotherapy: The mitotic checkpoint, adaptation, and cell death. *Cancer Cell* **2005**, *8*(1), 7-12.
- [60] Pujana, M.A.; Han, J.D.; Starita, L.M.; Stevens, K.N.; Tewari, M.; Ahn, J.S.; Rennert, G.; Moreno, V.; Kirchhoff, T.; Gold, B.; Assmann, V.; Elshamy, W.M.; Rual, J.F.; Levine, D.; Rozek, L.S.; Gelman, R.S.; Gunsalus, K.C.; Greenberg, R.A.; Sobhian, B.; Bertin, N.; Venkatesan, K.; yivi-Guedeoussou, N.; Sole, X.; Hernandez, P.; Lazaro, C.; Nathanson, K.L.; Weber, B.L.; Cusick, M.E.; Hill, D.E.; Offit, K.; Livingston, D.M.; Gruber, S.B.; Parvin, J.D.; Vidal, M. Network modeling links breast cancer susceptibility and centrosome dysfunction. *Nat. Genet.* **2007**, *39*(11), 1338-1349.
- [61] Hsu, L.C.; White, R.L. BRCA1 is associated with the centrosome during mitosis. *Proc. Natl. Acad. Sci. USA* **1998**, *95*(22), 12983-12988.
- [62] Hsu, L.C.; Doan, T.P.; White, R.L. Identification of a gamma-tubulin-binding domain in BRCA1. *Cancer Res.* **2001**, *61*(21), 7713-7718.
- [63] Starita, L.M.; Machida, Y.; Sankaran, S.; Elias, J.E.; Griffin, K.; Schlegel, B.P.; Gygi, S.P.; Parvin, J.D. BRCA1-dependent ubiquitination of gamma-tubulin regulates centrosome number. *Mol. Cell Biol.* **2004**, *24*(19), 8457-8466.
- [64] Sankaran, S.; Starita, L.M.; Groen, A.C.; Ko, M.J.; Parvin, J.D. Centrosomal microtubule nucleation activity is inhibited by BRCA1-dependent ubiquitination. *Mol. Cell Biol.* **2005**, *25*(19), 8656-8668.
- [65] Kurebayashi, J.; Yamamoto, Y.; Kurosumi, M.; Okubo, S.; Nomura, T.; Tanaka, K.; Sonoo, H. Loss of BRCA1 expression may predict shorter time-to-progression in metastatic breast cancer patients treated with taxanes. *Anticancer Res.* **2006**, *26*(1B), 695-701.
- [66] Kim, S.J.; Miyoshi, Y.; Taguchi, T.; Tamaki, Y.; Nakamura, H.; Yodoi, J.; Kato, K.; Noguchi, S. High thioredoxin expression is associated with resistance to docetaxel in primary breast cancer. *Clin. Cancer Res.* **2005**, *11*(23), 8425-8430.
- [67] Byrski, T.; Gronwald, J.; Huzarski, T.; Grzybowska, E.; Budryk, M.; Stawicka, M.; Mierzwa, T.; Swiec, M.; Wisniowski, R.; Siolek, M.; Narod, S.A.; Lubinski, J. Response to neo-adjuvant chemotherapy in women with BRCA1-positive breast cancers. *Breast Cancer Res. Treat.* **2008**, *108*(2), 289-296.
- [68] Wojciechowska-Lacka, A.; Markowska, J.; Skasko, E.; Kruczek, A.; Steffen, J. Frequent disease progression and early recurrence in patients with familial ovarian cancer primarily treated with paclitaxel and cis- or carboplatin (preliminary report). *Eur. J. Gynaecol. Oncol.* **2003**, *24*(1), 21-24.
- [69] Quinn, J.E.; James, C.R.; Stewart, G.E.; Mulligan, J.M.; White, P.; Chang, G.K. F.; Mullan, P.B.; Johnston, P.G.; Wilson, R.H.; Harkin, D.P. BRCA1 mRNA expression levels predict for overall survival in ovarian cancer after chemotherapy. *Clin. Cancer Res.* **2007**, *13*(24), 7413-7420.
- [70] Lee, M.N.; Tseng, R.C.; Hsu, H.S.; Chen, J.Y.; Tzao, C.; Ho, W.L.; Wang, Y.C. Epigenetic inactivation of the chromosomal stability control genes BRCA1, BRCA2, and XRCC5 in non-small cell lung cancer. *Clin. Cancer Res.* **2007**, *13*(3), 832-838.
- [71] Taron, M.; Rosell, R.; Felip, E.; Mendez, P.; Souglakos, J.; Ronco, M.S.; Queralt, C.; Majo, J.; Sanchez, J.M.; Sanchez, J.J.; Maestre, J. BRCA1 mRNA expression levels as an indicator of chemoresistance in lung cancer. *Hum. Mol. Genet.* **2004**, *13*(20), 2443-2449.
- [72] Wachters, F.M.; Wong, L.S. M.; Timens, W.; Kampinga, H.H.; Groen, H.J. M. ERCC1, hRad51, and BRCA1 protein expression in relation to tumour response and survival of stage III/IV NSCLC

- patients treated with chemotherapy. *Lung Cancer* **2005**, 50(2), 211-219.
- [73] Wang, L.; Wei, J.; Qian, X.; Yin, H.; Zhao, Y.; Yu, L.; Wang, T.; Liu, B. ERCC1 and BRCA1 mRNA expression levels in metastatic malignant effusions is associated with chemosensitivity to cisplatin and/or docetaxel. *BMC Cancer* **2008**, 8(1), 97.
- [74] Rosell, R.; Skrzypski, M.; Jassem, E.; Taron, M.; Bartolucci, R.; Sanchez, J.J.; Mendez, P.; Chaib, I.; Perez-Roca, L.; Szymanowska, A.; Rzyman, W.; Puma, F.; Kobierska-Gulida, G.; Farabi, R.; Jassem, J. BRCA1: A novel prognostic factor in resected non-small-cell lung cancer. *PLoS ONE* **2007**, 2(11), e1129.
- [75] Reguart, N.; Cardona, A.F.; Carrasco, E.; Gomez, P.; Taron, M.; Rosell, R. BRCA1: a new genomic marker for non-small-cell lung cancer. *Clin. Lung Cancer* **2008**, 9(6), 331-339.

Received: February 19, 2009

Revised: March 11, 2009

Accepted: March 20, 2009