The Response of CD24\(^{-/low}\)/CD44\(^{+}\) Breast Cancer–Initiating Cells to Radiation

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**Background:** If cancer arises and is maintained by a small population of cancer-initiating cells within every tumor, understanding how these cells react to cancer treatment will facilitate improvement of cancer treatment in the future. Cancer-initiating cells can now be prospectively isolated from breast cancer cell lines and tumor samples and propagated as mammospheres in vitro under serum-free conditions. **Methods:** CD24\(^{-/low}\)/CD44\(^{+}\) cancer-initiating cells were isolated from MCF-7 and MDA-MB-231 breast cancer monolayer cultures and propagated as mammospheres. Their response to radiation was investigated by assaying clonogenic survival and by measuring reactive oxygen species (ROS) levels, phosphorylation of the replacement histone H2AX, CD44 levels, CD24 levels, and Notch-1 activation using flow cytometry. All statistical tests were two-sided. **Results:** Cancer-initiating cells were more resistant to radiation than cells grown as monolayer cultures (MCF-7: monolayer cultures, mean surviving fraction at 2 Gy [SF\(_{2Gy}\)] = 0.2, versus mammospheres, mean SF\(_{2Gy}\) = 0.46, difference = 0.26, 95% confidence interval [CI] = 0.05 to 0.47; \(P = .026\); MDA-MB-231: monolayer cultures, mean SF\(_{2Gy}\) = 0.5, versus mammospheres, mean SF\(_{2Gy}\) = 0.69, difference = 0.19, 95% CI = −0.07 to 0.45; \(P = .09\)). Levels of ROS increased in both mammospheres and monolayer cultures after irradiation with a single dose of 10 Gy but were lower in mammospheres than in monolayer cultures (MCF-7 monolayer cultures: 0 Gy, mean = 1.0, versus 10 Gy, mean = 3.32, difference = 2.32, 95% CI = 0.67 to 3.98; \(P = .026\); mammospheres: 0 Gy, mean = 0.58, versus 10 Gy, mean = 1.46, difference = 0.88, 95% CI = 0.20 to 1.56; \(P = .031\)); phosphorylation of H2AX increased in irradiated monolayer cultures, but no change was observed in mammospheres. Fractionated doses of irradiation increased activation of Notch-1 (untreated, mean = 10.7, versus treated, mean = 15.1, difference = 4.4, 95% CI = 2.7 to 6.1, \(P = .002\)) and the percentage of the cancer stem/initiating cells in the nonadherent cell population of MCF-7 monolayer cultures (untreated, mean = 3.52%, versus treated, mean = 7.5%, difference = 3.98%, 95% CI = 1.67% to 6.25%, \(P = .009\)). **Conclusions:** Breast cancer–initiating cells are a relatively radiosensitive subpopulation of breast cancer cells and increase in numbers after short courses of fractionated irradiation. These findings offer a possible mechanism for the accelerated repopulation of tumor cells observed during gaps in radiotherapy. [J Natl Cancer Inst 2006;98:1777–85]

One view of cancer is that it may arise from a single cell that has the ability to self-renew and thus to maintain the growth of a tumor, whereas the majority of its cellular progeny does not. There is increasing evidence that such a cell population exists and that these cells can be prospectively identified in brain tumors (1), breast cancer (2), prostate cancer (3), and melanoma (4). A considerable effort is going into determining unique properties of these cells with the assumption that this cell population, more than any other, will determine the outcome of cancer treatment. Because such cells might be expected to share properties with adult stem cells in normal tissues, they are often termed cancer stem cells (5). However, in spite of old (6) and more recent (1,2,7–9) evidence that cancer stem cells exist, there is still a dearth of good phenotypic markers for such cells. In addition, many of the self-renewing cancer cell populations that are studied may also contain early progenitor cells that are derived from cancer stem cells but are also able to initiate and maintain tumor growth. Therefore, we join others (2) in preferring to use the term cancer-initiating cells. In breast cancer, a population of CD24\(^{-/low}\)/CD44\(^{+}\) cells has been isolated that is highly enriched for cancer-initiating cells (2). This population is 1000 times more tumorigenic than cell populations that are depleted of CD24\(^{-/low}\)/CD44\(^{+}\) cells, and injection of as few as 200 cells leads to tumor formation in SCID mice (2). Breast cancer–initiating cells can be established from patients’ surgical specimens or breast cancer cell lines and can be propagated in vitro as nonadherent mammospheres (7).

Stem cell properties in normal tissues are tightly regulated by the Wnt, Shh, and Notch signaling pathways (10,11). In addition, overexpression of Notch-1 was observed in breast cancer specimens, and the level of expression was associated with prognosis (12). Activation of the Notch-1 pathway is initiated by the binding of Notch-1 ligands, e.g., Jagged-1, to the extracellular domain of Notch-1. This binding causes a conformational change in Notch-1 that allows the protease tumor necrosis factor alpha converting enzyme to cleave the extracellular domain of the molecule. Notch-1 is thereafter processed by \(\gamma\)-secretase–regulated intramembrane proteolysis, which allows the intracellular domain of Notch-1 (Notch-1 ICD) to translocate into the nucleus where it binds to and activates the transcriptional repressor CBF1. Activation of Notch-1 signaling leads to increased transcription of ErbB2 (13), cyclin D1 (14), CDK2 (14), and Notch-4 (15). ErbB2 is related to radiation resistance (16), whereas cyclin D1 and CDK2 promote the transition from G1 to S phase of the cell cycle and thus promote proliferation. Notch-1 signaling promotes the self-renewal of mammary stem cells (17), and there is strong evidence that Notch-1 is involved in the carcinogenesis of breast cancer (17). In addition, Notch-1 maintains the malignant phenotype of Ras-transformed cells (15), and overexpression of Notch induces mammary tumors in mice (18).

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Radiation therapy (RT) is an integral part of the multimodal treatment concept for breast cancer. Its success depends on the complete elimination of all cancer stem cells. Radiation oncologists have been advocating the existence of stem cells in normal tissues and cancers for decades (6). Accelerated repopulation— the increase in the rate of growth as a result of time between treatments (19,20)—is a cancer stem cell–related phenomenon that occurs during fractionated RT. During accelerated repopulation, each day of a treatment gap decreases the efficacy of RT by approximately 0.6 Gy, making it one of the major reasons for local failure of RT. Accelerated repopulation was first described for head and neck epithelial tumors (21), but it also occurs in breast cancer even though it may be difficult to detect (22–24).

In this study, we investigated the radiation response of CD24−/low/CD44+ breast cancer–initiating cells, the population of cancer cells that are likely to be critical for success or failure of cancer therapy. We characterized the radiation sensitivity of these cells and the size of this cell population after clinical fractions of radiation and explored possible mechanisms for the failure of radiotherapy.

**Methods**

**Cell Culture**

MCF-7 and MDA-MB-231 breast cancer cells (American Type Culture Collection; Manassas, VA) were cultured in log-growth phase in modified Eagle medium (MEM) (supplemented with 0.1 mM nonessential amino acids and 1 mM sodium pyruvate; Cellgro, Kansas City, MO) and Dulbecco’s modified Eagle medium (DMEM) (Cellgro), respectively, supplemented with 10% heat-inactivated fetal calf serum (FCS) and 0.01 mg/mL bovine insulin (Sigma, St Louis, MO) at 37 °C in a humidified atmosphere (5% CO2). To obtain cancer-initiating cells and to propagate them as mammospheres, cells floating in the supernatant of 2-day-old cultures were collected by centrifugation for 5 minutes at 500 g, washed in Hanks’ buffered salt solution, and resuspended in phenol red–free DMEM–F12 (Cellgro) supplemented with 0.4% bovine serum albumin (BSA, Sigma), 5 μg/mL bovine insulin (Sigma), 20 ng/mL basic fibroblast growth factor 2 (bFGF, Sigma), and 10 ng/mL epidermal growth factor (EGF, Sigma) at a density of 1000 cells/mL. Growth factors were added to the mammosphere cultures every 3 days. To mimic mammosphere culture conditions in cells grown as monolayer cultures, cells were plated in MEM or DMEM media containing 10% FCS supplemented with 5 μg/mL bovine insulin, 20 ng/mL bFGF, and 10 ng/mL EGF.

**Irradiation**

For clonogenic assays, cells derived from monolayer cultures or 5-day-old mammospheres were enzymatically dissociated with trypsin–EDTA–MEM culture media or mechanically dissociated with a Pasteur pipette (mammospheres), both passed through a 40-μm sieve, and immediately irradiated (106 cells/mL) at room temperature with a 137Cs laboratory irradiator (Mark I, J.L. Shephard, San Fernando, CA) at a dose rate of 4.95 Gy/minute for the time required to generate a dose curve of 0, 2, 4, 6, and 8 Gy. Corresponding controls were sham irradiated. Colony-forming assays were performed immediately after irradiation by plating cells into triplicate 100-mm culture dishes. After 28 days, cells were fixed with 75% ethanol and stained with 1% crystal violet, and colonies containing more than 50 cells were counted. To generate a radiation survival curve, the surviving fraction at each radiation dose was normalized to that of the sham-irradiated control, and curves were fitted using a linear–quadratic model (surviving fraction = e^(-α dose-β dose^2), in which α is the number of logs of cells killed per gray from the linear portion of the survival curve and β is the number of logs of cells killed per [gray]2 from the quadratic component) (25). Three independent experiments were performed.

To evaluate H2AX phosphorylation, single-cell suspensions were irradiated as above with 0, 2, or 10 Gy. Cells were harvested by centrifugation (500g for 5 minutes at 4 °C) at 5 and 60 minutes after irradiation.

To measure reactive oxygen species (ROS) accumulation, 100,000 cells were treated with 0, 2, or 10 Gy. Cells were immediately analyzed as described below.

To measure Notch-1 activation and Jagged-1 expression, cells were treated with single and fractionated doses of radiation. Cells (400,000 per dish) were plated onto 100-mm tissue culture dishes and allowed to grow for 24 hours. Cultures were then irradiated as monolayers at room temperature with 3 Gy daily for 5 consecutive days (days 2–6) or with a single dose of 10 Gy on day 6. Control cells were sham irradiated. Nonadherent and adherent cells were harvested 48 hours after the last irradiation (on day 8).

For primary mammosphere formation assays, cells were irradiated with 3 Gy daily for 5 consecutive days (days 2–6) or with a single dose of 10 Gy on day 6. Control cells were sham irradiated.

**3-(4,5-Dimethylthiazol-2-yl)-2,5-Diphenyltetrazolium Bromide Assays to Measure Cell Proliferation**

For 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assays, MCF-7 cells in monolayer culture were irradiated; incubated for indicated times in MEM media supplemented with 10% FCS, 20 ng/mL bFGF, and 10 ng/mL EGF; washed twice with PBS; incubated with trypsin–EDTA–MEM; resuspended in MEM (containing 10% FCS); counted; and plated in 100 μL MEM (10% FCS) at 2000, 10,000, 15,000, and 20,000 cells per well into 96-well plates. After 7 days, 20 μL of MTT solution (5 mg/mL in PBS) was added to each well, and cells were incubated for 4 hours at 37 °C. Then 50 μL sodium dodecyl sulfate solution (20% sodium dodecyl sulfate, 0.01% HCl) was added to each well, and plates were incubated at 37 °C overnight. Absorbance was measured at 560 nm in a fluorescence plate reader (Spectrafluor, Tecan, San Jose, CA).

**Flow Cytometry to Measure CD24, CD44, and Jagged-1 Expression; Notch-1 Activation; and H2AX Phosphorylation**

CD24 and CD44 expression was analyzed in cells derived from monolayer cultures or in 5-day-old primary mammospheres following incubation in trypsin–EDTA or dissociation with a Pasteur pipette and passage through a 40-μm sieve. At least 10^5 cells were pelleted by centrifugation at 500g for 5 minutes at 4 °C, resuspended in 10 μL of monoclonal mouse anti-human CD24–fluorescein isothiocyanate (FITC) antibody (BD Pharmingen, San Jose, CA) and a monoclonal mouse anti-human CD44–phycoerythrin (PE) antibody (BD Pharmingen),
and incubated for 20 minutes at 4 °C. Ten independent experiments were performed.

To measure Jagged-1 expression and Notch-1 activation, cells were permeabilized with 4% formaldehyde and pelleted by centrifugation as above. Cells were then incubated with 0.25 μg of PE/Cy5-conjugated monoclonal mouse anti-human CD44 antibody, 10 μL of monoclonal mouse anti-human CD24–FITC antibody, and 200 μL of either polyclonal rabbit anti-human Jagged-1 antibody (Santa Cruz Biotechnology, Santa Cruz, CA) or polyclonal rabbit anti-human Notch-1-ICD antibody (Cell Signaling, Danvers, MA) that had been diluted 1:200 in PBS containing 2% BSA for 20 minutes at 4 °C. Cells were then washed with PBS/4% BSA and incubated with a secondary, PE-conjugated polyclonal goat anti-rabbit antibody (BD Pharmingen).

For analysis of H2AX phosphorylation, cells were centrifuged for 5 minutes at 500g and resuspended in 0.3 mL of PBS. To fix the cells, 0.7 mL of ethanol (99%) was added to the tube while vortexing, and samples were stored for 30 minutes at −20 °C. Cold Tris-buffered saline (TBS, pH 7.4, 1 mL) was added, and cells were pelleted by centrifugation at 500g and resuspended in 1 mL cold TST (TBS containing 4% FBS and 0.1% Triton X-100) for 10 minutes to permeabilize and rehydrate the cells. Cells were pelleted again and resuspended in 200 μL of monoclonal mouse anti-γH2AX–FITC antibody (Upstate, Charlottesville, VA) diluted 1:500 in TST, incubated on a shaker platform for 2 hours at room temperature, and washed twice in TST. Three independent experiments were performed.

Flow cytometry and cell sorting were performed on a FACScalibur flow cytometer (Becton Dickinson, Franklin Lakes, NJ). The CellQuest (Becton Dickinson) software package was used.

**Reactive Oxygen Species Formation Assay**

Cells derived from monolayer cultures or 5-day-old mammospheres were incubated with trypsin–EDTA or dissociated mechanically using a Pasteur pipette, respectively, resuspended in modified HBSS (10 mM HEPES, 1 mM MgCl₂, 2 mM CaCl₂, 2.7 mM glucose), passed through a 40-μm sieve, counted, and diluted to a final concentration of 10⁶ cells/mL in 15-mL Falcon tubes (Becton Dickinson). Aminophenyl fluorescein (Cell Technology, Mountain View, CA) was added to a final concentration of 10 μM, and cells were incubated for 30 minutes in the dark and irradiated as indicated above. A total of 100,000 cells per well were plated into black 96-well plates, and fluorescence was measured in a fluorescence plate reader (Spectrafluor, Tecan; excitation: 480 nm, emission: 520 nm). Fluorescence was normalized to the fluorescence readings of untreated monolayer culture cells. Three independent experiments were performed, each in triplicate.

**Primary Mammosphere Formation Assay**

The ability of cells in the nonadherent population of monolayer cultures to initiate mammosphere formation after irradiation was assessed by harvesting, washing, and resuspending nonadherent cells in phenol red-free DMEM–F12 medium (supplemented with 0.4% BSA, 20 ng/mL bFGF, and 10 ng/mL EGF). Cells were then passed through a 40-μm sieve, counted, diluted, and plated into 96-well plates at clonal densities. Mammospheres were counted on day 5.

**Statistical Methods**

All data are represented as means and differences of the means with 95% confidence intervals (CIs). P values of .05 or less, calculated using a paired two-sided Student’s t test, were considered to indicate statistically significant differences.

**RESULTS**

**Response of CD24⁻/low/CD44⁺ Breast Cancer–Initiating Cells to a Single Dose of Radiation**

We established nonadherent mammosphere cultures from both MCF-7 and MDA-MB-231 breast cancer cells and analyzed the percentage of CD24⁻/low/CD44⁺ cells on day 5 by flow cytometry. In general, by day 5, MCF-7 (Fig. 1, A) and MDA-MB-231 (data not shown) mammospheres showed dramatically elevated percentages of CD24⁻/low/CD44⁺ cells.

The responses of cells from monolayers and CD24⁻/low/CD44⁺-enriched mammospheres (day 5) to radiation were compared by clonogenic assay. The plating efficiencies of MCF-7 cells derived from monolayer cultures and mammospheres without irradiation were similar (mean = 7.2%, 95% CI = 0.73 to 13.7, and mean = 11%, 95% CI = 8.8 to 13.2, respectively). However, cells derived from MCF-7 mammospheres were more radioresistant than cells derived from monolayer cultures (monolayer-derived cells: α = 0.79, β = 0.011, mean surviving fraction at 2 Gy [SF₂ Gy ] = 0.2, versus mammospheres: α = 0.30, β = 0.044, mean SF₂ Gy = 0.46, difference = 0.26, 95% CI = 0.05 to 0.47; P = .026, n = 9; Fig. 1, B). Comparable results were found for mammospheres that were derived from MDA-MB-231 cells (monolayer-derived cells: α = 0.65, β = 0.0014, mean SF₂ Gy = 0.5, versus mammospheres: α = 0.31, β = 0.035, mean SF₂ Gy = 0.69, difference = 0.19, 95% CI = −0.07 to 0.45; P = .09, n = 6).

One hallmark of the recognition and repair of double-strand DNA breaks is phosphorylation of the replacement histone H2AX (26). Single-cell suspensions from MCF-7 mammosphere and monolayer cultures were irradiated with 0, 2, or 10 Gy, and H2AX phosphorylation (γH2AX) was measured by flow cytometry at 5 and 60 minutes after irradiation (n = 2). MCF-7 cells derived from monolayer cultures showed a time-dependent increase of γH2AX after irradiation, whereas cells derived from primary mammospheres showed little change in γH2AX (Fig. 1, C). At 60 minutes, the increase in γH2AX for cells derived from monolayer cultures was dose dependent, with 10 Gy being more effective than 2 Gy (monolayer cultures: relative to 0 Gy, 2 Gy, mean = 2.92, 10 Gy, mean = 3.2-fold, difference = 2.2, 95% CI = 1.46 to 2.92, P = .006, n = 3; mammospheres: relative to 0 Gy, 2 Gy, mean = 1.06-fold, not statistically significant, 10 Gy, mean = 1.3-fold, not statistically significant, n = 3); however, even the 10-Gy dose did not affect the phosphorylation of H2AX in mammospheres (Fig. 1, D).

The lack of γH2AX staining, and hence repair of DNA double-strand breaks in mammospheres, after irradiation could be due to a very rapid repair, failure of detection, or initially low induction of DNA double-strand breaks. Therefore, we next investigated whether irradiation induced the formation of ROS in MCF-7 monolayer cultures and mammospheres. Single-cell suspensions were irradiated with 0, 2, or 10 Gy. Cells derived from MCF-7...
monolayer cultures consistently showed dose-dependent formation of ROS (0 Gy, mean = 1.0, 2 Gy, mean = 1.45, difference = 0.45, not statistically significant; 10 Gy, mean = 3.32, difference = 2.32, 95% CI = 0.67 to 3.98; \( P = .026 \)). Cells derived from primary mammospheres did so as well, but at levels that were approximately 50% of those formed by cells from monolayer cultures (0 Gy, mean = 0.58, 2 Gy, mean = 0.647, difference = 0.067, not statistically significant; 10 Gy, mean = 1.46, difference = 0.88, 95% CI = 0.20 to 1.56; \( P = .031 \)).

Because EGF and bFGF, which were used to generate mammospheres, both decrease the radiation sensitivity of cells (27,28), independent of the presence of CD24^−/low/CD44^+ cancer-initiating cells, MCF-7 and MDA-MB-231 cells were cultured as monolayers for 5 days in MEM or DMEM (10% FCS), supplemented with EGF and bFGF. As expected, cells derived from EGF- and bFGF-treated monolayer cultures exhibited increased radiation resistance that was similar to that of cells derived from primary mammospheres (Fig. 2, A and B), which could be ascribed to the increased percentage of CD24^−/low/CD44^+ cancer-initiating cells in the nonadherent fraction (i.e., supernatant) of monolayer cultures after cytokine treatment (Fig. 2, C). To further exclude an acute direct radioprotective effect of EGF and bFGF, we exposed MCF-7 monolayer cultures to growth medium supplemented with or without EGF and bFGF
for 0.5, 1, 2, 3, 4, or 6 hours after irradiation with 4 or 6 Gy (n = 2). Cells were then washed twice with PBS, incubated with trypsin–EDTA and plated into 96-well plates at 2000, 10,000, 15,000, or 20,000 cells per well. Although cytokine treatment increased the viability of the cells as assessed by MTT assays on day 7, we could not detect a radioprotective effect of the EGF/bFGF treatment (data not shown).

Response of CD24^−/low/CD44^+ Breast Cancer Cells to Fractionated Radiation

To determine whether the CD24^−/low/CD44^+ -enriched cancer-initiating cells were truly more radioresistant than their non–CD24^−/low/CD44^+ -enriched monolayer cell counterparts, or if they might even increase in numbers after clinical fractions of radiation (accelerated repopulation), monolayer cultures of MCF-7 cells were irradiated with either a single dose of 10 Gy on day 6 or five daily doses of 3 Gy on days 2–6. When unirradiated cells were analyzed for CD24 and CD44 expression on day 8, the size of the CD24^−/low/CD44^+ population of cells in the nonadherent fraction was, as expected, higher than that of the adherent cells (mean = 3.52% versus mean = 0.86%, difference = 2.66%, 95% CI = 0.63 to 4.7; n = 5, P = .02; Fig. 3, A and B). For monolayer cultures, the percentages of CD24^−/low/CD44^+ cells on day 8 in the adherent and nonadherent cell populations were not altered by a single dose of 10 Gy given on day 6. In addition, after five fractions of 3 Gy, the percentage of CD24^−/low/CD44^+ cells in the adherent cell population did not change (Fig. 3, A and B); however, the percentage of CD24^−/low/CD44^+ cells in the supernatant (nonadherent cells) increased (untreated, mean = 3.52%, versus treated, mean = 7.5%, difference = 3.98%, 95% CI = 1.67% to 6.25%; n = 5, P = .009; Fig. 3, A and B).

To further explore the biologic relevance of the increase of the proportion of CD24^−/low/CD44^+ cells after fractionated
irradiation, we performed a primary mammosphere formation assay, which allows estimation of the number of breast cancer cells that exhibit self-renewal capacity (7). Primary mammosphere formation by nonadherent cells from cultures irradiated with a single dose of 10 Gy was similar to that of unirradiated control cultures. (Fig. 3, C). However, primary mammosphere formation capacity was increased in nonadherent populations from cultures that received five fractions of 3 Gy, although this increase did not reach statistical significance (Fig. 3, C).

**Fractionated Irradiation and the Notch-1 Pathway**

Self-renewal and lineage differentiation in normal mammary stem cells is regulated by the developmental Notch signal
on day 6. Nonadherent (cells were incubated with trypsin–EDTA. Cells were fixed and stained with a fluorescein isothiocyanate–conjugated monoclonal mouse anti-human CD24, a phycoerythrin-Cy5-conjugated monoclonal mouse anti-human CD44 antibody, and either a polyclonal rabbit anti-human Jagged-1 antibody (A) or a polyclonal rabbit anti-human Notch-1-intracellular domain antibody (B). Means and 95% confidence intervals are shown from seven (adherent cells 0 and 5 × 3 Gy), five (floating cells 0 and 5 × 3 Gy), or three (1 × 10 Gy) independent experiments. *P* values were determined using the twosided Student’s *t* test.

**Fig. 4.** Flow cytometry analysis of Jagged-1 expression and Notch-1 activation in adherent and nonadherent MCF-7 cells after irradiation. Monolayer cultures were exposed to five fractions of 5 Gy on days 2–6 or a single fraction of 10 Gy on day 6. Nonadherent (floating) cells were harvested 48 hours later, and adherent cells were incubated with trypsin–EDTA. Cells were fixed and stained with a fluorescein isothiocyanate–conjugated monoclonal mouse anti-human CD24, a phycoerythrin-Cy5-conjugated monoclonal mouse anti-human CD44 antibody, and either a polyclonal rabbit anti-human Jagged-1 antibody or a polyclonal rabbit anti-human Notch-1-intracellular domain antibody. Means and 95% confidence intervals are shown from seven adherent cells 0 and 5 × 3 Gy, five floating cells 0 and 5 × 3 Gy, or three (1 × 10 Gy) independent experiments. *P* values were determined using the two-sided Student’s *t* test.

of primary mammosphere formation. One possible interpretation is that mammospheres are not exclusively formed by breast cancer stem cells but also contain early progenitor cells. Such a situation would support the use of the term breast cancer–initiating cells for this population rather than breast cancer stem cells. Alternatively, breast cancer stem cells could be the only population capable of forming mammospheres but could also give rise to non–stem cells within the mammosphere. Although non–stem cells would be incapable of mammosphere formation and thus self-renewal, they would still be considered as clonogenic in clonogenic survival assays.

We found that breast cancer–initiating cells were more radioresistant than non–breast cancer initiating cells. Interestingly, the radiation survival curve of cells derived from mammospheres had a shoulder that is characterized by a comparably higher resistance at lower and thus clinically more relevant doses of radiation. This shoulder indicates an enhanced capacity to repair potentially lethal damage. Resistance to apoptotic stimuli, including radiotherapy, was recently reported for nonproliferating CD34+ chronic myeloid leukemia progenitor cells when compared with normal CD34+ cells.

Consistent with the increased radioresistance, treatment with ionizing radiation caused lower levels of ROS in cells derived from mammospheres compared with cells derived from monolayer cultures. This decrease in ROS levels indicated high intracellular levels of radical scavengers. Although cells in primary mammospheres may exhibit certain levels of hypoxia, as reported for spheroid cultures of tumor cells, the absence of oxygen did not account for the observed effect in our experiments because cells derived both from monolayer cultures and mammospheres were irradiated as single-cell suspensions.

To our knowledge, this is the first study to directly investigate the radiation resistance of breast cancer–initiating cells. Three-dimensional in vitro culturing techniques for tumor cells have been used previously using nonselective serum-containing conditions that caused cells to aggregate. These tumor spheroids also exhibit resistance to radiation and chemotherapeutic drugs
and have enhanced colony-forming efficiency (33). The mechanisms leading to increased resistance and enhanced colony-forming efficiency were incompletely understood. However, given the size of these aggregates and the gradient of cytokine concentrations and nutrients from the periphery to the center of these spheroids, the previous techniques may have also selected for therapy-resistant cancer stem cells. Our observation of increased radiation resistance in the cancer-initiating cell population most likely underestimates the resistance of breast cancer stem cells because the cycling population of progenitor cells present in the mammospheres are not necessarily as resistant as breast cancer stem cells. However, these results indicate that therapies that specifically target pathways that are deregulated in breast cancer stem cells may enhance the efficiency of radiotherapy in the future. In addition, these findings may have an impact on future design of predictive assays for drug or radiation sensitivity because the therapeutic response of cancer stem cells may not be reflected by the response of an unselected tumor cell population.

Using an in vitro system, we mimicked a week of clinical fractionated radiotherapy followed by a typical weekend gap of 2 days. This treatment increased the proportion of breast cancer-initiating cells. The observation that the increase in cell number was observed in the supernatant (i.e., nonadherent cells) of confluent monolayer cultures but not in adherent cells and the fact that these cells formed primary mamsospheres at a higher rate than untreated cells indicate that the increase in the proportion of cancer-initiating cells was not caused by simple selection of a radioresistant subpopulation but by an absolute increase in the number of viable breast cancer-initiating cells with increased capacity for self-renewal.

Activation of the developmental Notch-1 signal transduction pathway promotes self-renewal of early progenitor cells derived from normal mammary stem cells (29). In the present study, we investigated whether ionizing radiation interfered with the Notch-1 signaling pathway directly. Our observation that radiation induced Jagged-1 expression on the surface of cells from monolayer cultures and activated Notch-1 in cells in the supernatant is the first demonstration, to our knowledge, of an acute radiation effect on this developmental signaling pathway. Future studies will be necessary to define the population of cells in which this pathway is targeted by radiation.

The study has several limitations. Breast cancer stem cells have not yet been identified directly, although they can be enriched for and propagated in vitro with the techniques we used in this study. Still, these enriched populations are heterogeneous, and the results of our study may therefore actually underestimate the differences between breast cancer stem cells and non–stem cells. The number of different breast cancer cell lines used limits the conclusions for clinical radiotherapy that can be drawn from our study. Selection for a specific phenotype may have occurred during the establishment and maintenance of these lines, and thus, these cells may not accurately reflect the behavior of breast cancer cells in human tumors. Thus, our data need validation on mamsospheres derived directly from patients’ tumor specimens.

Taken together, our data indicate that breast cancer–initiating cells exhibit increased radiation resistance resulting from decreased ROS induction, followed by decreased double-strand break formation. Additionally, fractionated irradiation appeared to activate the Notch-1 developmental pathway, which may have caused the numbers of breast cancer–initiating cells to increase, offering a mechanism for accelerated repopulation during radiation therapy treatment gaps.

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NOTES

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