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## Introduction:

The current funded study entitled "Molecular mechanisms of radioresistance in prostate cancer", is investigating the role of DNA break repair in the radiation response of normal and malignant prostate epithelium. The overall hypothesis of this project is that the radiation response of normal and cancerous prostate tissues can be correlated to the appropriate sensing and repair of DNA breaks by repair complexes following exposure to ionizing radiation. Specific aims relate to determining the interaction of DNA repair proteins *in vitro* using immunofluorescent confocal microscopy and biochemical DNA rejoining assays under both hypoxic and oxic conditions (given *in vivo* tumour cell populations). An *in vivo* program of prostate xenograft radioresponse is also being initiated to determine the level of DNA repair *in situ* using immunohistochemistry and immunofluorescent markers. These initial studies will determine the heterogeneity in fractionated response in a series of prostate xenografts as relates to DNA repair capacity, which may be translated to novel markers for radiation response in patients who receive prostate radiation therapy. The relevance of this project is that this *in vitro* to *in vivo* pre-clinical approach may derive clinical biomarkers of radiation response which can predict which patients will most benefit from radiation therapy for prostate cancer. The project will also determine the molecular mechanisms behind radiation response, in general, in prostate epithelial tissues (1,2,5)

## Body:

**Task 1:** Initially, the first task was to primarily complete *in vitro* studies on PC-3; LNCaP, DU145 and normal prostate (PRSE and PREC) cells relating to DNA double strand break repair. Clonogenic radiation curves were derived for all 5 cell cultures, and complete apoptosis assays were determined in both a dose and time responsive manner. We observed that although there were differences in SF2 value for all 5 cell lines, there was little variability in radiation induced apoptosis and no evidence for dose-dependancy. This suggests that there were alternate death mechanisms for prostate cells following exposure to ionizing radiation which was determine to be post-mitotic cell death and senescence(2). This is important as it supports our grant's hypothesis that DNA repair is an important endpoint for study as it correlates more to cell survival using terminal growth arrest or cell senescence. For example, in all 5 cell lines, we found that there was an increase in the p16 superscript ink4a and p21<sup>WAFWAF</sup> genes at 5-9 days following 2-10 Gy of ionizing radiation. Furthermore, these cells were found to contain senescent populations which was quantitated and found to be dose responsive and correlated to their clonogenic survival (using a novel fluorescent flow cytometric proliferation assay). This work has been accepted for publication in *Prostate Cancer and Prostate Diseases* (Nature Publishing Group) and should be out in the fall issue of 2002 (Refer to text and figures contained in manuscript 1, Bromfield et al; appended as Appendix 1).

Task one projects were also completed for all 5 cell lines in determining the ability for the cells to repair double strand breaks, single strand breaks and DNA base damage (and oxidative damage) following ionizing radiation using the comet assay. Preliminary data with pulse field gel electrophoresis (PFGE) and continuous field gel electrophoresis

(CFGE) suggested that the results for DNA break assays correlated well to the Comet assay. As the Comet assay can give further information cell cycle distribution following DNA damage, we utilized this assay for all further experiments. We have observed a series of novel observations which currently suggests that malignant prostate cancer cells have a DNA repair defect in the repair of DNA-dsbs, DNA-ssbs and DNA-base damage and oxidative damage in relation to the two normal prostate epithelial and stromal cell cultures (4,6; see Figure 1). **This has not been reported before.** Current experiments are discerning whether or not repair is altered under oxic versus hypoxic conditions and early data suggest that rad51 is reduced in expression under hypoxic conditions. These studies will be completed in the next 6 months.

RNA protection and Western blot analyses suggest that that the non-homologous (ie Ku70/80/DNA-PK) and homologous(ie rad50/51/XRCC3) proteins are upregulated at the transcriptional level in the malignant prostate cells compared to normal prostate cells (see Figure 2). We therefore went onto to discern protein function in terms of protein-protein interactions during DNA repair. Antibody labeling conditions and image analysis programs have been completed to utilize quantitative confocal microscopy for DNA complexes regarding RAD51, RAD50, MRE11, P95, BRCA1, BRCA2, P53, RPA, ATM and DNA-PK protein co-localization following DNA damage. We initially utilized RNA protection analyses (RPA) and western blots to show that malignant prostate cancers have an increased expression of homologous recombination-associated protein complexes, including XRCC3 and RAD51 proteins. This result was also recently reported in a publication early in 2002 by Haaf and co-workers (7).

However, more importantly, our quantitative confocal microscopy has shown that although the 3 malignant prostate epithelial cell lines (PC-3, DU-145, LNCaP) have high levels of protein expression on western blot analysis, they do not have functional RAD51 in terms of forming nuclear complexes following DNA damage. We observed that there is a decreased incidence of ionizing radiation induced foci of RAD51 following 10 Gy of irradiation when compared to the normal cell cultures. In fact it appears, that the LNCaP cell line, shows perinuclear staining following ionizing radiation and cannot be transported into the nucleus following DNA damage. It may therefore be that there are mutations in the BRCA2 and BRCA1 genes which are responsible for complexing with the RAD51 protein, and all 5 cell lines are being sequenced for BRCA1 and BRCA2 and RAD51 in separate experiments (9). **This result has not been reported in the literature before, and may suggest that although there are increased levels of RAD51 and tumour cell lines, they may not have an increased fidelity of DNA repair if the protein cannot translocate from the cytoplasm to the nucleus.** A quantitative assessment of the DNA complexes following radiation by both RNA, protein and repair foci complex formation endpoints have been completed and a manuscript is in preparation to be submitted in the next 3 months regarding this (Fan et al., 2002; see Figures 3, 4).

Primary prostatic cultures were initiated as prostatectomy specimen cultures available through Coriell Laboratories. We were successful in culturing both the prostate stromal and the prostate epithelial cell cultures in vitro to be utilized in a radiobiology and DNA

repair experiments. DNA double strand break repair complexes have been determined in these cultures and are part of the data set contained in the manuscript in Appendix 1 and the manuscript in preparation, as noted above.

Xenografts from Erasmus University, Rotterdam were received after an MTA was signed and they were implanted into Balb/c mice for growth assays. An ethics approval for biopsies taken before and after 5 fraction (25 Gy in 5 fractions pre-operative radiotherapy) during clinical prostate radiotherapy was given by our research ethics board (REB) and this was submitted to the US Army as part of the documentation for this grant. Eight patients have been accrued to the phase 1 pilot study of preoperative radiotherapy, and we are using both pre and post radiotherapy biopsies on these patients to derive the markers related to *in vivo* irradiation or patient irradiation as outlined in Tasks 2 and 3. We have therefore completed all endpoints for Task 1, as a result, manuscripts are in preparation, or in press, in relation to Task 3.

### **Task 2: Complete *in vivo* radiobiologic studies on human prostate xenografts (months 12-24).**

We have determined that there can be cell cycle phase specific changes in DNA-double strand break foci formation, in relation to DNA rejoining, by irradiating cells under both a synchronous and G0-G1 synchronized conditions. However it was difficult to synchronize the malignant cells completely in G1 and we only could synchronize them to a point that 90% of cells were in G1 at the time of irradiation, compared to >95% for the normal cell lines. Our data suggests that DNA-double strand break foci, including homologous recombination-associated proteins, do form in the absence of DNA replication in G1 and are dose responsive. Selected experiments looking at G1 versus S versus G2 phase of the cell cycle and DNA double strand break foci formation in malignant and normal cell lines will take place over the next 6-12 months.

Single dose experiments have been completed for the PC-3 and the selected Rotterdam xenografts, utilizing the dose of 20 Gy, and then the xenografts were removed and stained for immunohistochemical markers pertaining to p53, apoptosis related genes (bax, BCL2 and TUNEL assay as well as survivin) and DNA repair markers (RAD50, BRCA1, BRCA2, RAD50, DNAPK<sub>cs</sub>, KU70, KU80, ATM, P21, RB, MYC and RPA). The xenograft histology was also stained for proliferation markers such as MIB-1, KI-67 and PCNA. Our early results suggest that RAD51 and RAD50 and BRCA2 increase in expression both in terms of the nuclear intensity of staining as well as a number of cells positively staining for protein following 20 Gy or irradiation *in vivo* at 24 hours (e.g. see Figure 4). **This has not been reported in the literature before (8,10).** It is unclear whether or not the increase in staining is occurring in the oxic versus hypoxic compartments and as such we are pursuing these studies relating to relative expression within the two compartments using hypoxic markers (GLUT-1 and HIF1alpha) in separate experiments.

Growth delay will be determined in the next 12 months for fractionated, single dose in control groups of animals containing the PC-3 DU-145 and PR-346C and other

Rotterdam xenograft to complete Task 2. IHC endpoints will be completed as in the previous paragraph for all animal treatment cohorts.

Unlike *in vitro* experiments, the observation of discrete DNA repair foci using normal microscopic IHC within histologic specimens of xenografts irradiated *in vivo* have been difficult and does not have the resolution of the confocal microscopy. We are continuing to modify the microscope technology in order to do this, and also optimize our tissue fixation prior to antibody use to allow for confocal microscopy based on frozen sections. However, it may be that the relative subcellular localization of repair proteins (cytoplasmic versus nuclear), such as that we have observed in studies described in Task 1 for RAD51, may give us a unique marker for malignancy, as well as radiation response that can not solely be quantitated using the number of foci, per se.

Accrual of peri-radiotherapy biopsies from clinical patients after fraction 5 for analysis will be starting in the next 6 months, as we have altered our radiation protocol to improve IMRT-treated patients as well as a new dose for dose escalated conformal radiotherapy (change from 75.6 to 79.8 Gy). Nonetheless, six patients so far have been accrued for the preoperative radiotherapy study, and we are just in the midst of sequencing their p53 status for all 11 exons of the p53 gene. Baseline immunohistochemistry for p53, p21, TUNNEL, bax and BCL-2 have been completed. We are currently staining the Phase I pre-operative radiation study patients (i.e. post 25 Gy) biopsies to compare pre and post radiotherapy specimens for the unique markers outlined above and this should be completed within the next 6-9 months.

### **Task 3: (Months 18-36)**

Task 3 is to primarily complete the clinical studies undergoing radiotherapy, and to determine DNA repair foci in human clinical biopsies pre and post radiotherapy in phase 3 and Phase 1 trials. We will continue our xenograft studies as it pertains to fractionated and single dose related growth delay experiments, and to ascertain the relative senescence-associated in DNA repair-associated markers that we have observed based on the manuscripts completed related to Task 1. As such we have already started some components of Task 3 and these studies will run long-term and parallel as patient biopsies are accrued for the assays.

### **KEY RESEACH ACCOMPLISHMENTS:**

1. Determination of clonogenic radiation survival for both normal malignant prostate epithelium, showing that normal epithelium is exquisitely sensitive to radiation which may therefore explain the glandular atrophy during clinical prostate radiotherapy.
2. Apoptosis is not the dominant mode of cell death in prostate cancer cells following ionizing radiation. Clonogenic survival can be better estimated by the number of cells undergoing a tumour arrest or senescence like phenotype which may explain the long time to PSA nadir in irradiated prostate patients..
3. Molecular markers pertaining to apoptosis and molecular endpoints of apoptosis are not correlated in malignant and normal prostate cell lines.

4. DNA repair complexes can be visualized using confocal microscopy and quantitative and are dose dependant for the RAD50, RAD51, BRCA2-associated complexes. The appearance and disappearance of these foci correlate to the kinetics of DNA biochemical rejoining assays (ie. Comet assay).
5. Malignant prostate epithelium has an inherent DNA defect in terms of DNA double strand break repair, single strand break repair and base damage repair. This may be related to carcinogenesis as well as irradiation response. The defect in repair can be associated with the defect in the RAD51 nuclear foci formation, even though these cell lines exhibit high levels of RAD51 protein expression on western blot analyses. There is therefore a disconnect between these two endpoints which speaks to function rather than expression.
6. Xenografts have been received from Rotterdam and are growing in nude mice. Preliminary single dose experiments (20 Gy) show that a number of DNA repair markers can be radiation induced and this now must be correlated to the overall radiation response in terms of in vivo growth delay analyses.
7. Accrual to the phase I pilot study of preoperative radiotherapy has achieved in 8 patients so far in which biopsies are available in pre and post radiotherapy for staining of DNA-repair associated markers.
8. These same biopsies have been successfully sequenced for the p53 gene in terms of all exons (2-11) and are being correlated with immunohistochemical endpoints relating to p53 function and expression and apoptosis.

#### **Reportable Outcomes:**

##### Manuscripts:

Milosevic M, Toi A, Sweet J, **Bristow R**, Warde P, McLean M, Crook J, Catton C, Catton P, Gospodarowicz M. Trans-rectal oxygen measurements in prostate cancer. Clin Invest Med 23 (Supp), S19, 2000.

Parker C, Milosevic M, Toi A, Sweet J, Panzarella T, Syed A, **Bristow R**, Catton C, Catton P, Crook J, Gospodarowicz M, Maclean M, Warde P, Hill R A polarographic electrode study of tumor oxygenation in localized prostate cancer; (Conditionally accepted, Radiotherapy and Oncology, 2002)

Bromfield G, Fan R, Meng A, Kumaravel Ts, **Bristow RG**. Radiation-Induced Death Pathways in Prostate Cells: Role of Apoptotic and Non-Apoptotic Cell Death (In press, Prostate Cancer and Prostate Diseases, Fall 2002).

Fan, R., Kumaravel, TS, Bromfield G. and **Bristow, R**. "Defective rad51 nuclear localization in malignant prostate cancer. Manuscript in preparation, Fall, 2002

##### Abstracts and Presentations:

Bromfield, G P, **Bristow, R G**. "Radiation-Induced Cell Death Pathways in Normal and Malignant Prostate Epithelial Cells", Radiation Research Society, San Juan, Puerto Rico, April 2001.

Bromfield, G P, **Bristow, R G**. "Relative Importance of Non-Apoptotic and Apoptotic Cell Death Pathways in Irradiated Prostate Cells", CARO Meeting, Quebec City, September 2001.

**Bristow R. G.**, Bromfield G, Fan R, Meng A, Kumaravel TS. "Radiotherapy-induced death pathways in prostate cells: Apoptosis versus permanent cell cycle arrest", 57th annual CUA Meeting, Newfoundland, June 2002.

Fan R, Kumaravel TS, Bromfield G, Jalali F, Meng A, **R. Bristow**. "DNA Repair in normal and malignant prostate epithelial tissues: implications for genetic stability and radiotherapy", ESTRO, Prague, September 2002.

#### Invited Lectures-R. Bristow:

"New Aspects of Radiation Oncology in Prostate Cancer", Astra-Zeneca Update on Urology, Invited Speaker, Deerhurst, Ontario, May 2001

"Molecular Biomarkers in Radiation Oncology", Target Insight DRO-CME Meeting; Invited Speaker; May 2001.

"The New Genetics and Radiation Oncology: Defining a Molecular Therapeutic Ratio" Invited Speaker, Cobalt 50th Anniversary in London, Advances in Radiation Therapy Symposium, London, Ontario, October 2001.

"Novel Biomarkers of DNA Damage Responses: Implications and Limitations for Predicting Radiotherapy Response", Invited Speaker, NIH Bio-targeting Workshop. Washington, April 2002.

"DNA Repair in normal and malignant prostate epithelial tissues: implications for genetic stability and radiotherapy", NIH Young Investigator's Meeting, NIH-Bethesda, August 2002.

#### **Other reportable outcomes:**

Ms. Gillian Bromfield obtained an MSc in Medical Biophysics (U Toronto) utilizing operating funds from this award relating to apoptosis and senescence in irradiated prostate cells. Furthermore, there is a continuous development of the tissue bank relating to irradiated prostate specimens as it relates to the phase I and phase III clinical trials. Funding was applied to the Canadian Prostate Cancer Research Initiative (CPCRI) regarding HDAC inhibitors and prostate cancer senescence, and a seed grant (\$ 37,500 CAN has been awarded. Although the proposed new studies are completely separate from the current US Army DOD grant, information gleaned from the US Army grant supported new hypotheses in the CPCRI grant.

Ms. Alice Meng, M.Sc. was hired as the technician for the technical aspects of the grant as outlined in the original budget. She came to our lab from the private biotechnology sector.

Dr. Rong Fan, a post doctoral fellow recruited following a previous post-doctoral fellowship at Harvard University, is supported by this US Army award. She has done extremely well in her studies relating to RAD51 and prostate cancer carcinogenesis in

radiation response. A manuscript will ensue from this work shortly in the next 3-6 months.

### **Conclusions:**

The importance of our work suggests that we can focus on DNA repair as an important endpoint in the radiation response of prostate cancer, given that we have shown the terminal growth arrest and cells senescence are associated with clonogenic survival rather than apoptosis.

Our important results currently suggest that cell senescence is an important factor that must be further looked at in terms of pharmacologic manipulation in relation to prostate cancer cell kill following radiation. Our studies also suggest that there are defects in DNA repair the novel in malignant cell lines compared to normal epithelial cell lines, and this is being investigated with confocal immunofluorescent biology in terms of function and repair complex formation (5). Currently our data suggests that in malignant prostate cancer, the RAD51 is dysfunctional even though it is expressed at high levels, which may explain prostate cancer carcinogenesis and relative response to radiation therapy(1). These studies also suggest that anti-RAD51 therapy, such as gene therapy using alogo nucleotides or adenoviral vectors(3), may be efficacious in targeting malignant versus normal prostate cells, given that the RAD51 protein is dysfunctional in malignant cancer epithelium.

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**Prostate  
Cancer**  
AND PROSTATIC DISEASES

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Dear Dr Bristow

**Re: Prostate Cancer and Prostatic Diseases – Manuscript 000223**

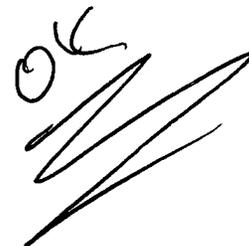
Thank you for sending in your revised paper entitled "Cell Death in Irradiated Prostate Epithelia Cells: Role of Apoptotic and Clonogenic Cell Kill". I am pleased to be able to inform you that the paper has now been accepted for publication in the journal *Prostate Cancer and Prostatic Diseases* and I have today forwarded it to the publishers for typesetting. You should receive author proofs in a couple of weeks.

Thank you for taking the time to submit to this journal.

Kind regards  
Yours sincerely



*RV* **Roger S Kirby**  
Professor of Urology  
Editor



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## Cell Death in Irradiated Prostate Epithelial Cells: Role of Apoptotic and Clonogenic Cell Kill

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Key Words: prostate cancer, epithelium, senescence, apoptosis, radiosensitivity

## ABSTRACT

Dose-escalated conformal radiotherapy is increasingly being used to radically treat prostate cancer with encouraging results and minimal long-term toxicity, yet little is known regarding the response of normal or malignant prostate cells to ionizing radiation (IR). To clarify the basis for cell killing during prostate cancer radiotherapy, we determined the IR-induced expression of several apoptotic- (bax, bcl-2, survivin and PARP) and G1-cell cycle checkpoint- (p53 and p21<sup>WAF1/Cip1</sup>) related proteins, in both normal (PrEC-epithelial and PrSC-stromal) and malignant (LNCaP, DU-145 and PC-3; all epithelial) prostate cells. For these experiments, we chose doses ranging from 2 to 10Gy, to be representative of the 1.8-2Gy daily clinical fractions given during curative radiotherapy and the 8-10Gy single doses given in palliative radiotherapy. We observed that IR-induced bax and p21<sup>WAF1/Cip1</sup> protein expression were attenuated selectively in normal stromal and epithelial cell cultures, yet maintained their p53-dependency in malignant cell lines. For each cell culture, we also determined total apoptotic and overall radiation cell kill using a short-term nuclear morphologic assay and a long-term clonogenic survival assay, respectively. Clonogenic survival, as measured by the surviving fraction at 2Gy (SF2), ranged from 0.05 (PrEC) to 0.55 (DU-145), suggesting that malignant prostate cells are more radioresistant than normal prostate cells, for this series. IR-induced apoptotic cell kill was minimal (less than 6% cell after a dose of 10Gy at times of 24-96 hours) and was not dose-dependent. Furthermore, apoptotic kill was not correlated with either molecular apoptotic response or clonogenic cell kill. Using a flow cytometric proliferation assay with the PrSC (stromal) and DU-145 (epithelial) representative cultures, we observed that a senescent-like phenotype (SLP) emerges within a sub-population of cells post-irradiation that is non-clonogenic. Terminal growth arrest was dose-responsive at 96 hours following irradiation and associated with long-term expression of both p21<sup>WAF1/Cip1</sup> and p16<sup>INK4a</sup> genes. Future strategies for prostate radiotherapy prediction or novel treatments should additionally focus on terminal growth arrest as an important endpoint in prostate cancer therapy.

Key Words: prostate cancer, epithelium, senescence, apoptosis, radiosensitivity

## INTRODUCTION

Dose-escalated (i.e. 76-80Gy) radiotherapy is an important treatment option for men with intermediate-risk prostate cancer who present with T1 or T2 disease, a Gleason score greater than 6 out of 10 and serum prostatic specific antigen (PSA) values in the order of 10-20ug/ml<sup>1</sup>. Successful radiotherapy results in a gradual decline of the serum PSA over 12-24 months following treatment where a PSA nadir of less than 1.0ug/ml predicts for 5-year, long-term local control<sup>2</sup>. With 3-dimensional conformal (3D-CRT) or intensity-modulated (IMRT) radiotherapy treatment protocols, 5-year PSA-free relapse rates are approximately 75-85% and associated with minimal late toxicity (less than 5% with Radiotherapy Oncology Group (RTOG) Grade 3-4 rectal or bladder damage)<sup>2</sup>.

Yet these same data predict that 15-25% will not achieve local control following radical radiotherapy, thought in part to be due to the intrinsic radioresistance of prostate cancer cells secondary to genetic (e.g. apoptosis, cell-cycle or DNA-repair-related gene expression) or microenvironmental factors (e.g. hypoxia or altered growth factor expression)<sup>3</sup>. The success of radiation therapy in prostate cancer treatment is therefore dependent on the eradication of all prostate tumor clonogens (i.e. tumor stem cells, estimated to be less than 1% of cells within a tumor), which are select tumor cells capable of unlimited proliferative potential. Failure to eradicate this particular population will result in the regrowth of the tumor following treatment<sup>4</sup>. Despite many advances towards understanding prostate carcinogenesis, little work has been published to date relating the mode of clonogenic cell kill following DNA damage in either normal and malignant prostate epithelial cell cultures. This information is important in defining new strategies to augment prostate cancer cell kill and understand the kinetics of cell kill following radiotherapy (in comparison to decreasing PSA value kinetics *in vivo*) and may allow optimal interpretation of post-radiotherapy biopsies as a secondary measure of local tumor control.

Apoptosis plays an important role in the death of both normal prostate and androgen-dependent malignant prostate tissue following androgen withdrawal, leading to a decrease in either glandular or tumor volume, respectively. This is supported by the observation of rapid apoptosis following castration in the rat prostate glands<sup>5,6</sup> (a response lacking in mice deficient in expression of the pro-apoptotic gene, *bax*<sup>7</sup>) and in patients treated with androgen-withdrawal therapy for locally advanced or metastatic prostate cancer<sup>8</sup>. The relationship between androgen ablation and apoptosis has led to a number of clinical studies that have attempted to determine whether local failure following radical radiotherapy is secondary to genetic factors that control radiation-induced apoptosis. However, taken together, clinico-pathologic studies that have attempted to correlate altered expression of the p53, p21<sup>WAF1/CIP1</sup>, *bax*, *bcl-2* and caspase apoptosis-related genes and radiocurability have been

inconclusive<sup>9,10</sup>. This may be due to small clinical sample size, differences in the quantitation or timing of immunohistochemical or gene expression endpoints<sup>11,12</sup>, variable clinical treatment parameters, or perhaps due to alternate mechanisms of prostate cell death that confound analyses focused solely on apoptotic endpoints.

Recent data has supported the hypothesis that apoptosis may not be the dominant mode of cell death following radio- and chemotherapy in stromal (i.e. fibroblast) and epithelial tissues<sup>13,14</sup>. Indeed, it has been suggested that in these and selected tumor models, apoptosis may actually occur in a non-clonogenic population following DNA damage<sup>15,16</sup>. Alternatively, a permanent cell-cycle arrest or senescence-like terminal growth arrest may also be a factor in determining prostate cell death following radiotherapy<sup>17</sup>. Markers of senescence, such as senescence-associated  $\beta$ -galactosidase (SA  $\beta$ -gal) activity and permanently elevated levels of p21<sup>WAF1/Cip1</sup> and p16<sup>INK4a</sup> are actively under investigation as biomarkers of terminal growth arrest in human tumors<sup>18</sup>. Chang and co-workers<sup>19</sup> observed that a number of DNA-damaging agents (including ionizing radiation) could induce a senescence-like phenotype (SLP) in 11/14 cell lines tested. Other laboratories<sup>13</sup> and reviews have outlined a number of considerations regarding radiation-induced cell-death, including cell-type dependency in defining the dominant mode(s) of death (i.e. apoptosis, mitotic-linked death and reproductive death (SLP)/necrosis)<sup>20</sup>. An improved understanding of death processes has been afforded by novel flow cytometric methods to detect terminally-arrested tumor cells following drug treatment<sup>19,20</sup>, and ascertain their relative morphology and clonogenic potential.

The purpose of the current study was to examine the mode(s) of prostate cell death *in vitro* following exposure to ionizing radiation to possibly refine clinical biomarkers for prediction of radiotherapeutic response and suggest future treatment strategies. Apoptosis, proliferation and clonogenic survival were assessed in a panel of cell lines comprised of both normal (stromal-PrSC and epithelial-PREC) and malignant (LNCaP, DU-145, PC-3; all epithelial) cultures, to determine the overall cellular response. We demonstrate that apoptosis is not the dominant mode of cell kill in this panel of cell cultures post-IR. Instead, data on selected cell lines supports the concept that long-term proliferative arrest relates to clonogenic radiation cell killing *in vitro*.

## **MATERIALS AND METHODS**

### ***Cell Culture***

All cell cultures were incubated in vented tissue culture flasks under 5% CO<sub>2</sub> and 37°C culture conditions. LNCaP cells (a gift from L. Chung, University of Virginia) were maintained in T-media (Gibco-BRL) and supplemented with 10% FCS. PC-3 and DU-145 cells were purchased from ATCC and maintained as suggested in Ham's F12K, and alpha-Modified Eagles Medium respectively,

supplemented with 10% FCS and 2mM L-glutamine. PrEC (normal prostate epithelial cells) and PrSC (normal prostate stromal cells) were purchased from Clonetics and maintained per suggested protocol in PrEGM media and SCGM media, without testosterone supplementation, respectively. Both cell cultures have limited lifespan and proliferative potential in culture according to the supplier and we have consistently observed decreased growth rates following passage 5 *in vitro* for both cultures. Immortalized myc-infected Rat-1 HO15.19 fibroblast cells (a gift from Dr. L. Penn, OCI/PMH<sup>21</sup>) were maintained in Dulbecco's H21 media supplemented with 10% FBS. Cultures were maintained without testosterone supplementation to ensure that radiation survival studies were completed under similar conditions in normal and malignant prostate cultures and as previous experiments have determined that exogenous testosterone may not always alter apoptotic responses, clonogenic survival or IR-induced p21<sup>WAF1/Cip1</sup> expression and cell arrest in androgen-*sensitive* cells (J. Tsihlias, personal communication, and <sup>22,23</sup>). Approximate doubling times for cell cultures under these conditions were as follows: PrEC: 36-48 hours (highly variable), PrSC: 18 hours, LNCaP: 36 hours, PC-3: 24 hours, DU-145: 18 hours, Myc-expressing Rat-1HO15.19: 16 hours.

#### ***SF2Gy and Clonogenic Radiation Survival Curves***

Logarithmically growing cells were rinsed with PBS/HBSS, trypsinized for 5 minutes at 37°C, and then were seeded at appropriate densities for colony formation in six-well dishes (Nunc). Asynchronous cultures were irradiated 16-20 hours post-plating to reduce the immediate effects of trypsinization and such that the multiplicity index was less than 1.1 <sup>24</sup>. At least two dilutions of cells in triplicate were used for each dose point for any given individual experiment. At least three independent clonogenic radiation experiments were completed for each cell line. Plated cells were either mock irradiated or irradiated with 0 to 10Gy under aerobic conditions using a <sup>137</sup>Cs irradiator at ~ 1Gy/min at room temperature. Plates were then incubated at 37°C for 7-14 days depending on cell doubling time *in vitro* and re-fed every 4-5 days before fixation and staining (methylene blue/50% methanol) of resulting colonies (aggregates of greater than fifty cells were scored as a colony). Radiation survival was calculated as the plating efficiency of treated cells divided by the plating efficiency of untreated cells and plotted as a function of dose on a semi-logarithmic plot as previously described <sup>24</sup>. We were unable to derive colonies at doses greater than 2Gy in the LNCaP and PrEC cell cultures due to poor plating efficiencies, and therefore only SF2 values are presented for these cultures. For a given cell culture, there was no correlation between the SF2 values and plating efficiency amongst individual experiments, although mean SF2 values were increased in cell lines which exhibited increased plating efficiency, as reported in the literature (i.e. DU-145 and PC-3) <sup>3,21</sup>.

### ***Western Blotting***

Logarithmically-growing cells were irradiated and lysed on ice for 20 minutes with E7 lysis buffer as previously described<sup>24</sup>. Protein quantification was performed determined using a commercial Pierce-BCA assay kit to derive a mean concentration value based on three assays per lysate. SDS-PAGE was performed using 7-12% bis-acrylamide (29:1) gels with a 4% stacking gel run in a Novex X-cell semi-dry Mini Cell western blotting apparatus at room temperature. Each well was loaded with 20µg of total protein plus loading buffer (final concentration 1x-6% glycerol, 0.83% β-mercaptoethanol, 1.71% Tris-HCl pH 6.8, 0.002% Bromophenol Blue) after boiling for 3 minutes. Samples resolved by electrophoresis at 80-110 Volts for 1.5-2.5 hrs were transferred onto nitrocellulose overnight at 14v/4°C or for 1.5 hours at 24v/room temperature in transfer buffer (75mM glycine, 10mM Tris, 20% methanol). For selected blots, pre-hybridization staining with Ponceau S confirmed equal loading and transfer between running lanes.

To detect protein, membranes were blocked in TBST/0-10% low fat milk and then exposed to the primary antibody 2-4 hours at room temperature constant rotation. Membranes were then rinsed with TBST and exposed to the appropriate secondary antibody for 1 hour under similar conditions, rinsed again with TBST, once with 10x TBS and finally incubated in Amersham ECL chemiluminescence solution for one minute. Membranes were exposed to Hyperfilm ECL from AmershamPharmacia and analyzed by densitometry (Molecular Dynamics Computing Densitometer, ImageQuant Mac v.1.2). Primary antibodies used in these studies included: p53-mouse monoclonal (Santa Cruz Bp53-12, 1:3000); p21<sup>WAF1</sup>-mouse monoclonal (Oncogene Ab-1, 1:3000); Bax-rabbit polyclonal (Santa Cruz N-20, 1:1000); Bcl-2-mouse monoclonal (Santa Cruz 509, 1:500); PARP-mouse monoclonal (BioMol SA-249, 1:1000), survivin-rabbit polyclonal (Alpha Diagnostics SURV11, 1:5000), and p16<sup>INK4A</sup> mouse monoclonal (Oncogene Ab-1, 1:1000).

### ***Assays for Apoptotic Cell Death***

Radiation-induced apoptosis was quantified on the basis of distinct nuclear morphology and associated apoptotic bodies based on a previously standardized immunofluorescence protocol (Hoechst 33342 staining)<sup>24</sup>. For the morphology assay, logarithmically growing cells were re-plated at appropriate densities in triplicate and mock/irradiated with 0, 2, 10 or 20Gy. These were scored for apoptotic morphology (i.e. apoptotic bodies and nuclear condensation-see sample in Figure 2a) at periods of 24 to 96 hours following irradiation. Total adherent and floating cells in each culture were fixed and stained in 4% formalin-PBS/10µM Hoechst 33342 DNA-specific dye for 30 minutes at RT. Cell counts to evaluate any cell loss/lysis into culture media were also performed at each time-point.

All experiments utilized Rat-1 HO15.19 cell line as positive control for gamma-irradiation induced apoptosis (L. Penn, personal communication and Lee et al.<sup>25</sup>).

### ***Radiation Survival in Proliferating and Non-proliferating Irradiated Cultures: The CFDA-SE Flow Cytometry Proliferation Assay***

To determine if permanent arrest is associated with decreased clonogenic survival, a modification of the protocol by Chang et al.<sup>19</sup> utilized the CFDA-SE (CFSE) fluorescent dye<sup>20,26</sup>. The CFSE compound (Molecular Probes, C-1157) is distributed throughout the cellular membranes and is divided evenly amongst subsequent progeny based on division of equal volumes of membrane at cell division. Multiple rounds of cell division are therefore represented by a corresponding decrease in total membrane fluorescence within a proliferating population, which can be detected by flow cytometry. Analyzing cell populations for relative fluorescence (FL1[CFSE] parameter; increased in non-proliferating cultures) and increasing side-scatter (SSC parameter; due to increased granularity associated with senescent cells) allows for flow cytometric analysis of senescent-like populations post-treatment.

Sub-confluent flasks of cells were trypsinized, collected and centrifuged into a pellet and  $5 \times 10^6$  cells were re-suspended in 1mL serum-free media plus 1uL of stock solution (5M CFSE in DMSO) at 37°C for 10 minutes with occasional inversion. Ice-cold RPMI 1640 + 10% FBS was then added prior to a subsequent cell centrifugation, and finally the cells were re-suspended in PBS. The cells were further washed twice in PBS, re-plated at low density (approximately 10% confluence) into multiple, 175cm<sup>2</sup> Falcon flasks for next-day irradiation (0 to 10Gy). As a control, all cells (floating and adherent) from one untreated flask were harvested one day post-plating and analyzed with flow cytometry to find baseline fluorescence (FL1[CFSE]) intensity. Remaining cultures were followed until day 5 when all cells (floating and adherent) were harvested, analyzed and sorted by FACS into “non-proliferating” (FL1[CFSE]<sup>hi</sup>SSC<sup>hi</sup>), and “proliferating” (i.e. all cells other than FL1[CFSE]<sup>hi</sup>SSC<sup>hi</sup>) populations to determine clonogenic potential within each population. The 5 day time point was initially chosen as it represents the point at which surviving cells would begin to declare their colony-forming ability<sup>3</sup>. Sorted populations of DU-145 and PrSC were used to derive colonies in each sub-group as examples of epithelial and stromal (i.e. fibroblast-like) models. Pre-sort samples were analyzed on a BDIS FACScan analyzer and samples sorted using either a Becton Dickonson Immunocytometry system FACStarPLUS or BDIS FACS Vantage system. BDIS CELLQuest Software v3.3 was used for both sorting and analysis. Cell lysates from adherent and floating cells in parallel cultures treated similarly (stained, irradiated with 0, 2 and 10Gy) were also harvested on days 5-9, and analyzed for expression of the p16<sup>INK4a</sup> and p21<sup>WAF1</sup> genes. Cultures were also stained for

senescence-associated  $\beta$ -galactosidase (SA  $\beta$ -gal) using the method of Chang et al.<sup>19</sup>, as a complementary biomarker of senescence-like death.

## RESULTS

### *Gene Expression of Apoptosis-related Genes Within Irradiated Prostate Cell Cultures*

As different laboratories may contain variants of original cell stocks, we initially determined the p53 status of the malignant prostate epithelial cell lines using full-length DNA sequencing of exons 1-11 of the p53 gene. Consistent with previous reports, LNCaP cells were found to express two wild type (WT) alleles, whereas the PC-3 cells were devoid of p53 protein expression due to chromosome 17p hemizyosity and a mutation in the remaining allele at codon 138 which results in a premature stop codon at position 169. The DU-145 cells express mutant (MT) p53 protein due to mutations at codons 223 and 274. We observed that the level of bax protein expression is p53-dependent following IR, given the increased expression in the WTp53-expressing LNCaP cells at 24 hours following 10Gy. This molecular response was attenuated, or absent, in the remaining PC-3 and DU-145 malignant epithelial cell lines, which have altered p53 protein expression. Of note, despite the western blots shown in Figure 1b, bax expression is detectable in DU-145 cells, albeit at a very low level. The response was also attenuated within the normal epithelial and stromal cultures (see Figure 1a, b, Table 1). Bcl-2 protein levels were low, yet detectable, using our antibody and remained unchanged in all cell cultures following 10Gy for periods up to 24 hours following radiation (see Figure 1c, d). In other experiments in our laboratory, the relative levels of bax and bcl-2 protein have been confirmed at the mRNA level by RNA protection analyses (Fan R. and Bristow R.G., manuscript in preparation). The IAP-related protein, survivin, has been suggested to be a prognostic indicator in a variety of cancers, presumably due to its influence on cellular apoptosis and G2 phase cell cycle control<sup>27</sup> and reported differential upregulation in malignant tissues, relative to normal tissues<sup>28</sup>. *In vitro*, endogenous survivin levels were observed to be detectable in all of the cell cultures within our series (normal and malignant), and were invariant following irradiation (Table 1) except for a slight (1.6-fold) increase in PrSC. Subsequent experiments have revealed lower levels of survivin in PrEC cultures than in their stromal and malignant counterparts.

Terminal apoptotic transduction involves altered expression and cleavage of the caspase family of proteins and the PARP protein<sup>29,30</sup>. Other laboratories have reported that caspase 1 and 3 protein expression can be deficient in some of our malignant cell lines<sup>31</sup>. In our experiments, analysis for PARP cleavage revealed that, although we detected an increase in the characteristic 89kD apoptotic-related PARP protein fragment in our highly-apoptotic Rat-1 HO15.19 cell line, there was no such change in any of the five prostate cell cultures at 24 hours following a dose of 10Gy (data not shown).

Our results (summarized in Table 1) suggest that gene and protein expression related to terminal apoptosis-defining events following IR is not consistent with observations made for other cells (e.g. lymphocytes or thymocytes) which are classically more susceptible to radiation-induced apoptosis; however we recognize that the molecular apoptotic and morphologic (see below) response of our cell panel may be variable dependent on type of cell stress and drug treatment.

### ***Minimal Evidence of Apoptotic Cell Death in Irradiated Prostate Cultures***

We next determined the level of radiation-induced apoptosis following various doses (2-20Gy) and time points (0-96 hours post-IR) using a distinct nuclear morphology assay (see Figure 2a) as previously described<sup>24</sup>. A dose of 10Gy has been shown to decrease clonogenic survival by 3 logs or more, in other malignant cell lines. The highly-apoptotic adherent Rat-1 HO15.19 cell line formed a positive control for IR-induced apoptosis in these experiments and irradiated cultures were observed to contain decreasing numbers of cells over 24-96 hours consistent with a rapid induction of cell death (data not shown). The level of apoptosis in Rat-1 HO15.19 control following 20Gy became difficult to quantify at 24 hours due to a large amount of cellular debris and may be underestimated as presented in Figure 2b. The apoptotic response of our prostate cell panel at times of 24 to 96 following 10Gy as determined by morphology is presented in Figure 2b, and reveals that neither normal or malignant prostate cells undergo high levels of apoptosis at any time point up to 96 hours (a time at which the earliest colonies indicative of clonogenic survival can be detected). Additionally, careful total cell counts of adherent and floating cells within all the irradiated cultures suggested that there was no decrease at any time point up to 96 hours in total cell number, which ruled out underestimating apoptotic responses (data not shown). Moreover, in contrast to the Rat-1 HO15.19 Myc-expressing control, there was no evidence for a dose-dependent increase in apoptosis in our panel of cultures (2Gy range=0-1%, 10Gy range=0-6%, 20Gy range=0-3%; see Figure 2c).

We observed a trend towards increased levels of apoptosis among the malignant cell lines as compared to the normal cell cultures, although these relative differences were not consistent. The data presented using the *in vitro* morphology assay was also supported by the absence of an apoptotic sub-G1<sup>29</sup> peak within DNA histograms of irradiated PC-3, DU-145 and LNCaP cells using flow cytometry, the lack of apoptotic morphology post-IR of the same cells as analyzed by the COMET DNA-damage assay<sup>32</sup>, and minimal TUNEL staining of the PC-3 cell line either *in vitro* or *in vivo* (growing as a xenograft i.m., in a nude mouse host) following irradiation (data not shown). These results suggest that cellular apoptosis is not a major mechanism of IR-induced prostate cell death under the culture and treatment conditions used in this study.

### ***Molecular Analysis of Checkpoint Control in Prostate Cells***

The p53 status in normal and malignant cells can be functionally related to either apoptosis or a G1 and G2 cell cycle arrest or checkpoint, and dependent on cell type, level of DNA damage or cell stressor<sup>33,34</sup>. We therefore confirmed the presence or absence of a molecular p53-dependent G1 checkpoint in the normal and malignant prostate cells by determining the IR-induced upregulation of the cdk-inhibitory protein, p21<sup>WAF1/Cip1</sup>. Following IR-induced DNA damage, the p53 protein is stabilized post-transcriptionally, by alternate phosphorylation of its amino terminus at serine residues 15 and 20 through both direct and indirect actions of the ATM protein. Stabilized p53 protein can then lead to a transcriptional upregulation of the p21<sup>WAF1/Cip1</sup> protein, which inhibits the G1 cyclin-cdk kinase complexes, and results in a G1 arrest secondary to hypo-phosphorylation of the pRB (retinoblastoma) protein. An increased level of p53 protein was observed following irradiation in all WTP53-expressing prostate cells and peaked at 2-6 hours following IR-treatment (Figure 3). As expected, we observed a lack of p53 protein expression in irradiated null-p53 PC-3 cells and elevated endogenous levels of p53 protein in the MTP53-expressing DU-145 cells (consistent with a longer half-life for the MTP53 protein; Figure 3b), which were invariant post-IR. The PrEC and PrSC normal cultures both showed similar stabilization of the p53 protein relative to  $\alpha$ -tubulin levels following irradiation. However, in the PrSC cells, the p21<sup>WAF1/Cip1</sup> levels were upregulated and sustained at 24 hours; in the PrEC cells, the response was relatively attenuated in level and was duration reaching almost pre-irradiation levels at 24 hours (Figure 3a). We failed to observe an increase in p21<sup>WAF1/Cip1</sup> expression in the MTP53-expressing and null-p53 cell lines (DU-145 and PC-3 respectively)<sup>35</sup>, however the WTP53-expressing LNCaP cell line did show a strong IR-induced upregulation of p21<sup>WAF1/Cip1</sup>. The p53 and p21<sup>WAF1/Cip1</sup> protein expression results were correlated to relative mRNA levels under similar culture conditions using RNA protection analyses in separate experiments (Fan R. and Bristow R.G., manuscript in preparation). These data support that p53 can induce a molecular G1 checkpoint in both normal and malignant prostate epithelium, but highlights previous observations that, in certain normal epithelial cultures, p21<sup>WAF1/Cip1</sup> expression may be attenuated relative to stromal cultures<sup>36</sup> in a tissue-specific manner. This may relate to relative control of cell-cycle related checkpoint and carcinogenesis in these two tissues<sup>37</sup>.

### ***SF2Gy and Clonogenic Survival for Normal and Malignant Prostate Cultures***

Colony-formation after DNA damage measures the long-term survival of cells that are capable of unlimited proliferation and summarizes all types of IR-induced modes of cell death including apoptosis, mitotic-linked death (death after 2-3 aborted divisions followed by apoptosis or necrosis) and permanent growth arrest leading to necrosis<sup>233</sup>. Consistent with selected reports<sup>38,39</sup> full

clonogenic survival curves could not be generated for our LNCaP cell line, due to poor plating efficiencies which made determination of colony-formation at doses greater than 2Gy difficult. We encountered similar difficulties with PrEC normal epithelial cultures, which also had a poor plating efficiency (0.1-1%). Nonetheless, for all cell lines we were able to generate radiation survival data after a low, clinically relevant dose of 2Gy (SF2), which approximates the daily fraction of radiation within curative radiation protocols. Full clonogenic survival curves following doses up to 10Gy (a dose approximating a single-fraction palliative treatment) were derived for the PC-3, DU-145, PrSC and Rat-1 HO15.19 cell cultures and the results are plotted in Figure 4a. The SF2 values for all cell cultures are shown in Figure 4b. The normal stromal and epithelial cultures were the most radiosensitive based on SF2 values, even though they had the lowest levels of IR-induced apoptosis at similar doses. Furthermore, the apoptotic kill response in the DU-145 and Rat-1 HO Myc cell lines was quite disparate, despite similar clonogenic survival (see Figure 2b,c). We observed that the DU-145 and PC-3 cell lines with altered p53 status were more radioresistant than the WTP53-expressing LNCaP cell line. However, defined experiments with prostate cell lines that are isogenic save for p53 status are required before concluding that p53 status correlates with radiosensitivity in prostate cancer cells. In summary, we have observed that the overall level of apoptosis was not correlated to the overall level of clonogenic cell survival in our panel of cell lines. Plotting the relative cell kill following 2Gy and 10Gy based on the two endpoints in Figure 4c illustrates the discrepancy between the results of two assays.

#### ***Permanent Arrest in Irradiated Prostate Cells***

Given that apoptosis was not a dominant mechanism for clonogenic cell kill, we next investigated the contribution of terminal growth arrest associated with senescence-associated markers to clonogenic survival using both a representative stromal culture (PrSC cells), and a representative epithelial culture (DU-145 cells). The choice of these two cultures was predicated on the need for cell lines which would readily form colonies following flow cytometric sorting procedures at 2 and 10Gy and to maximize the tissue-specific and genetic differences relating to propensity for senescence, clonogenic cell kill and G1 checkpoint control.

Using a flow cytometric assay that simultaneously determines relative levels of FL1-CFSE fluorescence (i.e. proliferation) and SSC-parameter (cell granularity), we determined that up to 87% of the PrSC population was non-proliferating with an associated increased granularity (FL1[CFSE]<sup>hi</sup>SSC<sup>hi</sup>) at 5 days, following a dose 10Gy of radiation. In similarly-plated cultures, only 14% and 8% showed the same cytometric profile in 2Gy-treated or control cultures; these relative proportions being consistent over 2-3 representative experiments (Figures 5a, c). By comparison, only

32% of DU-145 cells had a senescent-like cytometric profile, although upon closer inspection, the data suggest that the vast majority (i.e. greater than 70%) of DU-145 cells were actually non-proliferating, but that these cells were inconsistently associated with increased granularity when compared to stromal PrSC cells (compare CFSE-fluorescence axis in both cell lines following 10Gy in Figure 5). The FL1[CFSE]<sup>hi</sup>SSC<sup>hi</sup> cytometric profile was determined for 5% of DU-145 cells following 2Gy and 3% in the untreated DU-145 population (Figure 5a, b; note that cells not growth-arrested following 2Gy or in non-irradiated cultures may have undergone multiple rounds of division by this point differentially increasing the total “proliferating” population). We then sorted and plated cells from the senescent-like, non-proliferating population relative to the remaining cells and observed that relative colony forming ability (plating efficiency) was decreased in the FL1[CFSE]<sup>hi</sup>SSC<sup>hi</sup> (“non-proliferating”), SLP population in a dose responsive-manner (see Table 2).

In normal fibroblasts (i.e. stromal cells), cells undergo decreasing proliferative potential with increasing passage *in vitro*, until finally undergoing senescence associated with increased granularity, positive SA  $\beta$ -gal staining and upregulation of the p21<sup>WAF1/Cip1</sup> and p16<sup>INK4a</sup> proteins. Similar changes occur in normal fibroblast cultures when exposed to IR and has been referred to as a “premature IR-induced senescence”<sup>40-42</sup>. Although we observed greater SA  $\beta$ -gal staining intensity in an increased number of PrSC stromal cells following a dose of 10Gy (see Figure 6a), we found the endpoint to be highly variable across all cell lines and difficult to quantitate in epithelial cells (further data not shown; noted by others<sup>43</sup>). Whether upregulation of one, or both genes, are absolutely required for senescence and whether the process is p53-dependent in all cell types remains controversial.

In order to determine whether similar gene expression changes occurred in PrSC and DU-145 cells, we performed western blot analyses of cell populations obtained in parallel with flow cytometric experiments at day 5. These analyses showed high, IR-invariant levels of p16<sup>INK4a</sup> protein in both PrSC and DU-145 cultures and a dose-dependent increase in p21<sup>WAF1/Cip1</sup> levels in PrSC cells only (Figure 6b; confirmed using densitometry). We also analyzed p16<sup>INK4a</sup> expression in all of the cell cultures at 24 hours following 10Gy. In this case, levels of p16<sup>INK4a</sup> were either invariant (PrEC, LNCaP, DU-145) or undetectable (PrSC, PC-3) as confirmed by relative densitometry (data not shown). Long-term (up to 9 days) analysis of p16<sup>INK4a</sup> expression post-10Gy irradiation DU-145 and PrSC demonstrated increasing expression with time (data not shown), suggesting a time-dependent, though not dose-dependent, expression of p16<sup>INK4a</sup>. We conclude that cells within a terminally arrested population that have increased cellular granularity (SLP) are incapable of forming colonies and that the sub-population

of proliferating cells without associated increased granularity define the colony-forming potential of the entire irradiated culture.

## DISCUSSION

This is the first report, to our knowledge, documenting the relative role of apoptosis and terminal growth arrest as factors in determining overall clonogenic radiation cell survival for a panel of normal and malignant prostate cell cultures within the same laboratory setting. Using clinically relevant radiation doses, we observed a strong molecular apoptotic response in certain cell lines (bax and p53 upregulation in LNCaP cells, post-IR), yet this response did not correlate with quantitative determinations of apoptosis using morphology endpoints. The apoptotic response was not dose-responsive and did not correlate with final clonogenic cell kill. Further support for our data are the observations that manipulation of the ceramide-sphingomyelin and bcl-2 associated apoptotic pathways, or androgen ablation, can increase the apoptotic responses of prostate cells without altering final clonogenic radiation survival (Shim K. and Bristow R.G., unpublished observation and <sup>22,23,44</sup>). Many groups have indicated that apoptosis may be the primary mode of death following gamma-irradiation only in specific cell types such as hematopoietic or lymphocytic cells, but not in stromal- or epithelial-derived tissues<sup>16,44-47</sup>. Furthermore, many attempts to alter apoptotic indices in epithelial- and stromal-derived tissues have failed to affect clonogenic survival. This suggests that although the apoptotic pathway is intact in malignant prostate cells, other death mechanisms may over-ride this response following irradiation.

It has been suggested that epithelial cell G1 checkpoint may be abrogated or less efficient than that of its stromal counterpart, despite wild-type p53 status. Girinski et al. <sup>36</sup> found an abrogated p21<sup>WAF1/Cip1</sup> induction and G1 checkpoint in a panel of normal prostate epithelial cells as compared to a panel of normal prostate stromal cells following ionizing radiation. Meyer et al. <sup>48</sup> reported similar findings for mammary epithelial versus stromal tissues. Within the same group, Romonov et al. <sup>49</sup> observed an abrogated response to replicative crisis in the mammary epithelial cells suggesting a global defect in epithelial response to stress in comparison to its stromal counterpart. Our own experiments illustrated that, even for similar levels of p53 induction/stabilization, the p21<sup>WAF1/Cip1</sup> response in PrEC is greatly attenuated in comparison to its stromal counterpart. While the p53/p21<sup>WAF1/Cip1</sup> responses for our panel of malignant cell lines were as previously reported, the LNCaP cell line's strong p21<sup>WAF1/Cip1</sup> induction is still surprising in light of its epithelial nature. Girinski et al. <sup>36</sup> suggested that epithelial cell response might be partially dependant on interactions with surrounding stromal tissues<sup>37,50,51</sup>. LNCaP cells may have altered characteristics such that it does not require this interaction for a strong p21<sup>WAF1/Cip1</sup> induction following irradiation. Furthermore, studying G1 arrest alone may not be

sufficient, since cells lacking a functional G1 checkpoint can exhibit a G2 delay that may be linked to DNA repair<sup>52</sup> and cellular survival following radiation (reviewed<sup>53</sup>). Indeed, although our results suggest increased survival for cells which lack the G1 checkpoint, defined studies in isogenic tissue culture or solid tumor models which differ in p53 status and specific G1, S and G2 checkpoint control experiments are required to prove this hypothesis, and are part of a current research program<sup>11</sup>.

The success or failure of radical radiotherapy depends on the daily proportionate killing of tumor clonogens, which make up less than 1% of the total population of cells within a tumor. For example, it has been estimated that each gram of tumor contains approximately  $1 \times 10^9$  tumor cells, with approximately less than  $1 \times 10^7$  cells having clonogenic capacity. To date, no formal test or data exists for the pre-treatment determination of the number of clonogens existing prior to prostate radiotherapy. One can estimate that for a radiotherapy protocol using 35-40 fractions of 2Gy, the clonogenic SF2 value should be less than 0.60 (i.e. death after 35 treatments =  $0.6^{35} = 1.7 \times 10^{-8}$ ) to cure a 1 gram tumor, assuming equal killing per radiotherapy fraction<sup>4</sup>. Our data suggests that the SF2 *in vitro* is less than 0.6 for the cell lines tested. However, the effective SF2 may be higher *in vivo*, due to cell-cell interactions, hypoxia, altered gene expression or cell cycle phase during irradiation<sup>3</sup> and the relative importance of these factors remain to be in radiotherapy cohorts. Our observed *in vitro* radiosensitivity of normal epithelial and stromal cultures *in vitro* may explain the observation of glandular atrophy, fibrosis and decreased glandular function observed in prostate glands following irradiation. Exquisite sensitivity of normal epithelial cells may also explain why final post-therapy nadir PSA values in patients who achieve local control are lower than the PSA values in men without a diagnosis of prostate cancer, reflecting residual normal gland function after IR-induced cell kill<sup>54</sup>.

In our experiments, relative clonogenic cell kill was approximated by quantitative endpoints of a dose-responsive terminal growth arrest, in which certain cells acquired a senescent-like phenotype. Terminal growth arrest, rather than apoptosis, may begin to explain the slow kinetics of decreasing PSA values following radiotherapy over 12-16 months following treatment<sup>2</sup>. Recent experiments by Pollack and colleagues<sup>23,55</sup> are consistent with our data, as the supra-additive radioresponses observed in LNCaP and Dunning rat R3327-G tumor models following combined androgen withdrawal and fractionated radiation (mimicking clinical stage T3-T4 prostate cancer treatment protocols which increase overall patient survival)<sup>56</sup>, was secondary to factors which determined post-treatment cellular growth arrest rather than apoptosis.

If a surrogate measure of radiation sensitivity was developed to use prior to, or early during, the course of radiotherapy, specific measures could be used to increase radiocurability or abort radiotherapy altogether in favor of radical prostatectomy (if medically feasible). Crook et al.<sup>57</sup> found

that markers of proliferation (PCNA, MIB-1) in post- radiotherapy biopsies from 498 men were an independent indicator of treatment failure, but indeterminate biopsies do occur which complicate interpretation as to whether viable clonogenic cells remain 2 to 2.5 years following radical radiotherapy. Our data suggests that other surrogate predictive factors might include molecular or cellular senescence or cell cycle arrest factors, such as the cdk inhibitors, p21<sup>WAF</sup> or p16<sup>INK4a</sup> that are activated by DNA damage and lead to altered proliferation and terminal growth arrest.

At present, no predictive test can determine which cells in the tumor are prostate clonogens rather than non-clonogens, however we believe that terminal growth arrest should be further investigated as a major mechanism of cell death in addition to apoptosis, in protocols that utilize radiotherapy. If proven important in prostate cancer, the former mechanism of cell death might be augmented *in vivo* using radiotherapy in conjunction with inhibitors of prostate cancer cell proliferation such as retinoic acid, antisense to cdk inhibitors, inhibitors of telomerase, or inhibitors of histone deacetylase (HDAC)<sup>58,59</sup>. Indeed these agents are currently being prospectively tested as single agents or in combination with chemotherapy in Phase I/II trials; our results suggest further studies of the efficacy of these agents in combination with radiation as a novel prostate treatment strategy.

## **ACKNOWLEDGEMENTS**

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## TABLES

**Table 1:** Apoptosis- and cell cycle-related gene expression in prostate cell cultures 24 hours post-10Gy irradiation, as compared to mock-irradiated controls

<b>Normal</b>	<b>p53</b>	<b>p21</b>	<b>bax</b>	<b>bcl-2</b>	<b>survivin</b>
<b>PrEC</b>	↑ ↑	↑	↔	↔	↔
<b>PrSC</b>	↑ ↑	↑ ↑	↔	↔	↔
<b>Malignant</b>					
<b>LNCaP</b>	↑ ↑	↑ ↑	↑ ↑	↔	↔
<b>PC-3</b>	n-d*	low‡	↔	↔	↔
<b>DU-145</b>	↔	n-d	n-d	n-d	↔

\*n-d= non-detectable; ‡ low=barely detectable, no change post-XRT; ↔ less than 2-fold change; ↑ greater than 2-fold increase; ↑ ↑ greater than 4-fold increase (quantified using relative densitometry).

**Table 2.** Relative colony forming ability within FL1[CFSE]<sup>hi</sup>SSC<sup>hi</sup> (non-proliferating) and proliferating populations, as sorted by flow cytometry at day 5 post-irradiation.

Cell Type	Dose (Gy)	# of Cells Plated	Plating Efficiency (proliferating)	Plating Efficiency (Non-proliferating)
<b>PrSC</b>	0	100	0.33±0.34*	0.03±0.02
	2	1000	0.06±0.03	0.01±0.01
	10	1000	0.00±0.00	0.00±0.00
<b>DU-145</b>	0	100	0.41±0.35	0.15±0.14
	2	1000	0.22±0.17	0.01±0.01
	10	1000	0.01±0.00	0.00±0.00

\*mean values and associated S.E.M.

## FIGURE LEGENDS

**Figure 1.** Western blot analyses for apoptotic-related protein expression pre- and post-irradiation, in a panel of normal and malignant prostate cell cultures: (a) bax protein expression in normal prostate epithelial (PrEC) and stromal (PrSC) cell cultures; (b) bax protein expression in malignant prostate cell cultures (Rat-1 HO15.19 cell-lysate shown as positive control); (c) bcl-2 protein expression in normal prostate cell cultures; (d) bcl-2 protein expression in malignant prostate cell cultures (human bcl-2 transfected Rat-1 fibroblast lysate shown as positive control).

**Figure 2.** IR-induced apoptosis in normal and malignant cell lines: (a) Nuclear morphology of selected cell populations stained with Hoechst 33342 at 48 hours following 10Gy showing evidence of apoptotic bodies and chromatin condensation in cells denoted with white arrows: left panel, irradiated LNCaP cells; right panel, irradiated RAT-1 HO15.19 positive control cells (magnification 1000x); (b) Time course of IR-induced apoptosis following a dose of 10Gy (each bar represents the mean and S.E.M.); (c) Dose-dependence of IR-induced apoptosis assayed at 48 hours (error bars omitted for clarity in 3D plot).

**Figure 3.** Western blot analysis of p53 and p21<sup>WAF1/Cip1</sup> protein expression in (a) normal, and (b) malignant prostate cultures following 10Gy irradiation.

**Figure 4.** Clonogenic survival data for normal and malignant prostate cultures: (a) Full clonogenic radiation survival curves for PrSC, DU-145 and PC-3 and highly-apoptotic Rat-1 HO15.19 cell cultures (each point represents a geometric mean of 3-5 independent experiments plotted with associated geometric S.E.M.);

(b) Surviving fraction following 2Gy (SF2 values) with associated S.E.M. of normal and malignant prostate cell cultures; (c) Direct comparison of mean quantitative data for apoptotic and clonogenic kill following either 2Gy (upper panel) or 10Gy (lower panel).

**Figure 5:** Frequency histogram of FL1 fluorescence parameter (i.e. CFSE vital dye fluorescence) for (a) PrSC (left) and DU-145 (right) at 5 days post-irradiation following doses of 0Gy (control, mock-irradiated), 2Gy and 10Gy. Shown is a representative experiment with total cell population analyzed for each dose; (b) represents 2 dimensional plots of FL1[CFSE] fluorescence intensity versus SSC (side scatter-granularity) for total cell numbers in mock irradiated and irradiated flasks of cells (see text for details) for PrSC (top) and DU-145 (bottom). Note increasing FL1[CFSE]<sup>hi</sup> SSC<sup>hi</sup> fractional sub-population (representing a senescent-like phenotype) with increasing dose; similar cytometric data was observed in all replicate experiments. These populations as shown were sorted using flow cytometry to determine relative colony forming ability as tabulated in Table 2.

**Figure 6.** Senescent biomarkers in prostate cell populations: (a) Example of negative (left) and positive (right) SA  $\beta$ -gal staining in non-irradiated and irradiated PrSC cultures respectively, at 120 hours following a dose of 10Gy; (b) western blot analysis of p16<sup>INK4a</sup> and p21<sup>WAF1/Cip1</sup> protein expression in entire PrSC and DU-145 cultures at day 5 following irradiation.

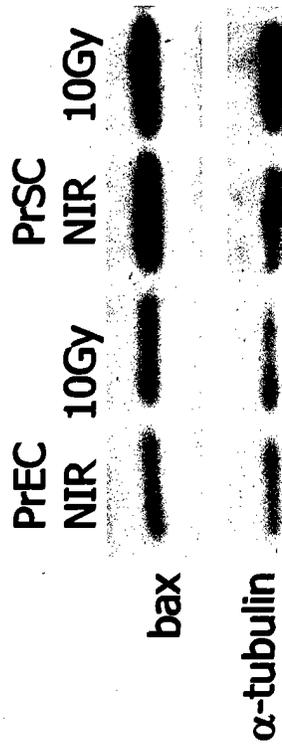
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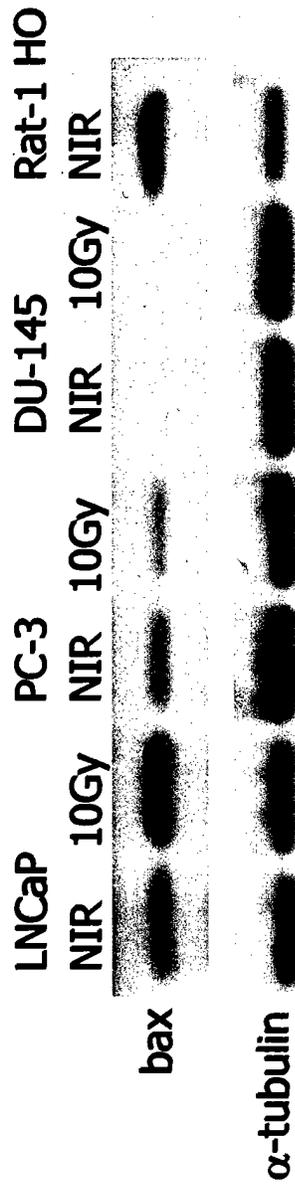
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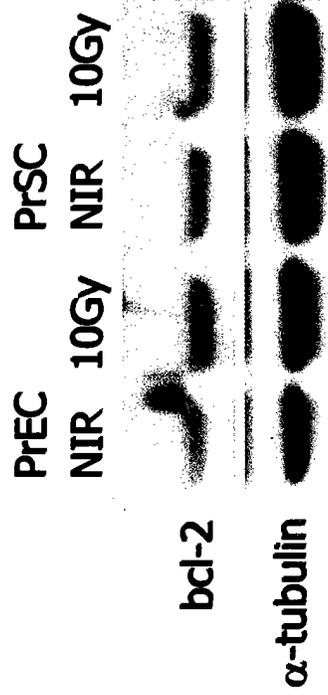
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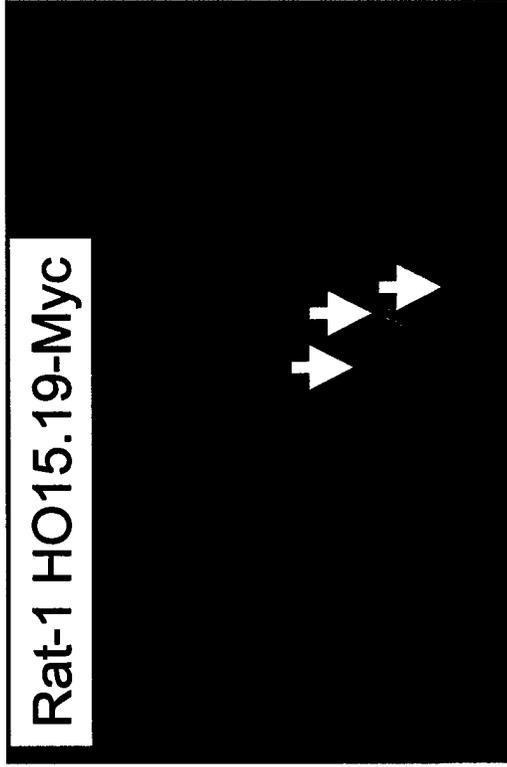
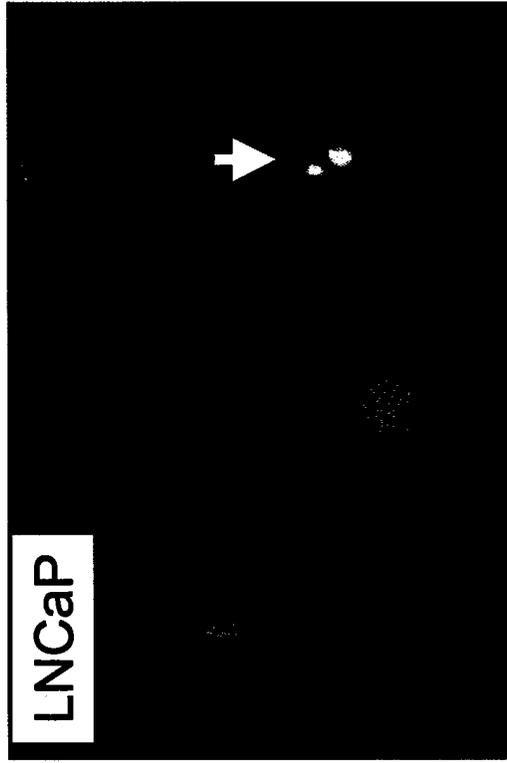
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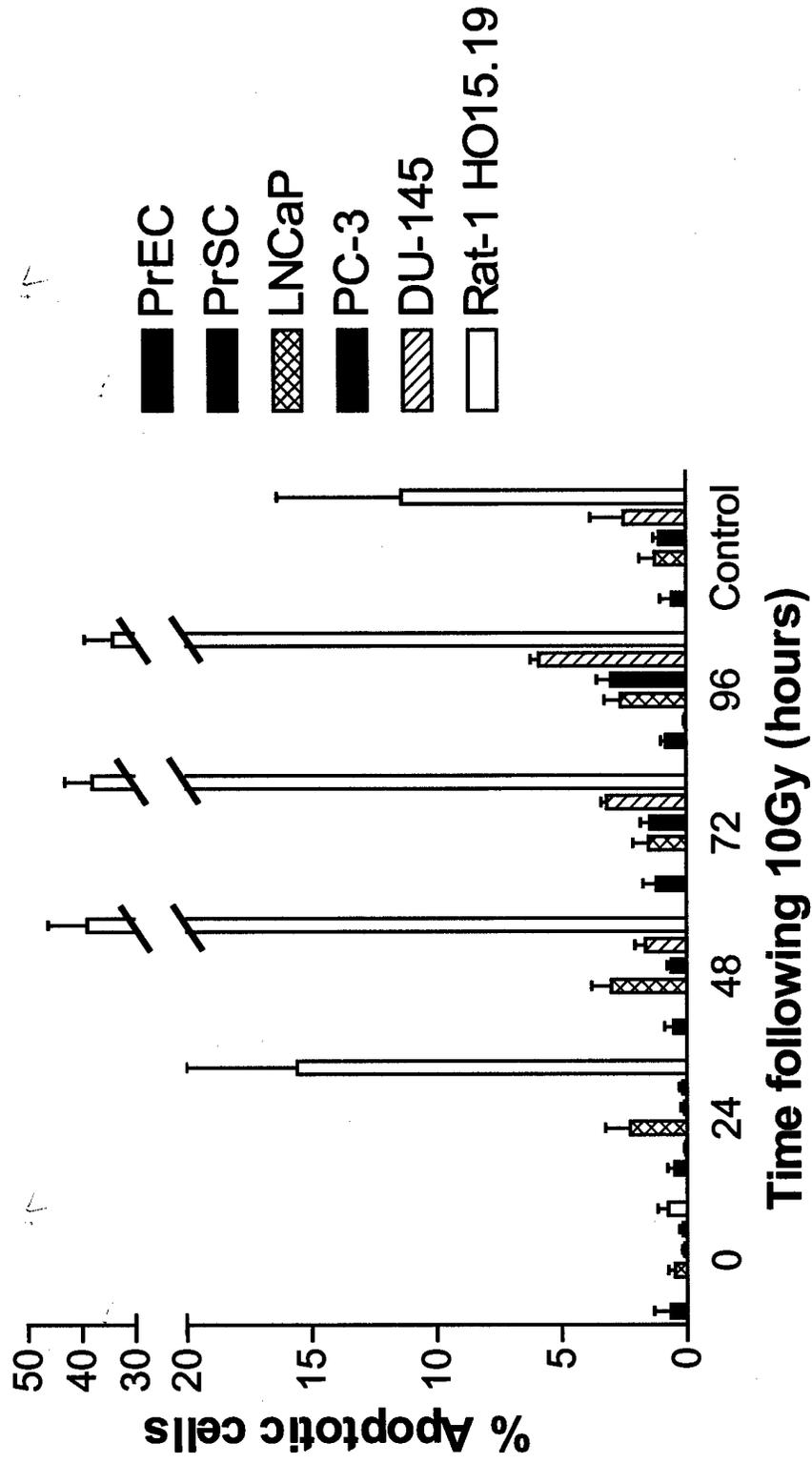
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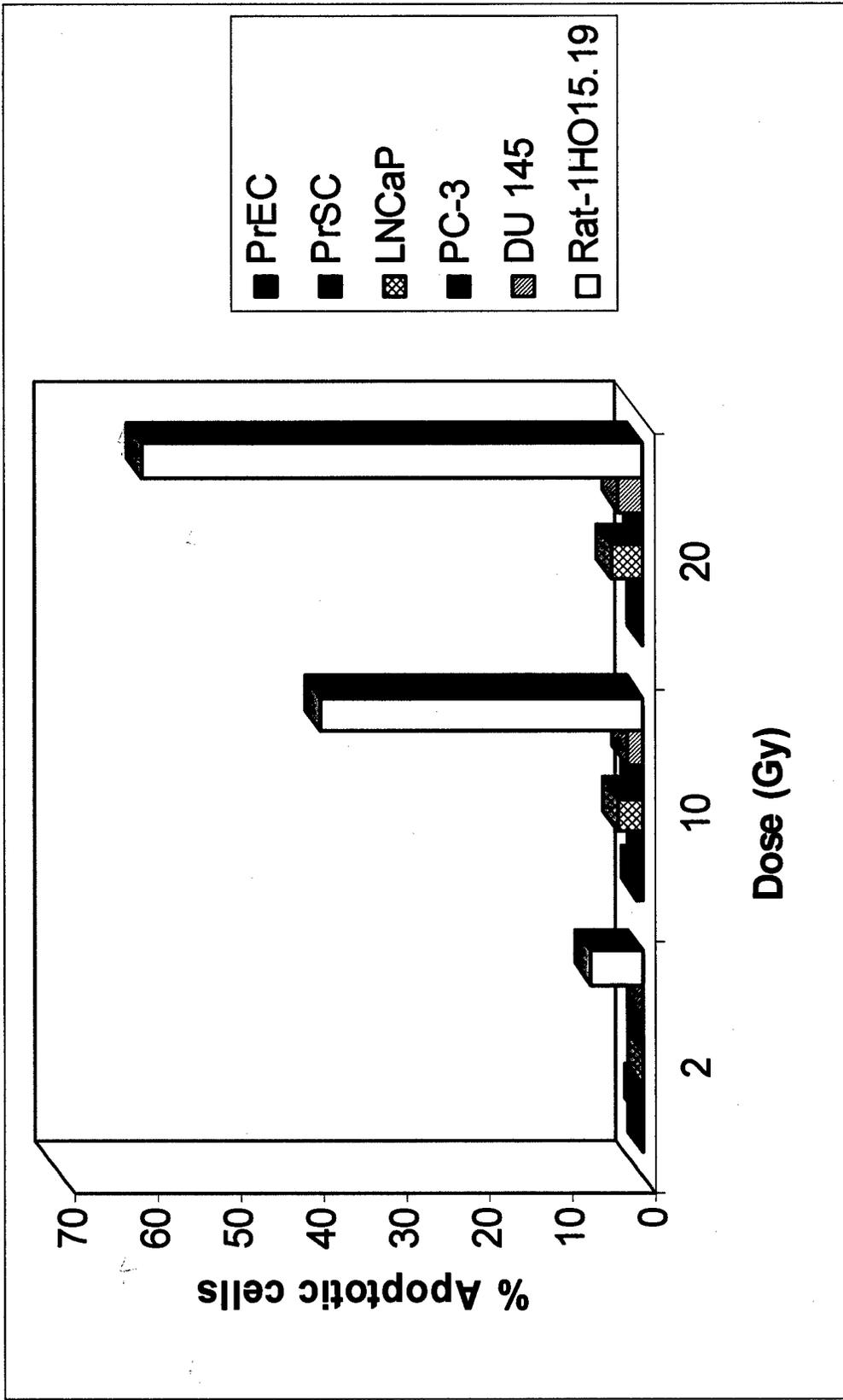


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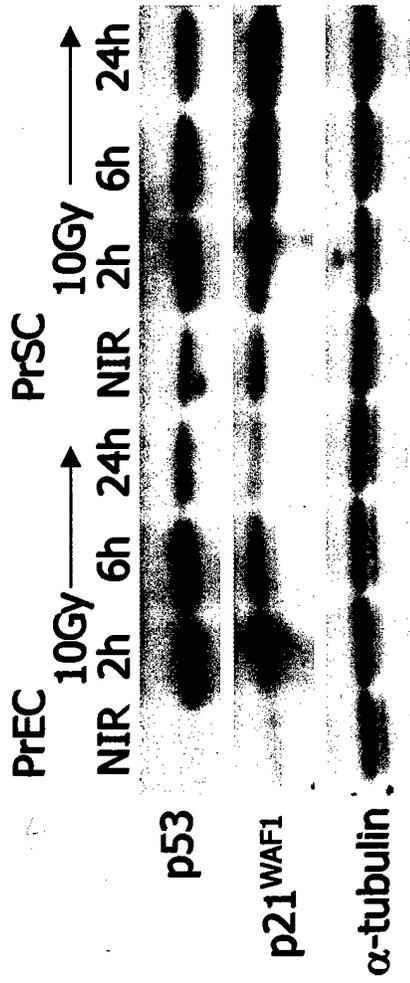
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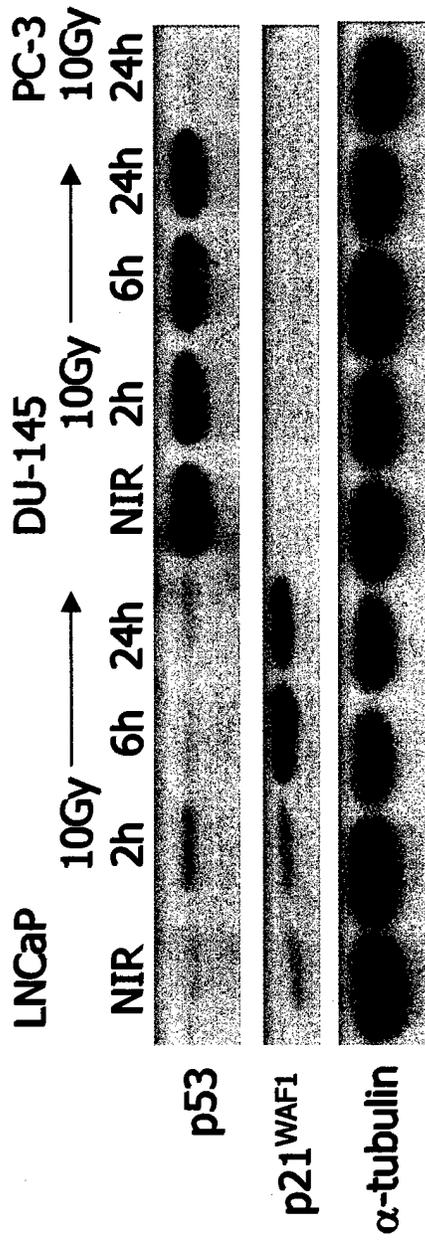


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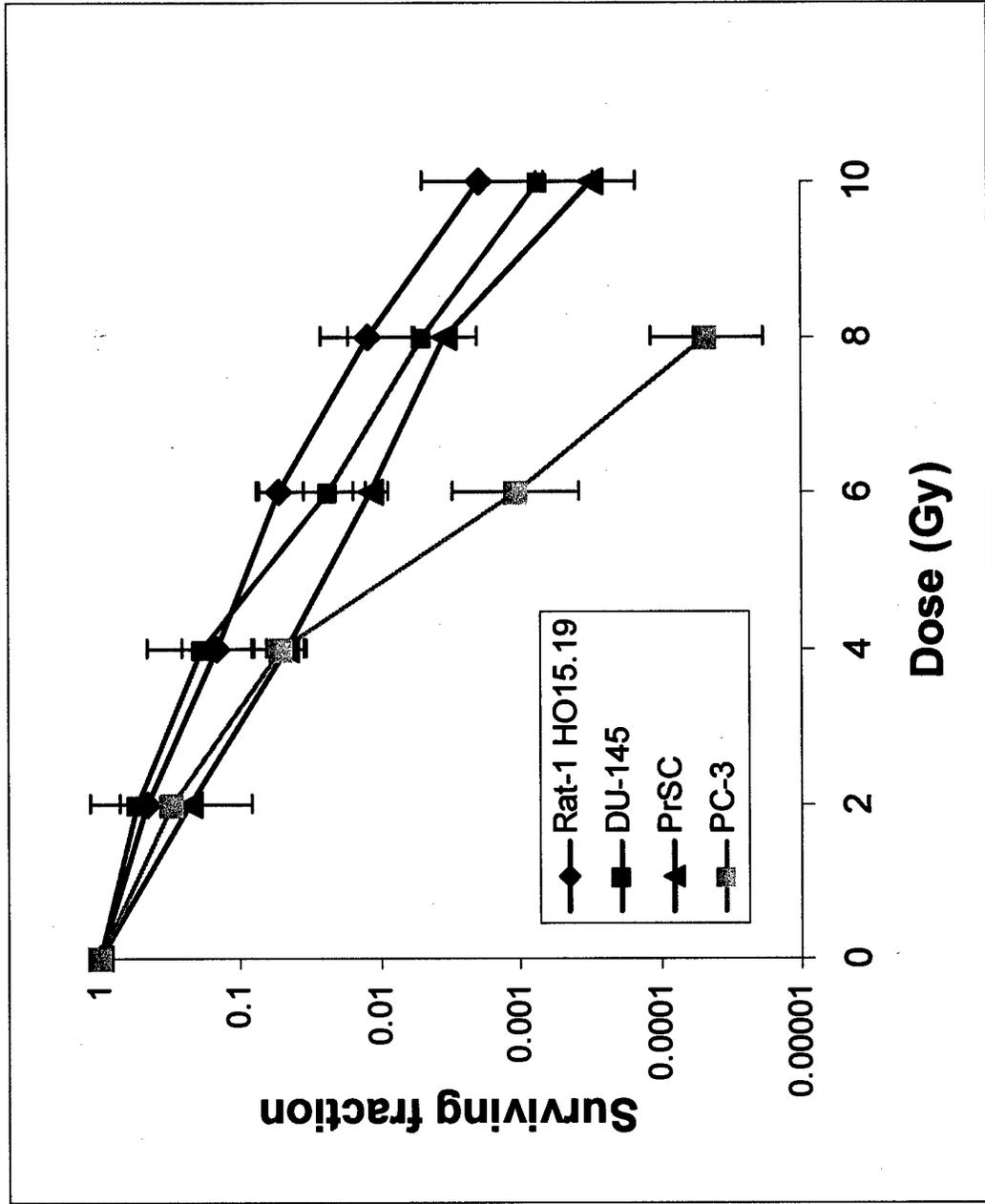
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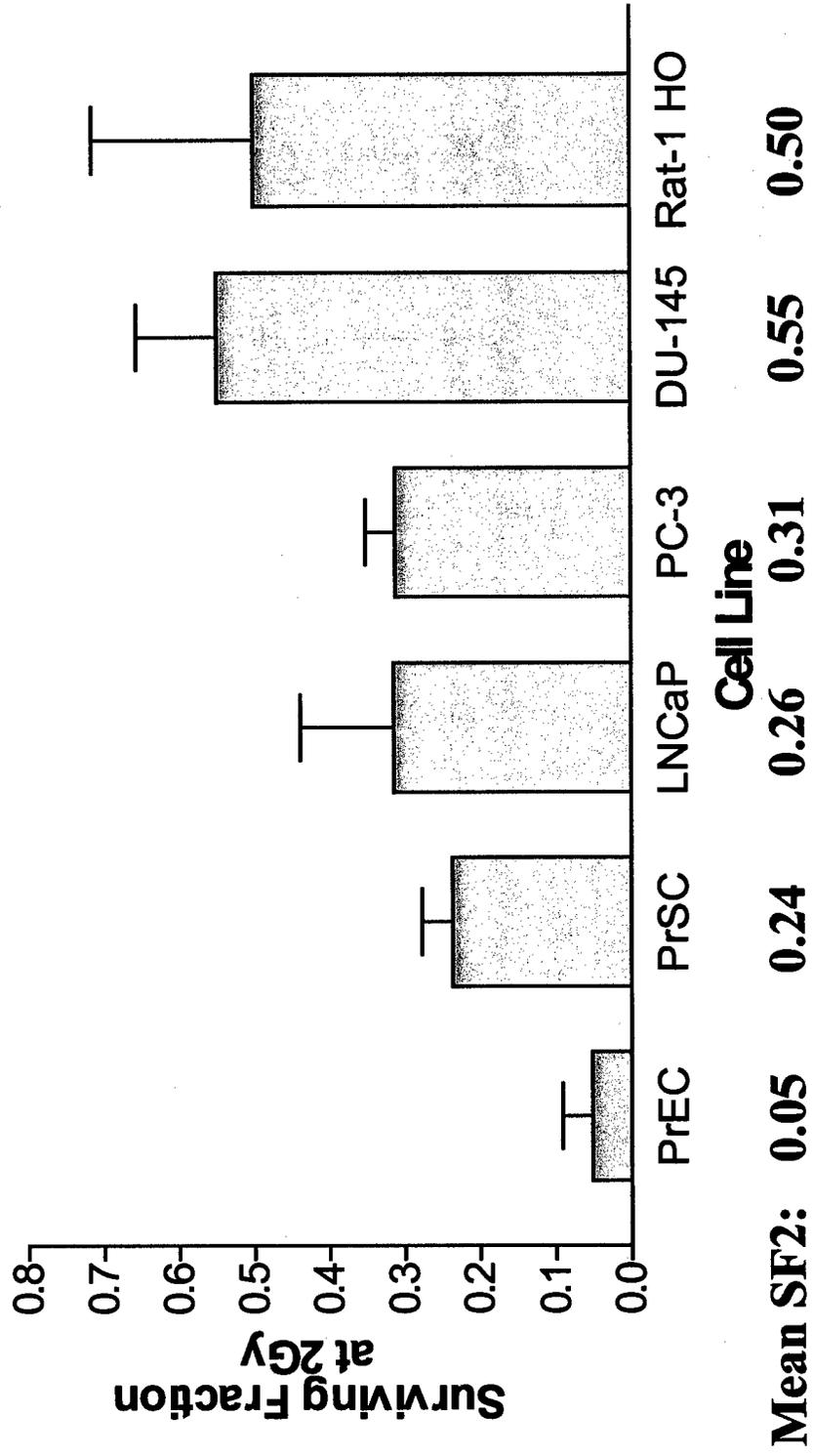
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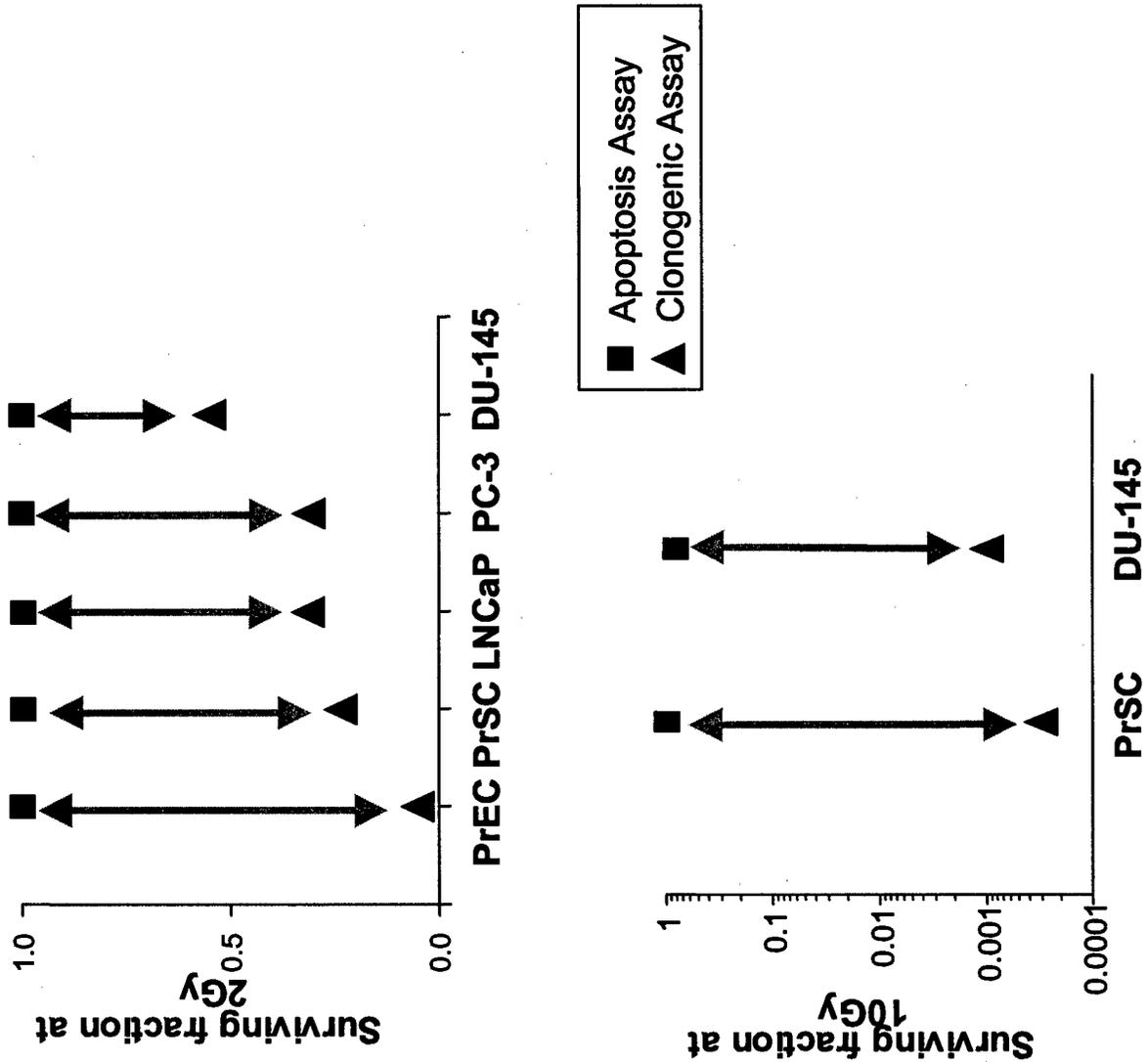
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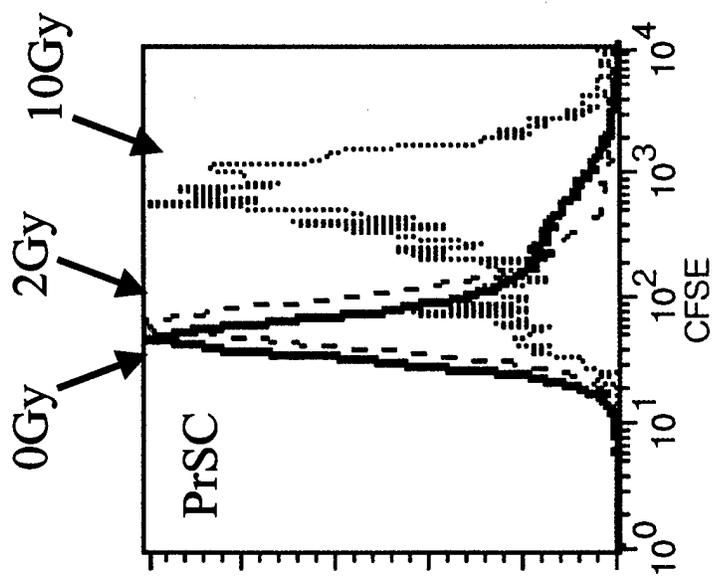
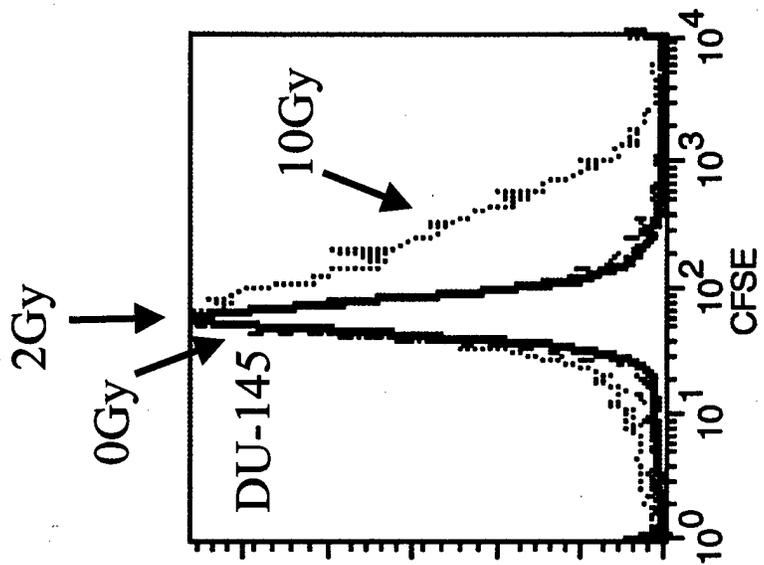


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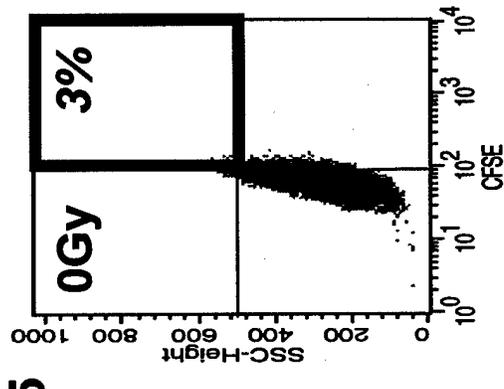
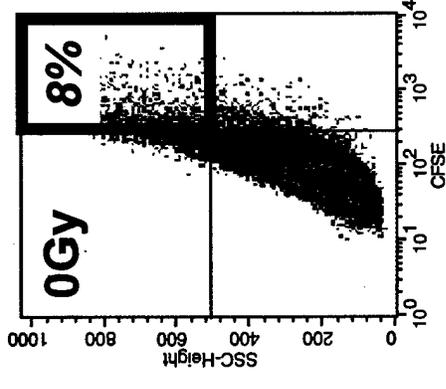
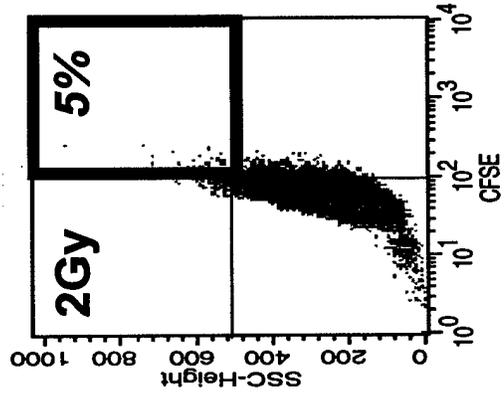
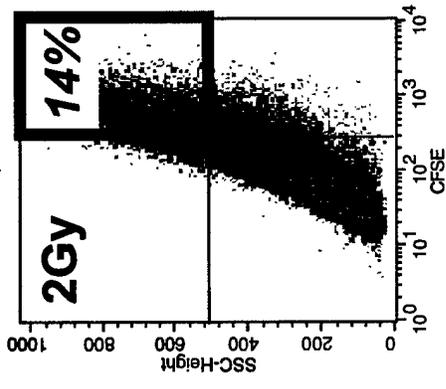
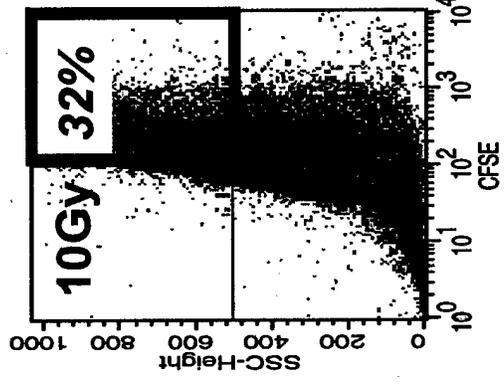
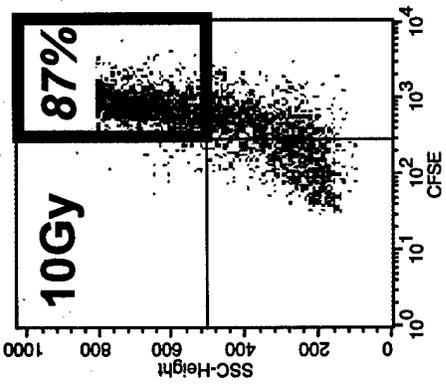


(c)





(a)



PrSC

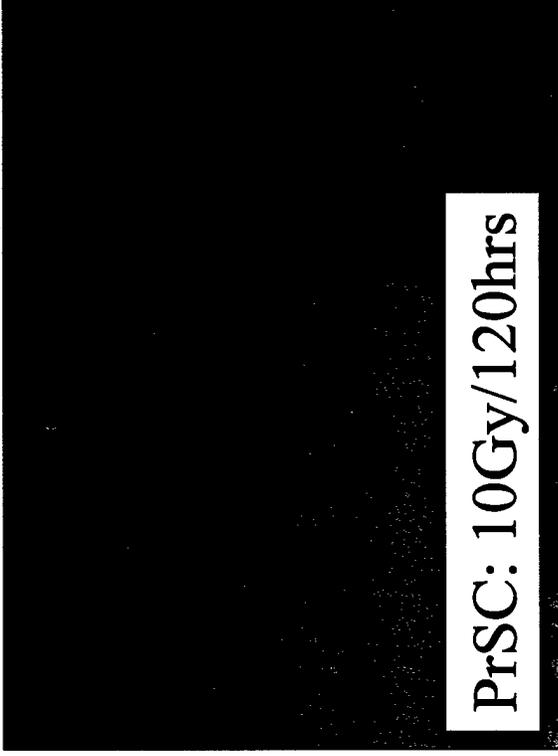
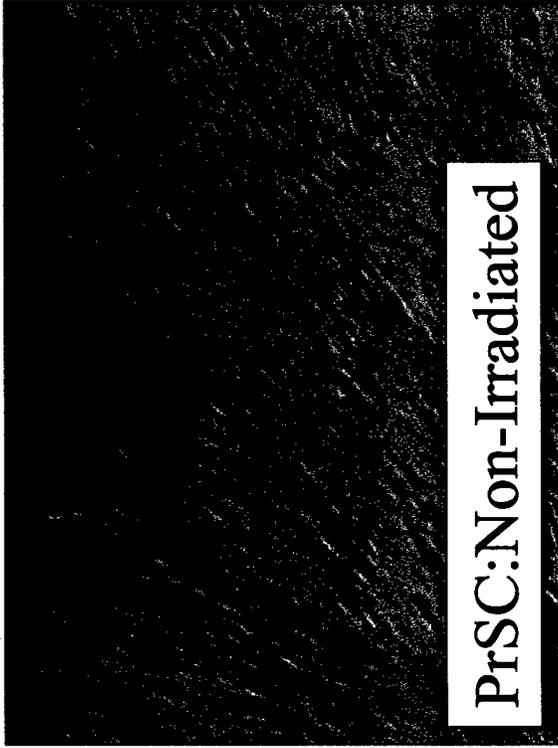
DU-145

(b)

Increasing granularity

Decreasing proliferation

(a)





## CURRICULUM VITAE

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1996 Fellowship of the Royal College of Physicians and Surgeons of Canada (FRCP(C.) Radiation Oncology)  
1/1995 Ph.D.; Molecular and Cellular Biology Program  
-11/1997 Department of Medical Biophysics University of Toronto

## APPOINTMENTS

### **University Appointments:**

- 6/1996-present Assistant Professor, Department of Radiation Oncology,  
University of Toronto
- 11/1998-present Cross-Appointed Associate Member, Department of Medical Biophysics,  
University of Toronto

### **Hospital/Staff Appointments:**

- 6/1996-present Staff Radiation Oncologist, Princess Margaret Hospital  
-Part-time practice-completing PhD: PMH-UHN Breast Group: 96/97
- 11/1998-present Scientist, Division of Experimental Therapeutics, Research Department,  
Ontario Cancer Institute
- 3/1999- present Full-time practice: PMH-UHN GU Group

## ADMINISTRATION/COMMITTEES

### **Department of Radiation Oncology/Research, PMH-UHN**

- 1994 Department of Radiation Oncology Representative for Association of Residents  
and Interns of Ontario (PAIRO), Princess Margaret Hospital
- 1999 – 2002 Secretary, DRO STAFF Monthly Meetings
- 1999 – present Member, Postgraduate Education Committee
- 1999 – present GU Rounds Organizer, PMH GU-Site Group
- 2000 - present Continuing Education Committee, DRO
- 2000 - present Section II Leader-Clinical Research Program-Prostate (UHN)
- 2000 - present Leader, Clinical Impact Team-Prostate (UHN)

### **University of Toronto**

- 1990 Member, Palliative Care Subcommittee of the Oncology Coordinating  
Council, University of Toronto
- 1991 Member, Aiken's Award Committee on Course Development and Coordination,  
Faculty of Medicine (Toronto)
- 1996 Departmental Representative, External Review for Department of Medical  
Biophysics, University of Toronto
- 1999 - present DRO-Departmental Representative, Faculty Council, University of Toronto

## Editorial/Review Responsibilities

- 2000-2001 External manuscript reviewer for:
- (i) International Journal of Radiation Oncology, Biology and Physics
  - (ii) Radiotherapy and Oncology
  - (iii) Cancer Research
  - (iv) Journal of Clinical Oncology
  - (v) Cancer Prevention and Detection
  - (vi) International Journal of Radiation Biology
  - (vii) Journal of the National Cancer Institute
  - (viii) Oncogene
  - (ix) Carcinogenesis
  - (x) Cancer letters
  - (xi) Cancer Epidemiology, Biomarkers and Prevention

## Federal/International Granting Bodies - Panels

- 2000-2003 Panel Member, NCIC Biomedical Awards Panel, Canada  
2000 Panel Member, NIH Biomedical Award Study Section, USA  
2001(+) Grant Panel Member, Prostate Cancer Research Foundation of Canada  
2001 CPCRI IDEA GRANT Panel, May, Toronto  
2002 CPCRI IDEA GRANT Panel, June, Toronto  
2002 US ARMY DOD Prostate Cancer Research Program Panel, July, Baltimore

## Meeting Chair/Co-Chair

- 2000 Chair; Session on "p53 Strategies", ESTRO Annual Meeting, Istanbul, Sept. 21  
2000 Co-Chair; Session on Gene Therapy, ESTRO Annual Meeting, Istanbul, Sept 21.  
2001 Chair, DNA Repair II, Radiation Research Society, San Juan, Puerto Rico, April  
2001 Chair, Poster Sessions, CARO  
2001 Chair, Poster Sessions, ASTRO  
2002 Co-Chair, CPC-BioNet National Satellite Meeting, San Francisco, April 2002.  
2002 Session Chair, NIH Bio-targeting Workshop, Washington, April 2002.  
2002 Chair, Teaching lecture "An introduction to proteomics, ESTRO Annual Meeting, Prague, September 17-21,

## Federal/International Panels

- 2000 Canadian Delegate, NIH Young Investigators Workshop, Bethesda, Maryland  
2000 Attendee, Controversies in Prostate Cancer Radiotherapy Meeting, Vancouver, BC  
2001 Panel Member, Astra-Zeneca Focus Group on Prostate Cancer, Miami, Jan. 2001  
2001 Invited Panel Member, Canadian Urology Association, Prostate Expert Panel  
2001 Course Director, UICC Cancer Research Training Course

- 2002 Member, Scientific Advisory Board, Prostate Cancer Research Foundation of Canada
- 2001-2002 Chair, National Task Force on Translational Sciences, Canadian Association for Radiation Oncology
- 2001-2002 ESTRO Scientific Panel Member and Planning Committee

**MEDICAL/SCIENTIFIC ORGANIZATIONS - MEMBERSHIPS**

American Association for Cancer Research  
 American Society for Therapeutic Radiology and Oncology  
 Canadian and Ontario Medical Associations  
 Canadian Association of Radiation Oncologists  
 Clinical Research Society of Canada  
 College of Physicians and Surgeons of Ontario  
 European Society for Therapeutic Radiology and Oncology  
 Radiation Research Society  
 Royal College of Physicians and Surgeons of Canada

**SCHOLARSHIPS & AWARDS (since 1994)**

- 1994 W.J. Simpson Award for Resident Research, Department of Radiation Oncology, University of Toronto
- 1994 1st Prize-Phillips Award for Resident Research  
 CARO-Royal College of Physicians and Surgeons Annual Meeting, Toronto, Canada
- 1995 Radiation Research Society Travel Award, ICRR, Wurzburg, Germany
- 1995 Junior Scientist Award, International Congress of Radiation Research Wurzburg, Germany
- 1995 AACR-Outstanding Poster Award, American Association for Cancer Research Annual Meeting, Toronto, Canada
- 1995 1st Prize-Phillips Award for Resident Research CARO-Royal College of Physicians and Surgeons of Canada, Annual Meeting, Montreal, Canada
- 1996 W.J. Simpson Award for Resident Research, Department of Radiation Oncology, University of Toronto
- 1996 1st Annual Brady Award for Resident Research, Joint Oncology Program, TTH/PMCCC, University of Toronto
- 1996 University of Toronto Resident Research Award, Canadian Society for Clinical Investigation and Medical Research Council of Canada

**ANIMAL PROTOCOL IN USE**

- 2001-2002 Studies in Molecular Carcinogenesis and Molecular Radiobiology in Genitourinary Oncology. University Health Network Animal Care Committee. #99-010.

## GRANTS

### i) Previous Grants Funded as Principal Investigator:

- 1998 - 1999      The molecular analysis of mammalian DNA double-strand break repair.  
Investigators: **R. Bristow (PI)**  
Sponsor:      Dean's Research Fund, University of Toronto.  
Amount:      \$9,791.68
- 1999 - 2000      PMH Foundation Start-up Funds  
Amount: \$100,000 (one-time award)
- 1999-2002      Molecular characterization of DNA-dsb repair in transformed cells  
Investigators: **R. Bristow (PI)**  
Sponsor:      National Cancer Institute of Canada, Operating Grant  
Amount :      \$ 320, 360 over 3 years
- 2000      Molecular and Clinical Aspects of DNA Repair  
Investigators: **R. Bristow (PI)**  
Sponsor:      Canada Foundation for Innovation, New Opportunities Fund  
Amount:      \$386,000 (one-time award; equipment/infrastructure only)
- 2001-2002      Molecular Radiobiology of Prostate Cancer: Utility and Feasibility of  
Novel Biomarkers  
Investigator:    **R. Bristow (PI)**  
Sponsor:      Prostate Cancer Research Foundation of Canada  
Requested Monies: \$18,350 over two years

### ii) Current Grants Funded as Principal Investigator:

- 2001-2004      Molecular determinants of radioresponse in prostate cancer  
Investigators: **Bristow R(PI)**, Warde P, Milosevic M, Lilge L, Squire J,  
Van Weerden W  
Sponsor: United States Department of Defence Prostate Cancer Research  
Amount: \$292,449 over 3 years
- 2001      A Molecular Radioresponse Program at PMH-UHN  
Investigators: P. Warde **Bristow R (Co-PI)**  
Sponsor:      GH Woods Foundation  
Seed Grant of \$50,000 over 2 years
- 2002      HDAC-Inhibition and Senescence as Potential Radiosensitizers in Prostate  
Cancer Radiotherapy.  
Investigators: **Dr. Robert Bristow (PI)**, Dr. Padraig Warde (Co-PI)  
Sponsor: Canadian Prostate Cancer Research Initiative (CPCRI) IDEA  
Grant  
Amount: \$39,800

2002-2003 Pilot Studies into the Anti-Apoptotic Protein, Survivin, as a Potential Target in Prostate Cancer Radiotherapy.  
Investigators: **Bristow R (PI)**, Sweet J, Squire J  
Sponsor: Abbot-CARO Uro-Oncologic Radiation Award (ACURA)  
Amount: \$30,500 yr renewable

**iii) Current Grants Funded as Co-Investigator/Collaborator:**

2000-2001 Molecular genetic mechanisms of prostatic oncogenesis: opportunities for new therapies and treatment options. Project II: Predicting individual treatment response  
Investigators: **Bristow R**, Milosevic M, Tsihlias J  
Sponsor: Princess Margaret Hospital Cancer Research Program  
Amount: \$70,000 in year 1

2000-2001 Implementing prostate core biopsies during radiotherapy to determine genetic and microenvironmental biomarkers relevant to prostate cancer radioresistance and metastatic spread  
Investigators: **Bristow R**, Milosevic M, Hedley D, Warde P, Khokha R  
Sponsor: Princess Margaret Hospital Cancer Impact Team  
Amount: \$114,000 in year 1

2001-2004 A Study of Transrectal Tumor Oxygen Measurements in Patients with Clinically Localized Prostate Cancer  
Co-Investigator (Translational DNA-protein studies);  
Investigators: M. Milosevic (PI), Toi A, Sweet J, **Bristow R**, Hedley D, Panzarella T, Hill R  
Sponsor: US Army Department of Defence Prostate Research Program  
Amount: 105,000/yr

2001-2006 A Micronutrient and Molecular Prostate Cancer Canadian Network  
Investigators: Fleshner N, **Bristow R (Co-Administrator)**, Gleave M, Rennie P, Klotz L, Khokha R, Squire J, Pollak M  
Sponsor: NCIC-Canadian Prostate Cancer Research Initiative Program Grant  
Amount: \$666,000/yr x 5 years renewable

2002 Equipment maintenance support for oncologic molecular micro-imaging (OMM)  
PI: Ming-Sound Tsao  
Co-applicants: **R. Bristow**, S. Done, D. Hedley, R. Hill, M. Ikura, R. Khokha, J. Squire, B. Wilson, S. Wong, G. Bradley.  
Amount: \$ 48,000 per year x 3 years

**iv) Clinical Trials as PI or Co-PI**

1999-2004 Phase III study of neoadjuvant hormonal therapy in patients with localized prostate cancer treated with escalated dose radiotherapy  
Investigators: Warde P, Catton C, Milosevic M, **Bristow R**, Catton P, Crook J, Gospodarowicz M, McLean M, Panzarella T  
Sponsor: AstraZeneca  
Amount: \$150,000

REB# 01-0555-C

2001 A Pilot Study of Pre-Operative Conformal Radiotherapy in 15 Patients Treated With Radical Prostatectomy – PMH Protocol  
Investigators: **Dr. Robert. Bristow (PI)**, Drs. P Warde (Co-PI), N. Fleshner (Co-PI)

REB# 01-0483-C

2000 Influence of tumor hypoxia on outcome following radiotherapy, and on prostate cancer malignant progression – PMH Protocol  
Investigators: Milosevic M (PI), Toi A, Sweet J, **Bristow R**, Hedley D, Panzarella T, Hill R.

REB#00-0443-C (Dr. Milosevic)

REB#01-0620-C (Dr. Bristow)

## PUBLICATIONS

### Refereed Publications

#### (i) *Published:*

1. **Bristow R**, Jang A, Peacock J, Chung S, Benchimol S, Hill RP: Acquired radioresistance in REF transformants expressing mutant p53 protein. *Radiat Res* 41:121-123, 1995.
2. Peacock J, Chung S, **Bristow R**, Hill R, Benchimol S: The p53-mediated G1 checkpoint remains intact in tumorigenic REF clones transformed by HPV16-E7 and EJ-ras. *Mol Cell Biol* 15(3):1446-1454, 1995.
3. **Bristow R**, Brail L, Jang A, Peacock J, Chung S, Benchimol S, Hill RP: P53-mediated radioresistance does not correlate with metastatic potential in tumorigenic REF cell lines following oncogene transfection. *Int J Radiat Oncol Biol Phys* 34(2):341-355, 1996.
4. **Bristow R**, Benchimol S and Hill RP: The p53 gene as a modifier of intrinsic radiosensitivity: implications for radiotherapy. *Radiother Oncol* 40: 197-223, 1996
5. **Bristow R.**, Laperriere N, Tator C, Milosevic M, Wong CS: Post-operative radiotherapy for dermoid tumours of the spine: a report of 3 cases. *J Neurooncol* 33:251-256, 1997
6. Reitmar A, Risley R\*, **Bristow R\***, Wilson T\*, Ganesh A, Jang A, Peacock J, Benchimol S, Hill RP, Fishel R, Mak TW, Meuth M: Mutator phenotype in Msh2 deficient mouse embryo fibroblasts. (\*1st four authors contributed equally) *Cancer Research* 57: 3765-3791, 1997.
7. **Bristow RG**, Hu Q, Jang A, Chung S, Peacock J, Benchimol S, Hill R: Radioresistant MTP53-expressing rat embryo cell transformants exhibit increased DNA-dsb rejoining during exposure to ionizing radiation. *Oncogene* 16(14): 1789-1802, 1998.
8. Warde P, O'Sullivan B, **Bristow RG**, Panzarella T, Keane TJ, Gullane PJ, Witterick IP, Payne D, Liu FF, McLean M, Waldron J, Cummings BJ: T1/T2 glottic cancer managed by external beam radiotherapy: the influence of pretreatment hemoglobin on local control. *Int J Radiat Oncol Biol Phys* 41(2): 347-353, 1998.
9. Jalali, F., Al-Rashid, S., Lilge, L. and **R. Bristow**; DNA Repair-related Protein Foci in Irradiated Human Fibroblasts: Preliminary Correlates to DNA-dsb rejoining and Radiosensitivity. *Radiotherapy and Oncology* 57: S35-38, 2000.
10. Milosevic M, Toi A, Sweet J, **Bristow R**, Warde P, McLean M, Crook J, Catton C, Catton P, Gospodarowicz M. Trans-rectal oxygen measurements in prostate cancer. *Clin Invest Med* 23 (Supp), S19, 2000.
11. Parker C, Milosevic M, Toi A, Sweet J, Panzarella T, Syed A, **Bristow R**, Catton C, Catton P, Crook J, Gospodarowicz M, Maclean M, Warde P, Hill R A polarographic electrode study of tumor oxygenation in localized prostate cancer; (Conditionally accepted, *Radiotherapy and Oncology*, 2002)

12. Gangopadhyay S, Jalali F, Reda D, Peacock J, **Bristow R** and Benchimol S: Expression of different mutant p53 transgenes in neuroblastoma cells leads to different cellular responses to genotoxic agents. *Exp Cell Res* 275(1):122-131, 2002.
13. Atsushi Hirao, Alison Cheung, Gordon Duncan, Andrew J. Elia, Andrew Wakeham, Hitoshi Okada, Talin Sarkissian, Jorge A. Wong, Takashi Sakai, Elisa de Stanchina, **Robert G. Bristow**, Penny A. Jeggo, Scott W. Lowe, Stephen J. Elledge and Tak W. Mak. Chk2 selectively regulates p53-mediated apoptosis in an ATM-independent manner (In press, *Molecular and Cellular Biology*, 2002).
14. Bromfield G, Fan R, Meng A, Kumaravel Ts, **Bristow RG**. Radiation-Induced Death Pathways in Prostate Cells: Role of Apoptotic and Non-Apoptotic Cell Death (In press, *Prostate Cancer and Prostate Diseases*, August 2002).
15. Cheung AMY, Prakash Hande M, Jalali F, Ming-Sound T, Skinnider B, Hirao A, McPherson JP, Karaskova J, Suzuki A, Wakeham A, Itie, A, Elia A, Squire J, **Bristow R**, Hakem R, Tak WM, Chromosomal aberrations and enhanced p53-dependent tumorigenesis in Brca2-deficient T cells (Conditionally accepted, *Cancer Research*, 2002).

### Manuscripts in Preparation

1. Al Rashid S T, Jalali F, Meng A, Lilje L, Benchimol S, Mak T and **Bristow RG**. the Ser15-phosphorylated form of the p53 protein: a sensor of DNA damage *in vivo*.
2. Jalali F, Al Rashid S, Meng A and **Bristow R**. DNA-dsb Rejoining in Fibroblast Strains of Differing p53 Status: Defect in Li-Fraumeni Syndrome?
3. **Bristow RG**, Peacock J, Jang A, Hill RP and Benchimol S: Radioresistance in murine ras-transformed cells due to gain of MTP53 function.

### Refereed Book Chapters

1. **Bristow R**, Hill RP: Molecular and Cellular Basis of Radiotherapy. In: The Basic Science of Oncology (3rd edition), ed I Tannock and RP Hill, McGraw-Hill Ltd.; New York, 1998.
2. Gospodarowicz MK, Warde P, **Bristow RG**: Definitive Radiation Therapy in Bladder Cancer. In: The Clinical Management of Bladder Cancer, ed R. Hall, 1999
3. Gospodarowicz, MK, O'Sullivan and **Bristow RG**: Host and Tumor-related Prognostic Factors, in UICC Handbook of Prognostic Factors; Chapter 6, pp. 71-94; (ed. MK Gospodarowicz) Wiley-Liss Inc., USA, 2001.
4. **Bristow, RG**, Blussien, H., de Klein, A. and van Gent, D. The PI3-Kinase family as Sensors and Signals for DNA Damage Responses; in Trends in Molecular Biology; Chapter 6, pp. 71-94; (ed. MK Gospodarowicz) Wiley-Liss Inc., USA, 2001.
5. Milosevic M, Gospodarowicz M, Jewett M, **Bristow R**, Haycock T. Intensity-modulated radiotherapy for lymph node metastases in bladder cancer. In: Gregoire V, Scalliet P, Ang KK (Eds). Clinical Target Volumes in Conformal and Intensity-Modulated Radiation Therapy. 2002.

### Non-Refereed Publications

1. **Bristow R**: Checks and balances: cell-cycle control and radiation oncology. Current Oncol 3(2):1-7, 1996
2. **Bristow R**, Benchimol S, Hill RPL: P53: protein expression or protein function ? Re: Awwad et al., IJROBP 34(2):323-332, 1996. Int J Radiat Oncol Biol Phys 35 (5):1123-1124, 1996 (letter).

## Abstracts Published & Presented

- (1) **Bristow R**, Sukhdeo, M. and D. Mettrick. "The effects of trichinella spirella infection on the crypt cell production rate in Wistar rats" Presented at the American Physiological Society, Niagara Falls, USA, October 1985.
- (2) **Bristow R.** and R.Hill. "In Vitro Prediction of Radioresponse and Predictive Assays". Prediction of Tumour Treatment Response Conference, Banff, April 1987.
- (3) **Bristow R.** and R.Hill. "In Vitro Prediction of Radioresponse and Predictive Assays". Radiation Research Meeting, Philadelphia, April 1988
- (4) **Bristow, R.** and R.Hill. "In Vitro Prediction of Radioresponse and Predictive Assays". Clinical Research Society of Toronto, April 1989.
- (5) **Bristow, R**, Savin, S., Hittelman, W. and W. Brock. "Chromosomal Damage Following XRT and 5-FU in CHO Cells". Presented at Radiation Research Society, New Orleans, April 1990.
- (6) Pardo, F., Kley, N., Fucarelli, A., **Bristow, R.**, et al." Biologic and Cell Kinetic Studies on primary and transformed rat embryo fibroblasts" Presented at the annual meeting of the American Society of Therapeutic Radiation Oncology, Miami, USA, October 1990.
- (7) **Bristow, R.**, Hunt, T. and F. Pardo. "Ras and radioresistance". International Congress of Radiation Research, Toronto, July 1991.
- (8) **Bristow, R**, Peacock, J., Benchimol, S. and R. Hill. "Effects of ras and mutant p53 on radioresistance and metastasis". National Medical Student Research Forum, Galveston, April 1991.
- (9) **Bristow, R.**, Peacock, J., Benchimol, S. and R. Hill. "Effects of ras and mutant p53 on radioresistance and metastasis". Symposium of Genetics of Radioresistance, Montreal, July 1991.
- (10) **Bristow, R.G.**, Peacock, J., Chung, S., Jang, S., Benchimol, S. and Hill, R.P. "Mutant p53-expression dependent changes in radioresistance in a REF transformant model" American Association of Cancer Research Special Conference on Perturbations in Cell Cycle Control and Genomic Stability, Banff, February 1994.
- (11) **Bristow, R.G.**, Peacock, J., Chung, S., Jang, A., Benchimol, S. and Hill, R.P. "Rat embryo cells transfected with a mutant p53 gene show increased radioresistance" Annual Meeting of the Radiation Research Society, Memphis, April 1994
- (12) Peacock, J., Chung, S., **Bristow, R.G.**, Hill, R.P., Benchimol, S. "The p53-mediated G1 checkpoint remains intact in rat mebroyo fibroblasts transfected with ras or HPV16-E7." The 7th International p53 Workshop, Muskoka, Ontario, June 1994.

- (13) **Bristow, R.G.**, Peacock, J., Chung, S., Jang, S., Benchimol, S. and Hill, R.P. "Acquired radioresistance in cells expressing a mutant p53 protein". Gene Induction and Adaptive Responses in Irradiated Cells: Mechanisms and Clinical Applications, Montreal, June 1994.
- (14) **Bristow, R.G.**, Peacock, J., Chung, S., Jang, S., Benchimol, S. and Hill, R.P. "Mutant p53 increases radioresistance in transfected rat embryo fibroblasts." Annual Meeting of the Royal College of Physicians and Surgeons of Canada, CARO session, Toronto, September 1994.
- (15) **Bristow, R.G.**, Peacock, J., Chung, S., Jang, S., Benchimol, S. and Hill, R.P. "Mutant p53 increases radioresistance in rat embryo fibroblast cell models". Annual Meeting of the American Society for Therapeutic Radiology and Oncology, San Francisco, October 1994.
- (16) **Bristow, R.G.**, Peacock, J., Chung, S., Jang, S., Benchimol, S. and Hill, R.P. "MTP53-mediated radioresistance in rodent tumour cells: Dominant-negative mechanism or gain of function?". Annual Meeting of the American Association for Cancer Research, Toronto, April 1995
- (17) **Bristow, R.G.**, Peacock, J., Chung, S., Jang, S., Benchimol, S. and Hill, R.P. "Mechanisms of MTP53-mediated radioresistance in rodent tumour cell models". Annual Meeting of the Royal College of Physicians and Surgeons of Canada, CARO session, Montreal, September 1995
- (18) **Bristow, R.G.**, Peacock, J., Chung, S., Jang, S., Benchimol, S. and Hill, R.P. "Mechanisms of MTP53-mediated radioresistance in rodent tumour cell models". International Congress of Radiation Research, Wurzburg, August 1995
- (19) **Bristow, R.G.**, Peacock, J., Jang, A., Penn, L., Hill, R.P., Benchimol, S. "Role of the c-myc gene in tumour progression following loss of p53 gene function". Annual meeting of the Royal College of Physicians and Surgeons of Canada, CARO session, Halifax, September 1996.
- (20) **Bristow, R.G.**, Jang, A., Peacock, J., Hill, R.P., Benchimol, S. "Radioresistant REF transformants expressing MTP53 are proficient in DNA dsb rejoining". Gordon Research Conference: "Molecular Biology of Radiation Oncology", Plymouth, New Hampshire, June 1997.
- (21) **Bristow, R.G.**, Jang, A., Peacock, J., Hill, R.P., Benchimol, S. "Increased DNA-dsb rejoining in tumour cells expressing MT-p53 protein", Poster: 21st Annual Meeting of the American Radium Society, Monte Carlo, May 1998.
- (22) **Bristow, R.G.**, Jang, A., Peacock, J., Hill, R.P., Benchimol, S. "Increased DNA-dsb rejoining in tumour cells expressing MT-p53 protein", Poster: Annual Meeting of Royal College of Physicians and Surgeons of Canada, Toronto, September 1998.

- (23) **Bristow, R.G.**, Jalali, F. Shim, K. Warde, P., and Benchimol, S. "Molecular Mechanisms of Radioresistance in Prostate Cancer", Poster; 3rd World Congress on Urological Research, Paris, France, September-October, 1999.
- (24) "DNA Repair-related Protein Foci in Irradiated Human Fibroblasts: Preliminary Correlates to DNA-dsb Rejoining and Radiosensitivity", ESTRO-MITRE Conference, Brussels, Belgium, Dec, 2000.
- (25) Jalali F, **Bristow, R G**. "Characterization of DNA-DSB Repair in Fibroblasts With Altered p53 Status", Radiation Research Society, San Juan, Puerto Rico, April 2001.
- (26) Bromfield, G P, **Bristow, R G**. "Radiation-Induced Cell Death Pathways in Normal and Malignant Prostate Epithelial Cells", Radiation Research Society, San Juan, Puerto Rico, April 2001.
- (27) Al Rashid S T, Jalali F, Lilge L, **Bristow R G**. "Ser15-phosphorylated p53: a Sensor of DNA-damage Following Ionizing Radiation", Radiation Research Society, San Juan, Puerto Rico, April 2001.
- (28) Al Rashid S T, Jalali F, Lilge L, **Bristow R G**. "The p53 Protein as a Direct Sensor of DNA-Damage in Human Cells Following Ionizing Radiation", CARO Meeting, Quebec City, September 2001 (abstract accepted).
- (29) Bromfield, G P, **Bristow, R G**. "Relative Importance of Non-Apoptotic and Apoptotic Cell Death Pathways in Irradiated Prostate Cells", CARO Meeting, Quebec City, September 2001 (abstract accepted).
- (30) Al Rashid S T, Jalali F, Lilge L, **Bristow R G**. "Ser15-phosphorylated p53 as a Sensor of DNA-damage Following Ionizing Radiation", ESTRO/ECCO Meeting, Lisbon, Portugal, October 2001 (abstract accepted).
- (31) Al Rashid S T, Jalali F, Lilge L, **Bristow R G**. "Ser15-phosphorylated p53 as a Sensor of DNA-damage Following Ionizing Radiation", ASTRO Meeting, San Francisco, November 2001 (abstract accepted).
- (32) Bromfield G, Fan R, Meng A, Kumaravel Ts, **Bristow R G**. "Radiation-Induced Death Pathways in Prostate Cells: Role of Apoptotic and Non-Apoptotic Cell Death", American Association for Cancer Research, San Francisco, April 2002.
- (33) Al Rashid S T, Jalali F, Lilge L, **Bristow R G**. "Ser15-phosphorylated p53 as a Sensor of DNA-damage Following Ionizing Radiation", Radiation Research Society, Reno Nevada, April 2002
- (34) **Bristow R. G.**, Bromfield G, Fan R, Meng A, Kumaravel TS. "Radiotherapy-induced death pathways in prostate cells: Apoptosis versus permanent cell cycle arrest", 57<sup>th</sup> annual CUA Meeting, Newfoundland, June 2002. (abstracted accepted)

- (35) Parker C, Panzarella T, Catton C, **Bristow R**, Crook J, Gospodarowicz M, McLean M, Michael Milosevic M and Warde P “The Effect of Haemoglobin Level on Biochemical Outcome following Radiotherapy in Localised Prostate Cancer”, CARO, Toronto, 2002.
- (36) **Bristow RG**, Fan R, Kumaravel TS, Bromfield G, Jalali F, Meng A. “DNA Repair in normal and malignant prostate epithelial tissues: implications for genetic stability and radiotherapy”, ESTRO, Prague, September 2002.

## TEACHING DOSSIER

### A) POSTGRADUATE MEDICAL EDUCATION

#### 1) Resident Training – Department of Radiation Oncology (Toronto)

- 1994 Department of Radiation Oncology, University of Toronto  
1) "Management of acute airway and superior vena caval obstruction"(PGY2)  
2) "Understanding the 4 R's of radiotherapy" (PGY3-4)  
3) "The molecular biology of cancer with respect to radiotherapy" (PGY5)
- 1996 1) PGY2 Resident teaching session, Radiation Oncology, University of Toronto  
-“Management of acute airway and superior vena caval obstructions”  
2) Resident Planning Drills - November 1996
- 1999 Resident rotation teaching: Dr. Jennifer Knox (Medical Oncology)  
RCPSC Mock Drill: Andrew Bailey (Radiation Oncology)  
Mock Examiner: DRO-Resident End of Year Planning Exams (Drs. Ian Poon, and Andrew Loblaw)
- 2000-2001 Senior DRO Resident’s Tutorial Sessions-“Clinical Radiobiology” 4 x 2 hours  
Junior DRO Residents Tutorial-“Molecular Radiobiology” 1 x 2 hrs
- 2002 (Residents) Medical Oncology Teaching. “Essential Elements of Radiation Oncology” x1hr – January 2002.
- 2002 Junior DRO Residents (PGY1 & 2) Tutorial – Radiobiology, “Molecular Radiobiology” Part I & II” 2 x 2hrs – January & February 2002.
- 2002 DRO Resident – Dr. Jackie Spayne
- 2002 DRO Fellow - Dr. Iain Ward
- 2002 DRO Fellow - Dr. Andrew Coleman

#### 2) Resident Training – External/National

- 1997-2001 Lecturer, Applied Radiobiology Resident Seminar "Molecular Biology, University of British Columbia and Washington
- 2000 University of Western Ontario, London, Ont. (8 hrs lecture)  
Radiobiology Review Course, January, 2000

### B) SCHOOL OF GRADUATE STUDIES, UNIVERSITY OF TORONTO

#### 1) Course Lecturer/Director:

- 1996-1997 MBP 1018Y, Department of Medical Biophysics, University of Toronto (2 Hours each): “Radiobiology and Breast Cancer”; "Radiation Response in Lymphoma and Leukemia"
- 1999–2001 MBP 1008, University of Toronto: Fundamentals in Cell Biology II (4 x 2 hr lectures in 2000; 1 x 2 hours in 2001; exam marking)
- 2001-2002 Course Director, MBP1018Y, Designed and administrated Course; 5 x 2 hr lecturers, set and marked examinations

*Teaching Dossier continued*

**2) Department of Medical Biophysics Supervised:**

- (i) Summer Students:
  - a) Katherine Shim (Summer 1999)
  - b) Wissam Assaily (Summer 1999)
  - c) Harshna Patel (Summer 2001 & 2002)
  
- (ii) Graduate Students:
  - MSc candidate – Gillian Bromfield (1999-2002; graduated)
  - PhD Candidate – Shahnaz Al-Rashid (1999-current; NCIC Studentship)
  - MSc Candidate – Dr. Andrew Coleman (2002-present)
  
- (iii) Post-Doctoral Fellows:
  - Dr. R. Fan (January, 2001-current)
  - Dr. T. Kumaravel (April, 2001-current; CPCRI-NCIC Fellow)
  
- (iv) Student committee member of following students (start-date in parentheses):
  - 2000-M.Sc - Lynn Shepherd (Supervisor: Dr. Ian Tannock)
  - 2000-PhD - Victor Yang (Supervisor: Dr. Brian Wilson)
  - 2000-MSc. - Patrica Ruozo (Supervisor: Dr. David Hedley)
  - 2000-PhD - Rebecca Gladdy (Supervisor: J. Danska/c. Guidos)
  - 2001-M.Sc. - Irina Matei (Supervisor: J. Danska/C. Guidos)
  - 2001-M.Sc. - Jorge Wong (Supervisor: Dr. K. Vallis)
  - 2001-M.Sc. - Wissam Assaily (Supervisor: Dr. Benchimol)
  - 2001-M.Sc. - Phillip Wong (Supervisor: Dr. I. Tannock)
  - 2001-M.Sc. – Jennifer Lau (Supervisor: Dr. D. Hedley)
  - 2001-M.Sc. – Richard Chahwan (Supervisor: Dr. Hakem)
  - 2001-M.Sc. – Carlos Rendon (Supervisor: Dr. Lothar Lilge)
  - 2002-MSc – Carol Lee (Supervisor: Dr. Malkin – HSC)

**C) UNDERGRADUATE – UNIVERSITY OF TORONTO**

**1) Individual Teaching:**

- 1996-1997 2 University of Toronto Medical Students; Clinical teaching x 1 month each
- 1998 University of Toronto 4<sup>th</sup> year B.Sc. Student (Bodour Salhia), PSL497F, Department of Physiology, University of Toronto-basic science mentor
- 10/1998- University of Toronto BSc. in Radiation Services
- 10/1999
  - 1) Predictive Assays (1 hr lecture)
  - 2) Molecular Radiobiology (1 hr lecture)
- 1999 Medical Student Teaching/Rotation: Greg Czarnotta, University of Toronto
- 2000 Medical Student Teaching/Rotation: David Robertson, University of Toronto
- 2002 Medical Student Teaching: Danny Vespini (4<sup>th</sup> year student)
- 2002 Medical Student Teaching: Alan Andrew (4<sup>th</sup> year, Ivan Smith Scholarship)

## 2) Course Lecturing:

- 2000 Course Lecturer – University of Toronto, ANA 401S, Cancer Biology (2 x 2 hr lectures; exam and written proposal marking)
- 2001 Med School: Molecular Mechanisms in Cancer I and II (Pathobiology Course), Faculty of Medicine, November 2001.

## Continuing Medical Education (CME) MEETINGS ATTENDED:

- 1988 CME-Pain Symposium, Medico-Legal Society, University of Toronto
- 1989 CME-HIV Infection, Mt. Sinai Hospital, University of Toronto
- 1991 CME: Update in Haematology/Oncology, Mayo Clinic, Scottsdale, AZ
- 1993 CME: Clinical Trials in Medicine, University of Toronto
- 1994 CME: Update in Radiation Oncology; University of Toronto
- 1994 CME Workshop on Methods in Medical Education/Teaching, TSRCC, University of Toronto
- 1995/1998 CME Workshop: Genito Urologic Oncology, University of Toronto
- 1999 CME Update: Trends in Radiation Oncology, University of Toronto
- 2002 CME Workshop on UroOncology,

## LOCAL/NATIONAL/INTERNATIONAL ROUNDS PRESENTED

- 1995 Grand Rounds, PMCCC "P53 and therapeutic response"
- 1995 University of Toronto Department of Radiation Oncology Rounds-"Primer on Molecular Radiobiology"
- 1997 PMCC Breast Group Rounds, "P53 as a determinant of Therapeutic Response in breast cancer: fact or fiction ?
- 1997 Research Rounds, Medical Genetics Centre, Erasmus University Rotterdam, Bristow, R.G., von Gent, D. "Molecular mechanisms of non-homologous recombination in DNA dsb repair following ionizing radiation", Oct 13, 1997
- 1998 Leiden University, The Netherlands. Joint Erasmus University-Leiden University MGC Rounds, "Micro-homology Usage as a Component of DNA-dsb repair", May, 1998.
- 1998 Erasmus University, Rotterdam. Departmental Research Rounds. "Linear DNA Constructs as Probes for DNA-dsb Repair Pathways". June, 1998.
- 1999 Experimental Therapeutics Seminar, Molecular Mechanisms of DNA-dsb repair", OCI, February, 1999.
- 1999 DRO-PMH Rounds: "DNA-DSB Repair: A discrete or indiscrete affair?" April/99.
- 1999 "Conformal radiotherapy", Oshawa Urologic Surgeons Meeting; sponsored by Zeneca, May/99.
- 2000 DRO-PMH Rounds, "Genetics of Connective Tissue Disorders: Relationship to DNA repair?"

2002

UHN Prostate Cancer Training Course, "Individualizing Prostate Cancer Radiotherapy: Focusing on Genetics Rather than Politics", PMH April/02

### VISITING PROFESSORSHIPS/INVITED LECTURES

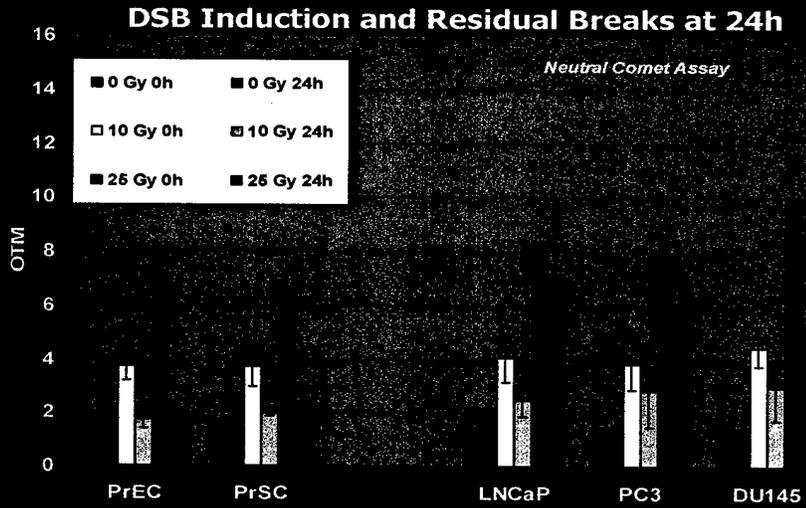
- (1) "P53 as a determinant of therapeutic response: fiction or function" ? Department of Radiation Oncology Visiting Professor, University of Pennsylvania, Philadelphia, December 17, 1996.
- (2) "P53 protein as a modifier of DNA repair", Invited Lecture, Dept. of Genetics, University of British Columbia, Nov. 1997.
- (3) "Apoptosis vs. Necrosis in Cancer Research", Invited Lecture, NCIC Palliative Care Meeting, Vancouver, B.C. , Nov. 1997.
- (4) "P53 as a determinant of therapeutic response", Invited Lecture, CERRO/ESTRO Meeting, Les Menuires, France, Jan. 1998.
- (5) "P53 and radioresistance: A role for DNA repair?" Invited Lecture, Department of Experimental Oncology, Netherlands Cancer Institute, Amsterdam, The Netherlands, May 1998.
- (6) "P53 and radioresistance: A role for DNA repair?" Invited Lecture, Department of Radiation Oncology and Radiobiology, Catholique University, Brussels, Belgium, June 1998.
- (7) "P53 and radioresistance: A role for DNA repair?" Invited Lecture, Department of Experimental Oncology, University of Aarhus, Aarhus, Denmark, May 1998.
- (8) "Increased DNA-dsb rejoining in tumour cells expressing MT-p53 protein", Invited Lecture, Second Wolfsberg Conference in Molecular Radiobiology, Ermatingen, Switzerland, May 1998.
- (9) "Mammalian DNA Double-Strand Break Repair: A Discrete, or Indiscrete, Affair?", Invited Lecturer, Molecular Biology Refresher Course, American Society of Therapeutic Radiation Oncology, New York, January 15-16<sup>th</sup>, 1999.
- (10) "P53 and DNA-dsb repair", Invited Lecture, CERRO/ESTRO Meeting, Les Menuires, France, Jan. 1999
- (11) "G1 Cell Cycle Checkpoint and DNA Damage Response", Invited Review Lecture; Future of Radiobiology in Radiation Oncology International Symposium, Department of Radio-Oncology, June, 1999, University of Essen, Germany.
- (12) Invited Speaker/Debator: Annual Debate: CME Course in Trends in Radiation Oncology, Univeristy of Toronto, Toronto. May 1999

- (13) "MTP53 Increases Cell Survival By Increasing DNA-dsb rejoining", Invited Lecture, 1<sup>st</sup> Annual Mid-West DNA Repair Meeting; University of Michigan, May, 1999.
- (14) Visiting Professor, " Genetics Determinants of Radiation Curability", Department of Radiation Oncology, University of British Columbia, February 2000.
- (15) "Modifying DNA repair capacity as genetic target for radiotherapy", Invited Lecture, First International Conference on Translational Research and Pre-Clinical Strategies in Radio-Oncology, Lugano, Switzerland, March 5-8<sup>th</sup>, 2000.
- (16) "p53 as therapeutic target", Invited Lecture, First International Conference on Translational Research and Pre-Clinical Strategies in Radio-Oncology, Lugano, Switzerland, March 5 – 8<sup>th</sup>, 2000
- (17) "P53-DNA damage and repair responses" Invited Speaker/Review, European Society for Therapeutic Radiation Oncology, Istanbul, Sept. 21, 2000.
- (18) " DNA-dsb Repair Foci: Implications for DNA Biomarkers: Invited Speaker, ESTRO-CERRO Annual Meeting, Les Menuires, France, March 2001
- (19) "The p53 tumour suppressor protein and DNA repair: new tricks for the old dog?": Invited Speaker, University of Pennsylvania Medical Center, April 2001
- (20) "The p53 tumour suppressor protein and DNA repair: new tricks for the old dog?" Invited Speaker, University of Ottawa, April 2001
- (21) "DNA Repair and Carcinogenesis" UICC Cancer Research Training Course, Invited Speaker and Course Director, Toronto, May 2001
- (22) "New Aspects of Radiation Oncology in Prostate Cancer", Astra-Zeneca Update on Urology, Invited Speaker, Deerhurst, Ontario, May 2001
- (23) "Molecular Biomarkers in Radiation Oncology", Target Insight DRO-CME Meeting; Invited Speaker; May 2001
- (24) "The p53 tumour suppressor protein and DNA repair: new tricks for the old dog?" Invited Speaker, Amgen Scientific Retreat, Collingwood Ontario, April 2001
- (25) "Combined Modality Therapy for Prostate Cancer"; Invited Speaker, Canadian Association of Urology Annual Meeting, Toronto, June, 2001
- (26) "New techniques in external beam radiation treatment for prostate cancer" Invited Speaker, Bierstock Family Symposium, Toronto, September 2001.
- (27) "The New Genetics and Radiation Oncology: Defining a Molecular Therapeutic Ratio" Invited Speaker, Cobalt 50<sup>th</sup> Anniversary in London, Advances in Radiation Therapy Symposium, London, Ontario, October 2001.

- (28) Bristow R. "Novel Biomarkers of DNA Damage Responses: Implications and Limitations for Predicting Radiotherapy Response", Invited Speaker, NIH Bio-targeting Workshop. Washington, April 2002.

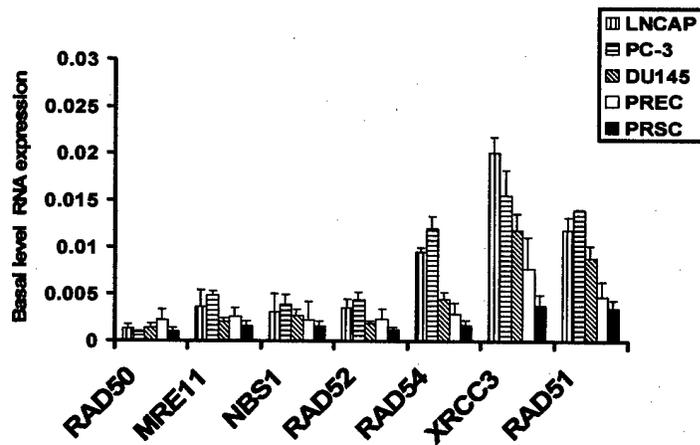
**FIGURE 1:**

Neutral comet assay results show increased residual DNA breaks at 24 hours following irradiation (10 and 25 Gy; aerobic, RT) in malignant prostate cells in comparison to normal repair kinetics in normal prostate cells. Similar findings were observed utilizing the alkaline comet assay.



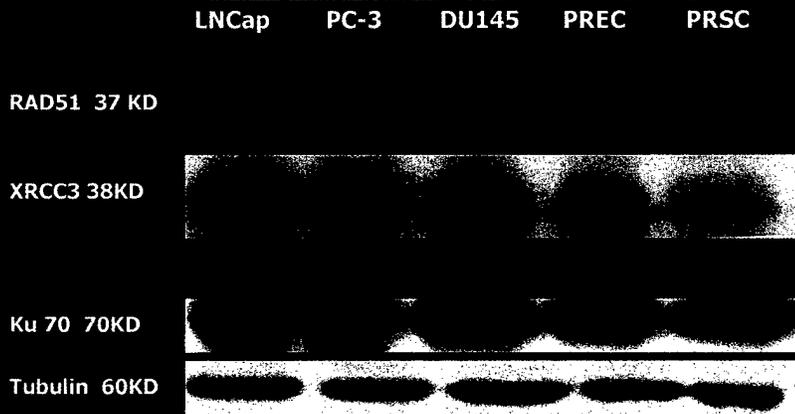
**Figure 2a**

RNA Protection Analyses suggests increased basal level of transcription for homologous recombination genes involved in DNA repair in malignant cell lines compared to normal cell lines. Error bars represent SE.



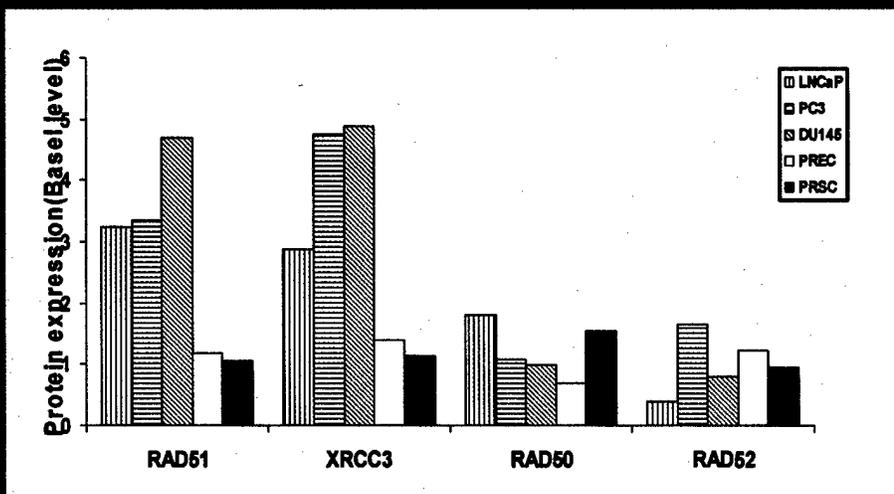
**Figure 2b**

Increased HR-Associated Protein Expression in malignant prostate cell lines compared to tubulin loading controls; these results correlated to RNA overexpression profile seen in Figure 2.



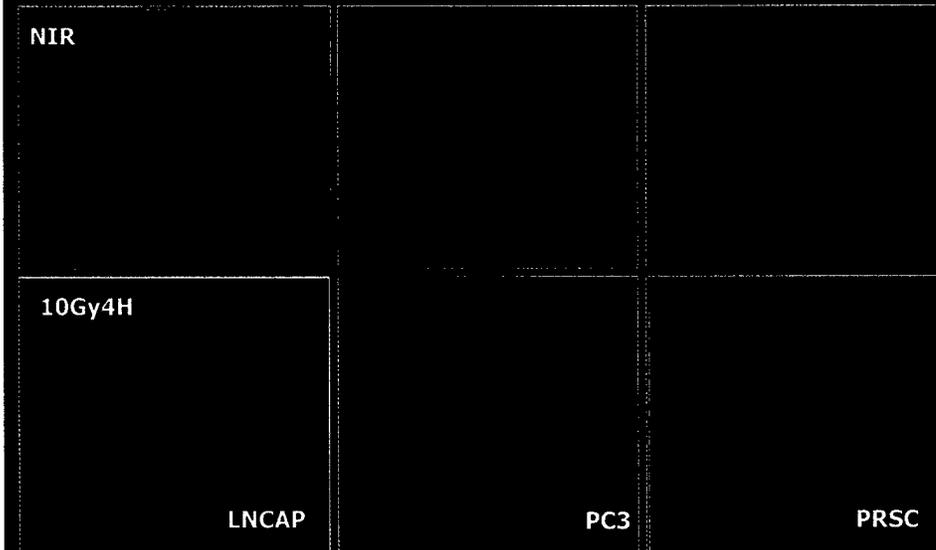
**Figure 2c**

Increased HR-Associated Protein expression in malignant prostate cell lines based on densitometry of Western Blot analyses shown in Figure 2b with b-tubulin as loading control



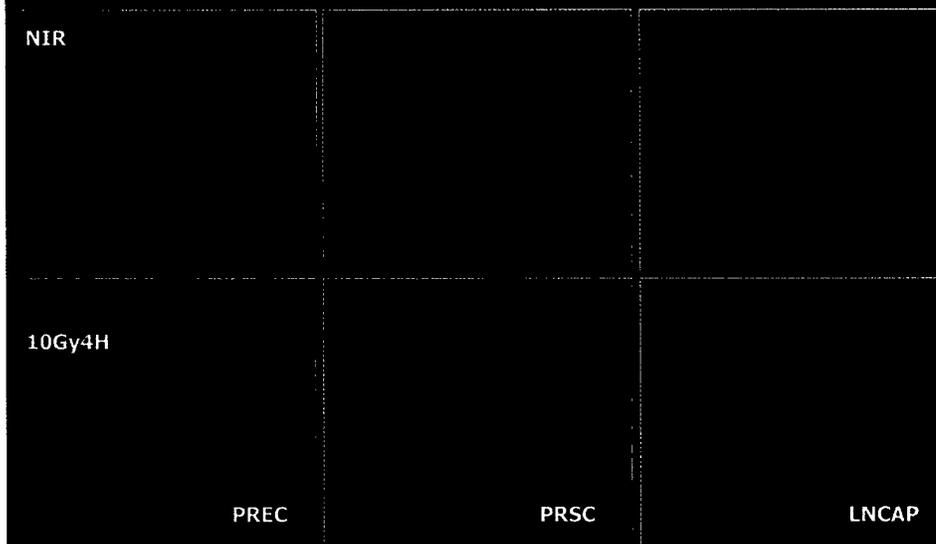
### Figure 3a

Positive control for irradiation-induced nuclear foci: Formation of gamma-H2AX protein is normal; dose-responsive, in normal and malignant prostate cell lines. Cells were stained with antibodies to H2AX post 10Gy XRT at 4 hrs; counterstained with DNA-DAPI stain.



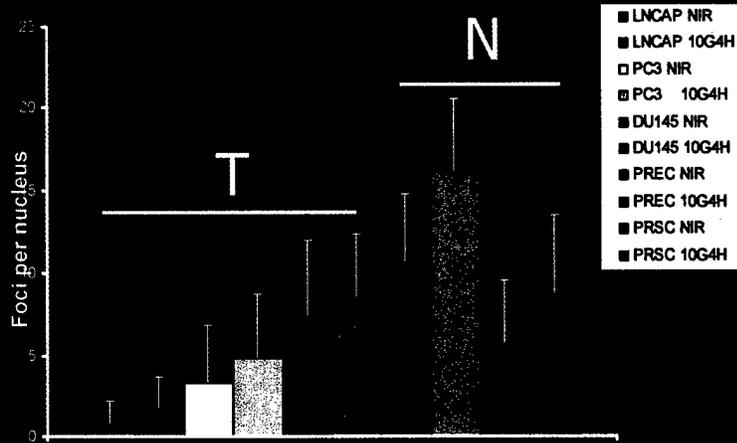
### Figure 3b

Rad51 foci formation is defective following XRT (same conditions as in Figure 3a) in malignant LNCaP, PC-3 And DU-145 cells and is not dose-responsive; evidence for nuclear transport defect



**Figure 3c**

Quantitation of Data shown in Figure 3b: Decreased IRIF Rad51 Nuclear Response Following 10 Gy at 4 hours in malignant prostate cell lines



**Figure 4**

Immunohistochemistry for HR-associated repair proteins in PC-3 xenografts growing in nude mice and irradiated with 20 Gy; removal of tissues at 24 hours post irradiation and formalin fixation. Staining for rad51 and BRCA2 proteins show increased intensity post-XRT. Similar results were observed for rad50.

