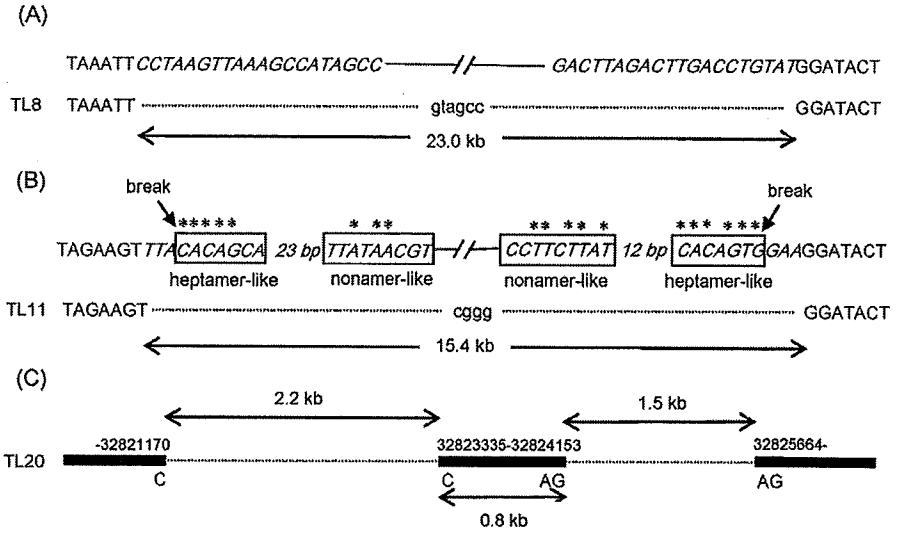

Fig. 4. Sequence analysis of *Pten* focal deletion breakpoints. Schematic diagram representing sequence analysis of focal deletion breakpoints in *Pten* in TL8 (A), TL11 (B) and TL20 (C) lymphomas. Dotted lines indicate deleted genomic regions, and the deleted wild-type sequence is shown in italics in (A and B). Boxes indicate heptamer-like or nonamer-like motifs, and nucleotides marked with asterisks are identical to the canonical heptamer or nonamer sequences. Arrows indicate the sites of Rag-mediated DNA breakage. Lowercase letters indicate nucleotide insertions. Black bars indicate the positions (mm8 assembly) of the retained DNA ends. The uppercase letters below the line in (C) indicate the sequences used to locate microhomology at both ends of each deletion.

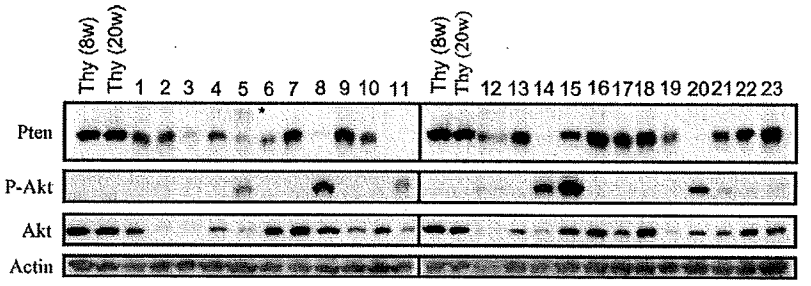

Fig. 5. Analysis of Pten expression and Akt phosphorylation in radiation-induced thymic lymphomas. Western blot analysis of lysates from 23 radiation-induced T-cell lymphomas was performed using antibodies to the proteins indicated at left. Lanes 1 and 2, control thymocytes (Thy) of 8- and 20-week-old mice, respectively. Actin was analyzed as loading control. Asterisk indicates polypeptide with larger mass than expected.

TL5, 19 and 21 expressed mutant Pten containing amino acid substitutions in the phosphatase domain. In TL5 and 21, Akt phosphorylation was weakly observed, suggesting dysfunction of Pten. In TL19, Akt phosphorylation was not observed. The lack of phosphorylation of Akt might have resulted from decreased levels of Akt protein. In TL3 and 12, in which the Pten expression level was low, Akt phosphorylation was not observed owing to negligible expression of Akt protein. In contrast, Akt was highly phosphorylated in TL15, which expressed wild-type Pten. It is possible that other factors that regulate the phosphorylation of Akt, such as PI3K and Ship, may activate Akt independently of Pten [28,29].

3.7. *Levels of Pten-targeting microRNAs do not correlate with Pten protein levels in lymphomas*

Lymphomas TL3, 6 and 12 contained low levels of Pten protein, although neither a decrease in the amounts of RT-PCR product nor genetic aberrations were observed. Recent reports have revealed the involvement of microRNAs in downregulation of Pten expression [13,14,30–33]. We therefore examined whether certain microRNAs contributed to post-transcriptional downregulation of the expression of Pten. For all lymphomas with sufficient available RNA, expression levels of the well-studied *Pten*-targeting microRNAs miR-19a and miR-21 were analyzed using real-time RT-PCR (Supplementary Fig. 3). Expression of miR-19a was almost constant among all lymphomas and was similar to the expression levels in normal thymocytes from 20-week-old mice. Some lymphomas exhibited relatively high miR-21 expression, but there was no significant inverse correlation between miR-21 expression level and Pten protein level.

4. Discussion

In our present study of radiation-induced thymic lymphomas, *Pten* inactivation occurred with a frequency of 30% (7 of 23 lymphomas) and was caused by a variety of biallelic structural abnormalities including base substitutions, long and short (1 and 3 bp) insertions, duplication, and deletions (Table 1). Epigenetic silencing was not observed.

Frequent LOH around the *PTEN* locus has been reported in human leukemias (20% frequency) and lymphomas (23% frequency) [34,35]. *PTEN* alterations, however, have only been sporadically detected in hematopoietic neoplasms [36–42]. In contrast, aberrant DNA methylation in the *PTEN* promoter region has been detected at a frequency of 20% in T-cell ALLs and at a frequency of 18% in B-cell ALLs [26], suggesting that epigenetic silencing is a dominant mechanism of *PTEN* inactivation in hematopoietic neoplasms. Santos et al. [22] has suggested that

Pten in radiation-induced mouse thymic lymphomas also undergoes epigenetic silencing in C57BL/6J and BALB/c F1 hybrid mice. In our present study, however, no aberrant DNA methylation was detected in CpG islands located in the 5′ (upstream) region of *Pten*. Thus, epigenetic silencing does not play a major role in *Pten* loss in radiation-induced thymic lymphomas in B6C3F1 mice. Mao et al. [61] also reported that *Pten* does not undergo methylation-mediated transcriptional silencing in $p53^{+/-}$and $p53^{-/-}$mice. The reason for these discrepancies is not clear, although different mice strains may exhibit distinct patterns of CpG island methylation. Indeed, it has been reported that patterns of CpG island methylation in T-cell lymphomas are driven by the genetic configuration of tumor cells [43]. Santos et al. [22] reported that intragenic mutations do not occur in any genes on chromosome 19, including *Pten*, in C57BL/6J and BALB/c F1 hybrid mice. In contrast, our data indicated frequent intragenic mutations of *Pten* in C57BL/6J and C3H/HeJ F1 hybrid mice, as was suggestive of the influence of the host genetic background on the mutation spectrum. We previously demonstrated strain-based differences between C57BL/6 and C3H mice with respect to genomic alterations of *Kras* and genome-wide copy numbers in thymic lymphomas [44,45].

We have shown that LOH of *Pten* occurred at a frequency of about 30% (7 of 23 lymphomas) and that 8 lymphomas contained complex *Pten* structural abnormalities. Most of the available information regarding the mutation spectrum of *PTEN* has been derived mainly from epithelial cancers such as endometrial carcinomas, glioblastomas, prostate carcinomas, and others [6,7]. In these cases missense, nonsense and frameshift mutations predominate; missense mutations have been found to cluster in exons 5 and 6, encoding the PTEN phosphatase domain, and nonsense and frameshift mutations cluster in the poly $(A)_6$ stretches and in exons 7 and 8, encoding the C2 domain [6]. Comparison of mutations has shown that *PTEN* mutations in tumors depend on tissue type. Endometrial carcinomas predominantly contain frameshift mutations (>60% frequency), whereas glioblastomas contain fewer frameshift mutations but more missense mutations (61% frequency). Recently, *PTEN* frameshift mutations were found to cluster exclusively in exon 7 in human T-cell ALLs [29]. On the other hand, hemizygous *PTEN* deletions have been reported in 39% of prostatic adenocarcinomas, and homozygous *PTEN* deletion has been observed in 5% of prostate tumors [46]. Of note, hemizygous *PTEN* deletion is usually accompanied by an interstitial microdeletion.

In this study, we detected focal homozygous deletions at *Pten* in 13% of lymphomas (3/23; TL8, 11 and 20), all of which resulted in dearth of Pten protein. In two lymphomas (TL8 and 11), homozygous deletions were positioned within hemizygous deletions, possibly resulting from independent deletions occurring in both alleles in these lymphomas. On the other hand, TL20 had a homozygous deletion without adjacent hemizygous deletions. The observation that TL20 contained distally extending continuous LOH on chromosome 19 suggests that this homozygous deletion might have been caused by sequential events, in which one small deletion within the *Pten* locus was followed by subsequent mitotic recombination. Notably, microdeletions have been reported in several key tumor-related genes, such as *IKZF1*, *PAX5* and *CDKN2A*, in human ALLs [47–51] and in *Nocth1* and *Bcl11b* in murine thymic lymphomas [52,53]. The sequence at the deletion breakpoint strongly suggests that these deletions were generated by illegitimate V(D)J recombination and microhomology-mediated rearrangement [49,52–54]. Homozygous *PTEN* deletions were recently identified in 4% of human primary childhood T-cell ALLs [29].

A previous study on T-cell lymphomas developed in chromosomally unstable *Terc*-, *Atm*- and *Trp53*-null mice also reported frequent homozygous deletions at the *Pten* locus [39]. In addition, recent reports on breast cancers [55] and medulloblastomas [56] demonstrated that *Pten* was selectively targeted in a background of defective homologous recombination repair of DNA double-strand breaks (DSBs). Importantly, radiation is a genotoxic stress that increases the frequency of DSBs and stimulates V(D)J rearrangements at cryptic recombination signal sequences [57]. Therefore, radiation-induced DNA DSBs may facilitate hemi- and homozygous deletions of the *Pten* locus.

The two-hit model posits that both copies of a tumor suppressor gene must be inactivated before cancer can develop [58]. Some tumor suppressor genes, however, are inactivated solely by hemizygous loss, indicating the involvement of haploinsufficiency. Several lines of evidence suggest that *Pten* is such a haploinsufficient tumor suppressor gene, at least in epithelial cancers such as prostate cancer [59,60]. A study of radiation-induced lymphomas from *Trp53* heterozygous and/or null mice suggested that *Pten* is a haploinsufficient tumor suppressor gene and that *Pten* haploinsufficiency is a common characteristic of radiation-induced lymphoma development [61]. It is unclear whether *Pten* is inactivated in a bi- or mono-allelic manner in thymic lymphomas of wild-type mice. In the present study, biallelic *Pten* inactivation occurred in seven of eight lymphomas. Although complete loss of *Pten* resulted in increased phosphorylation of Akt, lymphomas with decreased *Pten* expression or monoallelic inactivation (TL15) did not always exhibit increased Akt phosphorylation. Together with the frequent biallelic point mutations and microdeletions observed at the *Pten* locus, these findings suggest that decreased *Pten* dosage alone is not sufficient for activation of the PI3K/Akt signaling pathway during radiation-induced lymphomagenesis. Manifestation of *Pten* haploinsufficiency may require other genetic or epigenetic aberrations. It has been suggested that in tumors of defined tissue origin and genetic background, *Pten* functions in a haploinsufficient manner, but that for others both alleles need to be inactivated [62].

Conflicts of interest

The authors declare that there are no conflicts of interest.

Acknowledgements

The authors thank Dr. K. Ariyoshi, Mr. Y. Kodama and Ms. Y. Nishimura for their valuable technical tutorship and discussion. We also express our gratitude to all laboratory members for their encouragement throughout this work, and to the Laboratory Animal Science Section in National Institute of Radiological Sciences for animal management. This work was supported by institutional funds from the National Institute of Radiological Sciences (Chiba, Japan). This work was also supported financially by a Grant-in-Aid from the Ministry of Education, Culture, Sports, Sciences, and Technology of Japan (to Y.S.) and by a grant from the Long-Range Research Initiative of the Japan Chemical Industry Association (to Y.S. and S.K.).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.mrfmmm.2009.12.011.

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JRR09137A

J. Radiat. Res.

Review

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Recent Advances in the Biology of Heavy-Ion Cancer Therapy#

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Heavy ions/DNA double-strand break repair/Intratumor quiescent cell population/p53/Bcl-2/Metastasis and angiogenesis /Carcinogenesis.

Superb biological effectiveness and dose conformity represent a rationale for heavy-ion therapy, which has thus far achieved good cancer controllability while sparing critical normal organs. Immediately after irradiation, heavy ions produce dense ionization along their trajectories, cause irreparable clustered DNA damage, and alter cellular ultrastructure. These ions, as a consequence, inactivate cells more effectively with less cell-cycle and oxygen dependence than conventional photons. The modes of heavy ion–induced cell death/inactivation include apoptosis, necrosis, autophagy, premature senescence, accelerated differentiation, delayed reproductive cell death of progeny cells, and bystander cell death. This paper briefly reviews the current knowledge of the biological aspects of heavy-ion therapy, with emphasis on the authors' recent findings. The topics include (*i*) repair mechanisms of heavy ion–induced DNA damage, (*ii*) superior effects of heavy ions on radioresistant tumors/cells (intratumor quiescent cell population, *TP53*-mutated and *BCL2*-overexpressing tumors), (*iii*) novel capacity of heavy ions in suppressing cancer metastasis and neoangiogenesis, and (*iv*) potential of heavy ions to induce secondary (especially breast) cancer.

INTRODUCTION

Energetic heavy ions are defined as charged particles heavier than helium ions, and they generally have high relative biological effectiveness (RBE).[1–4] Unlike conventional photons such as X- and γ-rays, heavy ions form a sharp Bragg peak (a pronounced rise in energy deposition of radiation during its travel through matter), with a steep dose falloff downstream. Because of the primarily narrow Bragg peak, spread-out Bragg peaks (SOBP) have been devised to obtain broad and uniform dose distribution,[5] thereby enabling dose escalation to the target tumor volume without much exacerbation of normal tissue complications. Such excellent biological properties and dose conformity represent a rationale for heavy-ion cancer therapy. Ever since the first clinical experience in 1977,[6] the number of treated patients has been growing steadily and has already exceeded 6,000. So far, heavy-ion therapy has achieved good cancer controllability in short treatment times while sparing critical normal organs.[7–9] A number of new facilities are becoming operational worldwide in addition to the currently available ones, leading to a wider popularization of heavy-ion therapy.

It is well established that biological effectiveness of ionizing radiation varies with its linear energy transfer (LET), namely, the rate of energy loss along the trajectory of an ionizing particle (usually expressed in keV/μm).[10] High-LET

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doi:10.1269/jrr.09137

#Abstract, Sections 1 and 8 were written by N. H. and T. I. Sections 2–7 (Section 2 by R. O. and T. K., Section 3 by S. M. and K. O., Section 4 by A. T. and T. Ohnishi, Section 5 by N. H. and Y. K., Section 6 by T. Ogata and T. T., and Section 7 by T. I. and Y. S.) were translated and modified from Radiat. Biol. Res. Commun. 44(2): 182–232 (2009, in Japanese).

heavy ions produce dense ionization along their trajectories, and cause complex and irreparable clustered DNA damage.[11,12] Heavy ions are generally more genotoxic and cytotoxic to irradiated cells than low-LET photons.[1–4] The biological effectiveness depends not merely on LET but also on ion species (or ion track structure), such that the RBE of carbon and neon ions for the clonogenic survival peaks at LET of ~100 and ~200 keV/μm, respectively.[13–15] Changes in cellular ultrastructure at the electron-microscopic level (e.g., irregular protrusions and invaginations of plasma membrane, distended sarcoplasmic reticula, and increased autophagic vacuoles) occur as early as a few minutes after heavy-ion exposure, and autophagy might be involved in removal of such disruption.[16–18] The mode of heavy ion–induced cell death/inactivation includes apoptosis, necrosis, autophagy, premature senescence, accelerated differentiation, delayed reproductive death in the descendants of irradiated cells, and bystander cell death.[1–4,19–32] Heavy ions are effective at killing cells with little cell-cycle and oxygen dependence of radiosensitivity,[1–4] and possess high potential to suppress angiogenesis, metastasis and arrhythmia.[33–35] Moreover, heavy ions may overcome tumor radioresistance caused by mutation of the tumor suppressor gene *TP53* (also known as *p53*), overexpression of the oncogene *BCL2* (also *Bcl-2*), and intratumor hypoxia.[36–40] Although heavy-ion therapy has provided favorable clinical outcome with irradiation alone, interest is increasing in combined modalities, especially with molecularly targeted approaches. In comparison with heavy ions alone, the combination with chemical agents (e.g., Bcl-2 inhibitor HA14, anticancer drug docetaxel, and halogenated pyrimidine analogue 5-iodo-2'-deoxyuridine), hyperthermia and gene therapy enhances tumor cell killing.[41–48] Beer, its constituents (β-pseudouridine and glycine betaine), melatonin and α-lipoic acid ameliorate heavy ion–induced damage to normal cells.[49–57] Such approaches may further increase the therapeutic ratio (i.e., ratio of lethal dose to effective dose). On the other hand, the potential of heavy ions to cause adverse effects must not be overlooked. Although clinical efforts have succeeded in reducing acute reactions after treatment, late effects such as secondary cancer induction are gradually becoming a matter of concern. Absolutely no information is currently available on the secondary cancer risk from heavy ions; however, some evidence has accumulated regarding cancer induction in experimental animal models. For example, in a series of studies on mouse Harderian gland tumor, RBE increased with LET, reaching a maximum of 30–45 at 100–200 keV/μm, and did not decrease substantially thereafter up to 650 keV/μm.[58,59] Experimental evidence for cancer induction in other organs is currently being accumulated.

This paper briefly reviews the current knowledge of the biological aspects of heavy-ion therapy, focusing on the recent findings of the authors. Firstly, the basic mechanisms of DNA repair for heavy ion–induced damage are reviewed, which underlie their high biological effectiveness. Secondly, as examples of the superior biological characteristics of heavy ions in preclinical settings, the targeting and overcoming of radioresistant tumor cells are reviewed particularly in the case of intratumor quiescent cell populations and radioresistant cells due to *p53* mutation and *Bcl-2* overexpression. The antimetastatic and antiangiogenic potential of heavy ions is also reviewed as another example of their potential advantage in therapy. Finally, experimental information on the cancer-inducing potential of heavy ions is reviewed especially in regard to breast cancer induction. The companion articles by Okada *et al.* and Minohara *et al.* review the clinical and physical aspects of heavy-ion therapy, respectively.[60,61]

BIOLOGICAL EFFECTS OF HIGH-LET HEAVY-ION RADIATION FROM THE ASPECT OF DNA DOUBLE-STRAND BREAK REPAIR

It is important to explain the biological basis for the successful world-leading carbon-ion therapy at the Heavy-Ion Medical Accelerator in Chiba (HIMAC) of the National Institute of Radiological Sciences (NIRS), Japan. In this section, our focus is on the repair of DNA double-strand breaks (DSBs) induced by low- and high-LET radiation. By demonstrating the inefficient repair of DNA and chromosome damage with high-LET radiation, the crucial basis for its high biological effectiveness can be demonstrated.

Inefficient rejoining of DNA DSBs induced by high-LET heavy-ion irradiation

A substantial number of studies on DNA DSB and its repair in cells exposed to high-LET heavy ions have been reported.[62,63] In general, DSB repair is inhibited as a function of LET (up to 200 keV/μm), and the degree of rejoining correlates with cell survival. If the rejoining is inefficient, a high number of remaining DSBs persist after irradiation, leading to lower cell survival. We have also shown this tendency by experiments performed with constant-field gel electrophoresis (M. Noguchi and R. Okayasu, personal communication).

Inefficient repair of DNA DSBs with high-LET irradiation as measured by γH2AX assay

The commonly used gel-electrophoresis method as discussed above may be convenient and useful, but it usually requires the use of a high radiation dose such as 20 Gy, which is significantly higher than the dose range used for cell survival.[64,65] Thus, many researchers have recently employed another method called γH2AX focus assay, which assumes that there is a one-to-one correlation between one DSB and one γH2AX focus.[66] The sensitivity of this assay is also higher than the gel method.[66,67] An example of data using this assay is shown in Fig. 1 for γH2AX appearance and disappearance kinetics after irradiation of cultured

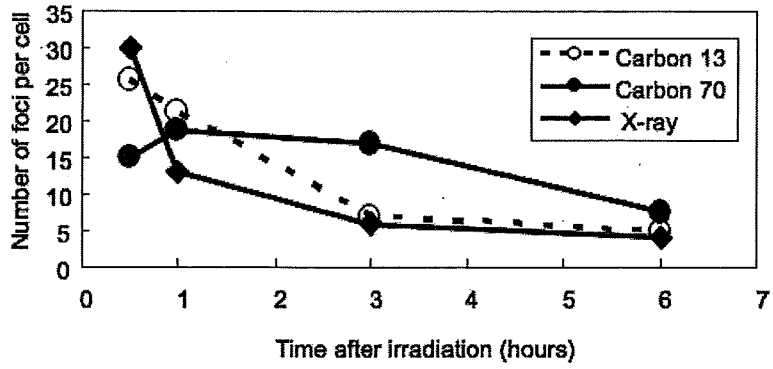

Fig. 1. Kinetics of γH2AX foci formation/disappearance in G_0/G_1 human cells irradiated with 1 Gy of X-rays and carbon ions (linear energy transfer, 13 and 70 keV/μm).

human cells in G_0/G_1 phases with 1 Gy of X-rays and carbon ions (290 MeV/u). Two LET values, 13 and 70 keV/μm, were used for carbon-ion experiments. The focus kinetics for X-rays and low-LET carbon ions (13 keV/μm) revealed efficient disappearance of the foci. In contrast, the focus kinetics for high-LET carbon ions (70 keV/μm) showed inefficient focus disappearance, leading to more cell killing when compared to low-LET irradiation cases. Since 13 keV/μm is the LET for the flat portion of the SOBP for carbon-ion beam, our data help explain the successful carbon-ion treatment outcome; a tumor mass can be targeted with the high-LET portion (e.g., 70 keV/μm), and surrounding normal tissue can be spared with the low-LET portion (13 keV/μm). These γH2AX data seem to substantiate the data obtained by the traditional gel-based assay.

Table 1. Frequency of chromosome aberrations in G_1 phase human cells irradiated with 2 Gy of X-rays, carbon (linear energy transfer [LET], 13 and 70 keV/μm) and iron (200 keV/μm) ions as measured by the premature chromosome condensation and fluorescence *in situ* hybridization technique, where 50–70 cells were scored for each radiation type.

Radiation type	LET (keV/μm)	Exchange frequency	Fragment frequency
X-rays	2	0.23	0.16
Carbon ions	13	0.40	0.37
	70	0.45	0.71
Iron ions	200	0.61	0.88

Effect of high-LET heavy ions at the chromosome level

The DNA DSB repair results described in Fig. 1 should be reflected at the chromosome level as the remaining DSBs that could be converted into chromosome aberrations. Here the results with the premature chromosome condensation (PCC) assay are mentioned to determine the early post-irradiation behavior of cells. Prematurely condensed chromosomes can be obtained by fusing interphase cells such as cells in G_1 or G_2 phase with mitotic cells using facilitating agents such as Sendai virus or polyethylene glycol. By fusing these cells, factor(s) to condense chromosomes would be transferred from mitotic to interphase cells, and condensed interphase chromosomes can be observed.[68–71] By this method, kinetics of chromosome-break rejoining can be measured at comparatively low doses (< 5 Gy). Furthermore, if one combines the PCC assay with fluorescence *in situ* hybridization (FISH), information on mis-rejoined chromosomes can be obtained. Our data from these measurements using irradiated primary human cells at G_0/G_1 phases are shown in Table 1. Regarding the data in Table 1, chromosomes 1 and 2 are stained by individual whole chromosome painting probes; "fragment" means an isolated stained chromatid shorter than the original unbroken chromatid, and "exchange" indicates chromatid partially stained with the probe. LET-dependent increases can be observed in these aberrations, and this is more true in the frequency of fragments, while there is a much smaller increase in the frequency of exchanges as a function of LET. For example, the exchange rate at 13 keV/μm is not much different from that at 70 keV/μm, suggesting that high-LET radiation may induce more chromosome breaks than exchanges.

Gene expression after high-LET heavy ions differs from that after X-rays

At NIRS, a unique gene expression analysis method called HiCEP (high coverage expression profiling) was developed. Although more effort and resources may be needed to obtain the expression data with HiCEP when compared with other assays such as microarray, this method can provide more accurate and reproducible results with a great sensitivity.[72,73] Genes not previously identified after a specific damaging agent could be uncovered.[74] In our recent HiCEP experiment with normal human cells, differences were observed when the profile obtained with high-LET car-

bon ions (70 keV/μm) was compared to that with X-rays or low-LET carbon ions (13 keV/μm). For example, *ATF3* (activating transcription factor 3) gene was significantly upregulated after both high- and low-LET radiation at 2 h post-irradiation, while at 6 h post-irradiation this gene remained at a high level only with high-LET irradiation (A. Fujimori and R. Okayasu, personal communication). Thus, it is evident that the cellular response to high-LET radiation is different from that to low-LET radiation at the gene expression level.

Variation in cell survival levels throughout the cell cycle is reduced in mammalian cells exposed to high-LET radiation

The variation in radiosensitivity throughout the cell cycle has been known for a long time in the case of low-LET radiation in mammalian cells. In general, mitotic cells are most radiosensitive and late S-phase cells are most radioresistant; cells with a long G_1 phase can have another radioresistant peak in G_1.[10] With high-LET irradiation, this may not be the case. In 1975 in Berkeley, USA, using an accelerator, Bird and Burki showed an LET-dependent variation in radiosensitivity as a function of the cell cycle phase in hamster cells.[75] With increasing LET (up to ~200 keV/μm), the variation throughout the cell cycle was significantly reduced; there was very little variation as LET reached about 200 keV/μm. Although that work was very significant, cell cycle work with high-LET radiation has not been repeated until very recently.[76] At HIMAC, we have repeated experiments similar to those at Berkeley using Chinese hamster ovary (CHO) cells. We also found that the cell survival variation throughout the cell cycle became much less with 70 keV/μm carbon-ion irradiation, and this was further reduced with 200 keV/μm iron ions. Moreover, using two types of DNA DSB repair deficient CHO mutants, we found that the cause of such reduced variation in radiosensitivity may stem from the inhibition/reduction of both non-homologous end-joining and homologous recombination repair as a consequence of complex DNA damage induced by high-LET radiation.[70] Further detailed studies on this subject are currently underway in our laboratory.

Conclusion

Here we emphasized the importance of DNA DSB repair induced by high-LET radiation. If DSB repair is inefficient with high-LET heavy ions, this leads to chromosome damage and eventually cell killing. Since the DNA damage induced by high-LET radiation is different from that by low-LET radiation, different mechanisms to repair DNA damage by high-LET radiation might be necessary. This could contribute to the elucidation of a novel DNA damage repair pathway. Heavy-ion facilities such as HIMAC may prove to be very useful for the investigation of fundamental cell biology, in addition to their proven clinical benefit.

RADIOBIOLOGICAL SIGNIFICANCE OF THE SENSITIVITY AND RECOVERY FOLLOWING EXPOSURE TO ACCELERATED CARBON-ION BEAMS COMPARED WITH γ-RAYS, WITH REFERENCE TO THOSE IN INTRATUMOR QUIESCENT CELLS

Background

Human solid tumors are thought to contain moderately large fractions of quiescent (Q) tumor cells, which are out of the cell cycle and stop cell division, but they are as viable as established experimental animal tumor lines that have been employed for various oncology studies.[77] The presence of Q cells is probably due, at least in part, to hypoxia and the depletion of nutrition in the tumor core, a consequence of poor vascular supply.[77] As a result, Q cells are viable and clonogenic, but cell division has ceased. In general, radiation and many DNA-damaging chemotherapeutic agents kill proliferating (P) tumor cells more efficiently than Q tumor cells, resulting in many clonogenic Q cells remaining following radiotherapy and chemotherapy.[77] Therefore, it is harder to control Q tumor cells than to control P tumor cells, and many post-radiotherapy recurrent tumors result partly from the regrowth of Q tumor cell populations that could not be sufficiently killed by radiotherapy.[77] Further, sufficient doses of drugs cannot be distributed within Q tumor cell populations mainly due to the heterogeneous and poor vascular distributions within solid tumors. Thus, one of the major causes of post-chemotherapy recurrent tumors is an insufficient dose distribution in Q cell fractions.[78]

Meanwhile, high-LET radiation provides higher RBE for cell killing, reduced oxygen effect, and reduced dependence on the cell cycle,[12] making it potentially superior to low-LET radiation in the treatment of malignant tumors. Therefore, using our method for selectively detecting the response of Q cells within solid tumors,[39] we have examined the characteristics of radiosensitivity in total (= P + Q) and Q cell populations in solid tumors irradiated with carbon ions at various LET values in a 6-cm SOBP compared to those irradiated with ^{60}Co γ-rays and reactor thermal and epithermal neutrons at the Kyoto University Research Reactor Institute. Further, we have examined the effect of the post-irradiation oxygenation status on recovery from radiation-induced damage in total and Q cell populations in solid tumors *in vivo* after low-LET γ-ray and carbon-ion irradiation. In addition, in the future, we will analyze the relationship between the depth within the SOBP and the value of RBE based on the sensitivity of Q tumor cells, and further optimize carbon-ion therapy.

Method for selectively detecting the response of Q cells in solid tumors to DNA-damaging treatment

Using asynchronous tumor cell cultures and cell cultures

blocked for a short time with an S phase cell toxin, hydroxyurea, the cell-survival curve, which cannot be obtained directly by routine colony formation assay, can be calculated using the micronucleus (MN) frequency and the regression line between the surviving fraction and MN frequency for asynchronous cell cultures.[79] Therefore, it was thought to be possible to detect the response of Q cells in solid tumors using immunofluorescence staining for 5-bromo-2'-deoxyuridine (BrdU) and the MN assay following continuous BrdU labeling of intratumor P cells.

Tumor-bearing mice received various DNA-damaging treatments after 10 injections of BrdU at 12-h intervals or continuous administration of BrdU to label all P cells in solid tumors. The tumors were then excised and trypsinized. The obtained tumor cell suspensions were incubated with a cytokinesis blocker cytochalasin-B for 48–72 h, and the MN frequency in these cells without BrdU labeling was determined using immunofluorescence staining for BrdU. This MN frequency was then used to determine the surviving fraction of the BrdU-unlabeled cells from the regression line obtained between the MN frequency and the surviving fraction determined for total cells in the tumor. Thus, a cell-survival curve could be determined for cells not labeled by BrdU, which could be regarded for all practical purposes as Q cells in a solid tumor.[80] Incidentally, the apoptosis frequency instead of the MN frequency was also shown to be applicable to this method.[39]

Demonstrated characteristics of quiescent cells in solid tumors

Using our method after low-LET irradiation of tumor-bearing mice, the following characteristics of Q cells in murine solid tumors were clarified: Q tumor cells are more radioresistant than total (P + Q) tumor cells; Q cells have greater potentially lethal damage repair (PLDR) capacity than total cells; and Q cell populations include a higher hypoxic fraction (HF) than total cells.[80] It was also indicated that the clonogenicity of Q cells is lower than that of P cells, and that the HF of Q cells is largely comprised of chronically HF with a smaller proportion of acutely HF. Concerning the *p53* status of tumor cells, SAS/m*p53* tumors (which harbor mutated *p53*) include a larger size of not only HF but also chronically HF than SAS/neo tumors (which harbor normal *p53*), and Q cell populations in both tumors include higher HF, particularly chronically HF, than total cell populations, especially in regard to SAS/neo tumors.[39]

Meanwhile, when the solid tumors were irradiated with high-LET fast neutrons or reactor neutrons, the difference in intrinsic radiosensitivity between total tumor and Q cells was markedly reduced, compared with low-LET photons, especially at high radiation doses.[81,82] As for neutron capture reaction with ^{10}B-compounds, L-*para*-boronophenylalanine (BPA) increased the sensitivity of the total cells more than sodium mercaptoundecahydro (BSH). However, BPA-treated Q cells were less sensitive than BSH-treated Q cells. The difference in sensitivity between total and Q cells was greater with ^{10}B-compounds, especially BPA.[82] Q cells showed greater PLDR capacity than total cells. γ-Ray irradiation and neutron irradiation with BPA induced greater PLDR capacity in both cell populations. In contrast, thermal neutron irradiation without the ^{10}B-compound induced the smallest PLDR capacity in both. The use of the ^{10}B-compound, especially BPA, increased the PLDR capacity in both cell populations, and made the PLDR patterns of both look like those induced by γ-ray irradiation.[83] In both total and Q tumor cells, HF increased immediately after neutron irradiation. Reoxygenation after each neutron irradiation occurred more rapidly in total cells than in Q cells. In both cell populations, reoxygenation appeared to be rapidly induced in the following order: neutron irradiation without ^{10}B-compounds > neutron irradiation following BSH injection > neutron irradiation following BPA administration > γ-ray irradiation.[84]

Response of total and quiescent tumor cells in vivo to carbon ions compared with γ-rays and reactor neutrons

SCC VII tumor–bearing mice were continuously given BrdU to label all intratumor P cells. Then, they received carbon ions or γ-rays at a high dose rate (HDR, 1.0–2.0 Gy/min) or reduced dose rate (RDR, 0.035–0.040 Gy/min). Other tumor-bearing mice received reactor thermal or epithermal neutrons at RDR. Immediately after HDR and RDR irradiation and 12 h after HDR irradiation, the response of Q cells was assessed for MN frequency using immunofluorescence staining for BrdU. The response of total (= P + Q) tumor cells was determined from the BrdU non-treated tumors.

The difference in radiosensitivity between total and Q cell populations under γ-ray irradiation was markedly reduced with reactor neutrons and carbon ions, especially at higher LET, which is available at a deeper point within SOBP of carbon ions. More pronounced repair in Q cells than total cells through a delayed assay or a decrease in dose rate under γ-ray irradiation was efficiently inhibited with carbon ions, especially at higher LET. Under RDR irradiation, the radiosensitivity to high-LET carbon ions was quite similar to that to reactor thermal and epithermal neutrons (Fig. 2). In terms of tumor cell–killing effect as a whole, including Q tumor cells, carbon ions, especially at higher LET, are very useful for suppressing dependence on the heterogeneity within solid tumors as well as depositing radiation dose precisely.[38,85]

Relationship between post-irradiation tumor oxygenation status and radiosensitivity of irradiated tumors in vivo

BrdU-labeled SCC VII tumor–bearing mice received γ-

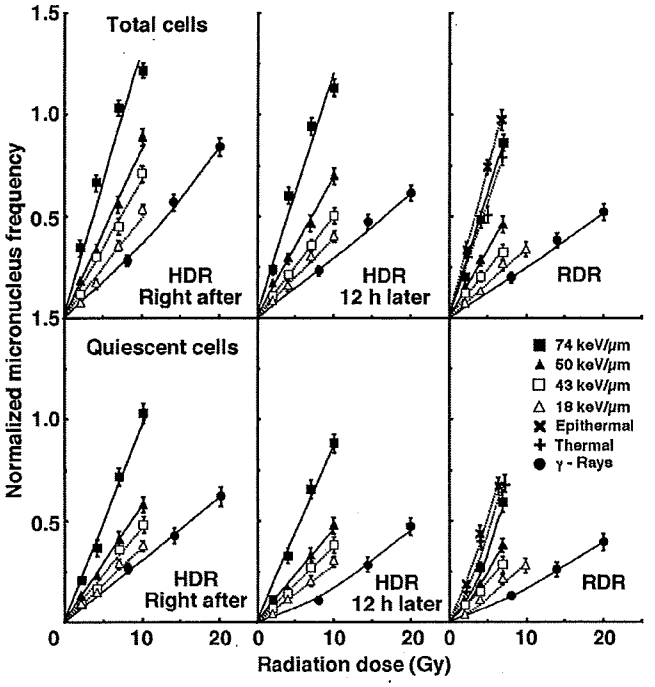

Fig. 2. Dose-response curve of normalized micronucleus frequency for total (upper panel) and quiescent (lower panel) tumor cell populations as a function of radiation dose immediately after high dose-rate (HDR) irradiation, 12 h after HDR irradiation, and immediately after reduced dose-rate (RDR) irradiation are shown in the left, middle, and right panel, respectively. Open triangles, open squares, solid triangles, and solid squares represent the normalized micronucleus frequency after carbon-ion irradiation at linear energy transfer of 18, 43, 50 and 74 keV/μm, respectively. Solid circles represent the data after γ-ray irradiation. The cross- and X-shaped symbols represent the data after reactor thermal and epithermal neutron irradiation, respectively. Bars represent standard error.

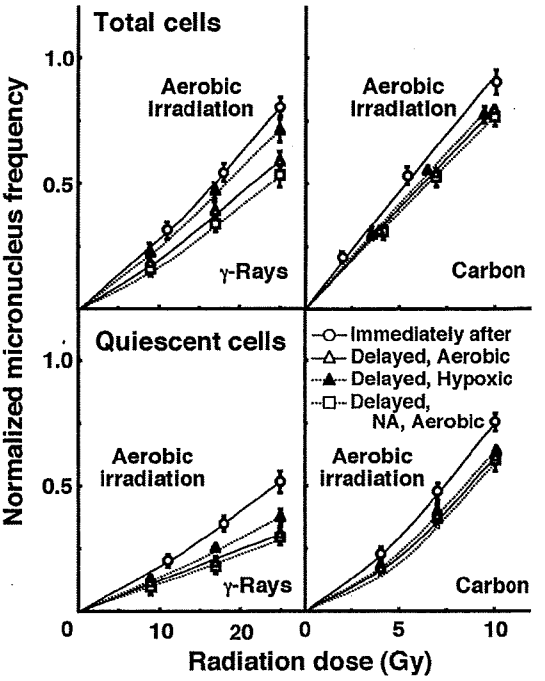

Fig. 3. Dose response curve of normalized micronucleus frequency for total (upper panel) and quiescent (lower panel) tumor cells as a function of dose immediately and 9 h after irradiation. The data after γ-ray and carbon-ion irradiation are shown in the left and right panels, respectively. The data after irradiation under aerobic condition are shown. Open circles, open triangles, solid triangles, and open squares represent the data immediately after irradiation, after keeping tumors aerobic for 9 h following irradiation, after keeping tumors hypoxic for 9 h following irradiation, and after keeping tumors aerobic for 9 h following the administration of nicotinamide (NA) immediately after irradiation, respectively. Bars represent standard error.

rays or carbon ions with or without tumor clamping to induce hypoxia. Immediately after irradiation, cells from some tumors were isolated, or acute hypoxia-releasing nicotinamide was loaded to the tumor-bearing mice. For 9 h after irradiation, some tumors were kept aerobic or hypoxic. Then, isolated tumor cells were incubated with a cytokinesis blocker. Finally, the response of Q and total tumor cells was assessed for MN.

Inhibition of recovery from radiation-induced damage by keeping irradiated tumors hypoxic after irradiation and promotion of recovery by nicotinamide loading were observed more clearly with γ-rays, after aerobic irradiation and in total cells than with carbon ions, after hypoxic irradiation and in Q cells, respectively (Fig. 3). The tumor oxygenation status following irradiation can influence recovery from radiation-induced damage, especially after aerobic γ-ray irradiation in total cells. In other words, the tumor oxygenation status not only during irradiation but also after irradiation can affect the radiosensitivity of solid tumors, and especially with γ-rays. In this respect, carbon ions are promising because of their efficient suppression of recovery almost independently of the tumor oxygenation status.[86]

Carbon ions – conclusion

In terms of the tumor cell-killing effect as a whole, including intratumor Q cell control, carbon-ion therapy can be a very promising treatment modality for deep-seated refractory tumors because of its very efficient cytotoxic effect on intratumor Q cell populations particularly at a deeper point within SOBP of carbon ions, taking into account the very advantageous potential of depositing the radiation dose very precisely using SOBP.[38] Further, in both total and Q tumor cells, carbon-ion irradiation is less dependent on the oxygen condition at the time of irradiation, with little or no recovery from radiation-induced DNA damage, as well as being without dependence on the post-irradiation intratumor oxygenation status, thus leading to higher RBE

compared with γ-ray irradiation.[86]

p53-INDEPENDENT APOPTOSIS IS A POTENTIAL TARGET FOR HIGH-LET HEAVY-ION THERAPY

Background

The evaluation of biological markers is of interest in view of their potential ability to predict the outcome of cancer therapy. It has been reported that *p53* mutations and deletions occur in many advanced human cancers,[87] and lead to resistance to X-rays[44–46,88,89] used for cancer therapy (Fig. 4*a*). Thus the genetic and functional *p53* status may be important in guiding therapeutic strategy for cancer patients.[90] The p53 protein has multiple functional activities, (e.g., as a sequence-specific transcription factor whose transcriptional target genes induce growth arrest and apoptosis).[91] In mutated *p53* (m*p53*) tumors, resistance to radiotherapy may result from failure to induce apoptosis, because X-rays kill cancer cells partly *via* apoptosis. The involvement of *p53* in the sensitivity of many cell types to low-LET radiation is well established.

As discussed in the Introduction, high-LET heavy ions have several potential advantages over photons: (*i*) excellent dose distribution, (*ii*) high RBE, (*iii*) reduction in oxygen enhancement ratio, (*iv*) little variation in cell cycle-related radiosensitivity, and (*v*) small influence from radiation repair process. The spatial distribution of nuclear DNA lesions produced by charged particles depends on the ion track structure.[92] As a result, high-LET heavy ions have highly lethal effects, even on radioresistant tumors. It is conceivable that effective therapeutic strategies may be designed based on the genetic and biochemical events involved in cell death. Therefore, accurate characterization and quantification of the process by which radiation leads to cell death (e.g., apoptosis and necrosis) have become increasingly important in further understanding the biological effectiveness of high-LET radiation. Currently, little information is available on the relationship between *p53* status in tumor cells and on the ability to undergo apoptosis after high-LET irradiation. However, work has been done in this area, and some basic studies are reviewed here concerning the possibility that *p53*-independent apoptosis offers an effective target for high-LET heavy-ion therapy.

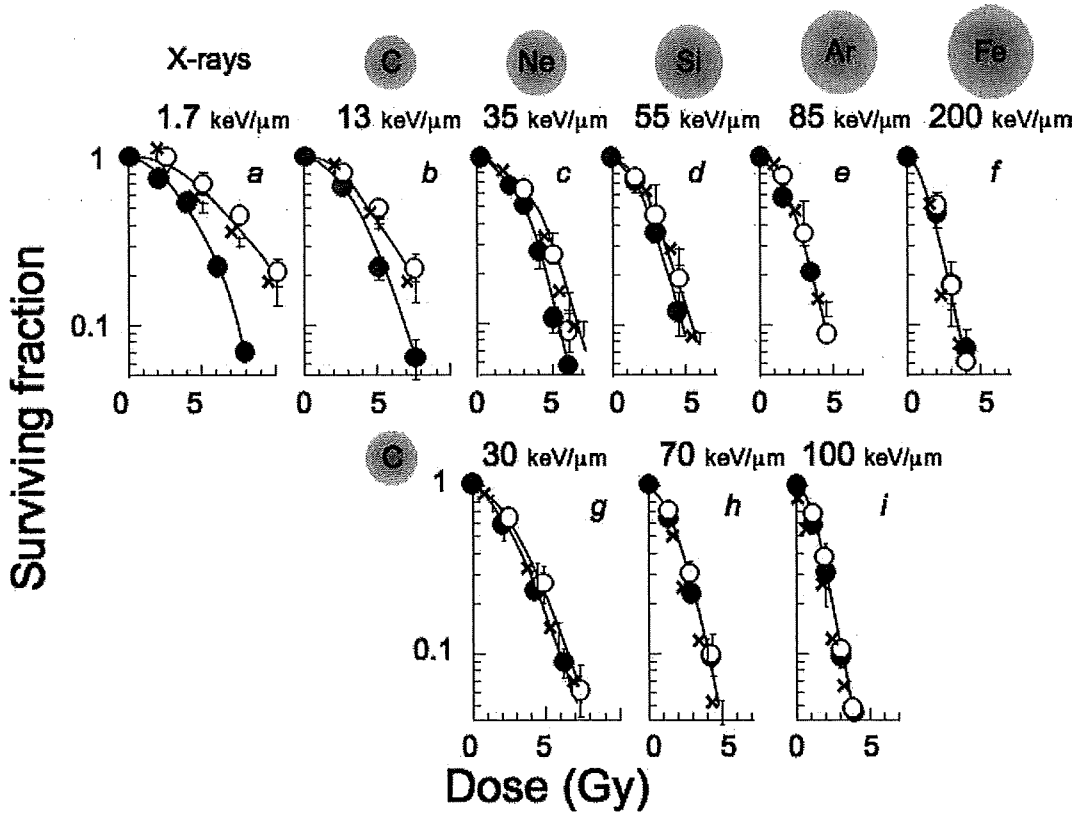

Fig. 4. Survival curve for cultured human lung cancer cells.[93,94] Panel *a*, X-rays (200 kVp, 1.7 keV/μm); *b*, carbon (290 MeV/u, 13 keV/μm); *c*, neon (400 MeV/u, 35 keV/μm); *d*, silicon (490 MeV/u, 55 keV/μm); *e*, argon (500 MeV/u, 85 keV/μm); *f*, iron (500 MeV/u, 200 keV/μm); *g*, carbon (290 MeV/u, 30 keV/μm); *h*, carbon (290 MeV/u, 70 keV/μm); *i*, carbon (290 MeV/u, 100 keV/μm) ions. x, *p53*-null cells; ○, m*p53* cells; ●, wt*p53* cells. Error bars indicate standard deviation.

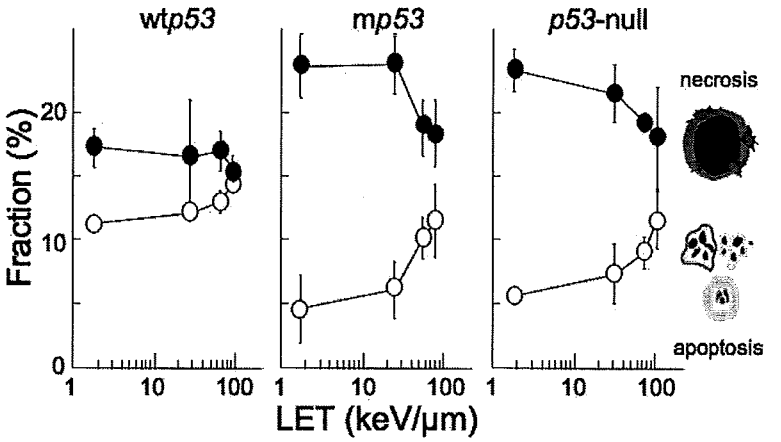

Fig. 5. Radiation-induced apoptosis and necrosis dependence on linear energy transfer (LET).[94] Cells were cultured in normal medium for 48 h after irradiation with a 30% survival dose and analyzed by acridine orange/ethidium bromide staining method. ○, apoptotic cells; ●, necrotic cells. Error bars indicate standard deviation.

Survival after exposure to different heavy-ion beams

Wild-type (wt) *p53*, m*p53* and *p53*-null cell lines used were derived from H1299 human lung cancer cell line that is *p53*-null. At HIMAC of NIRS, cells were exposed to different types of heavy ions, such as carbon (energy, 290 MeV/u; LET, 13 keV/μm), neon (400 MeV/u, 35 keV/μm), silicon (490 MeV/u, 55 keV/μm), argon (500 MeV/u, 85 keV/μm) and iron (500 MeV/u, 200 keV/μm) ions (Fig. 4*b–f*). Cellular radiosensitivity was determined using the colony formation assay. It was observed that wt*p53* cells were about 1.6-fold more sensitive to X-rays than the other cell lines (Fig. 4*e* and *f*).[93] However, it is still unclear which factor affects *p53*-independent radiosensitivity: ion species or LET.

Survival after exposure to carbon ions at different LET

Using polymethyl methacrylate or plastic film absorbers, cellular sensitivity to 290 MeV/u carbon ions at different LET (13, 30, 70 and 100 keV/μm) was examined (Fig. 4*b*, *g–i*). As LET increased up to 100 keV/μm, there was almost no significant difference in survival among the cell lines (Fig. 4*h* and *i*).[94] Thus, the range of LET, but not ion species, appears to determine *p53*-independent radiosensitivity.

LET dependence of radiation-induced apoptosis and necrosis

Cell death through apoptosis and necrosis was evaluated with acridine orange (AO)/ethidium bromide (EB) double staining for fluorescence microscopy. This method employs the differential uptake of the fluorescent DNA binding dyes AO and EB, allows morphologic visualization of chromatin condensation in the stained nucleus, and permits distinguishing viable, apoptotic, and necrotic cells. Apoptosis increased with increasing LET, even at isosurvival doses among cell lines (Fig. 5).[94] These results also agree well with a previous report using *p53*-deficient human lymphoblastoid cells[95] and Chinese hamster cells bearing an m*p53* gene.[96] It was suggested that high-LET radiation might induce not only *p53*-dependent apoptosis but also *p53*-independent apoptosis, resulting in much more severe DNA damage than low-LET radiation. The fact that the surviving fraction after high-LET irradiation was almost the same among wt*p53*, m*p53*, and *p53*-null cells suggests that these cells may die through *p53*-independent pathways. Therefore, radiotherapy with high-LET radiation is certainly of interest as a modality in interdisciplinary cancer therapy regardless of the cellular *p53* status.

p53-independent apoptosis pathways

Caspases serve as the main effectors of apoptosis. Two distinct pathways upstream of the caspase cascade have been identified: death receptor-induced apoptosis and mitochondrial stress-induced apoptosis. Death receptors (e.g., CD95/APO-1/Fas, TNF-R, TRAIL-R) trigger caspase-8, and the mitochondria subsequently release apoptogenic factors (cytochrome *c*, Apaf-1, AIF), leading to the activation of caspase-9.[36] Although the two pathways are intimately connected, any cross-communication or crosstalk is minimal, and the two pathways operate largely independently of each other. The caspase systems remain largely unknown in *p53*-independent apoptosis after high-LET irradiation. Human gingival cancer cells (Ca9-22 cells) containing m*p53* gene also showed high sensitivity to high-LET radiation with high apoptotic frequency.[97] Caspase-3 activity was analyzed by Western blotting and flow cytometry. Caspase 3 was cleaved and activated upon high-LET irradiation, leading to cleavage of poly (ADP-ribose) polymerase.[97] In addition, caspase-9 inhibitor suppressed caspase-3 activation and apoptosis induction resulting from high-LET radiation to a greater

extent than caspase-8 inhibitor.[97] These results suggest that caspase-9 may contribute to caspase-dependent apoptosis after high-LET irradiation, i.e., high-LET radiation may activate the mitochondrial-associated apoptotic pathway in a *p53*-independent manner.[36] Apoptotic pathways triggered by high-LET radiation do not require *p53*. Severe damage induced by high-LET radiation acts as a trigger for activation of the caspase-9–related apoptotic pathway, rather than the caspase-8 apoptotic pathway. After caspase-9 activation by high-LET radiation, caspase 3 is activated by caspase-9, and this leads to *p53*-independent apoptosis. In this situation, caspase 8 would not be activated because p53 is defective and not functional, and activation of the death receptor pathways would make minor contributions to apoptosis induction.

High-LET radiation can induce apoptosis effectively regardless of the *p53* status. Thus, cells exposed to high-LET radiation appear to enter apoptosis through the action of downstream effectors of *p53*-centered signal transduction pathways, regardless of the presence or absence of functional p53. The question of whether high-LET radiation triggers the mitochondrial apoptosis pathway directly or activates upstream effectors of the mitochondrial pathway remains to be addressed. Further studies should provide new insights into high-LET radiation–enhanced apoptosis, observed to occur in response to selective activation of the mitochondrial apoptotic factor caspase 9 in a *p53*-independent manner.

Prospective views

These findings suggest that high-LET heavy-ion therapy would be a valid application for patients harboring m*p53* and *p53*-null cancer cells. In addition, an advanced charged particle therapy for cancer should be a human-friendly therapy that places fewer physical burdens on patients. However, because of the prohibitive cost and huge accelerator size, there are as yet only a few heavy-ion therapy facilities in the world. Consequently, at present, not many cancer patients can receive heavy-ion therapy. For future investigation, it is proposed that the elucidation of *p53*-independent apoptosis-related genes could provide new insights into cancer radiotherapy that can be used regardless of *p53* status (Fig. 6). Therefore, it is important to characterize these radiation-regulated genes and pathways in heavy ion–irradiated cells, and to elucidate the regulatory mechanisms involved in the expression of these genes.

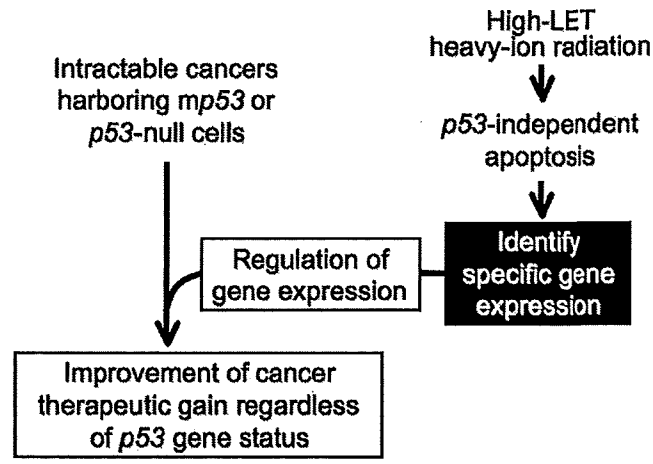

Fig. 6. Strategy for improving cancer therapy regardless of *p53* status. LET, linear energy transfer.

BCL-2 AS A POTENTIAL TARGET FOR HEAVY-ION THERAPY

As mentioned in the previous section, genetic changes that accompany cancer development and progression endow tumor cells with a survival advantage over their normal counterparts, often leading to a poor prognosis because of resistance to a multitude of therapeutic modalities. Of these, Bcl-2 is an anti-apoptotic protein initially identified as an oncogene in follicular B-cell lymphoma where the t(14;18) chromosomal translocation results in constitutive upregulation of *Bcl-2* expression.[98,99] *Bcl-2* overexpression occurs in the tumors of 35–50% of cancer patients; for instance, *Bcl-2* is overexpressed in 50–100% of colorectal cancer, 60–80% of breast cancer, 60–80% of small cell lung cancer, and 65% of melanoma.[99,100] Significant evidence has accumulated that *Bcl-2* overexpression has been associated with resistance to conventional photons and chemotherapeutic agents.[99–101] Restoring susceptibility by nullifying the effects of Bcl-2 would hence be an attractive strategy to improve therapeutic efficacy. Despite a series of studies having focused on tumor sensitization to photons by chemical and antisense-based Bcl-2 inhibitors,[100–102] the potential impact of heavy ions on *Bcl-2* overexpressing tumors remains uncharacterized. To address this, we used Bcl-2 cells (human cervical cancer–derived HeLa cells stably overexpressing *Bcl-2*) and Neo cells (neomycin resistant gene–expressing HeLa cells), with the former expressing nine-fold higher levels of Bcl-2 proteins than the latter.[26,102,103]

At first, the effect of heavy-ion irradiation alone was examined.[37] Colony formation assay revealed that, while Bcl-2 cells were more resistant to ^{60}Co γ-rays (LET, 0.2 keV/μm) and helium ions (energy, 12.5 MeV/u; LET, 16.2 keV/μm) than Neo cells, exposure to five different types of heavy ions (76.3–1610 keV/μm) yielded similar clonogenic survival regardless of *Bcl-2* overexpression.[37] Terminal deoxynucleotidyl transferase-mediated dUTP-biotin nick-end labeling assay showed that irradiation with carbon ions (18.3 MeV/u, 108 keV/μm), which gave maximum RBE for survival, enhanced the apoptotic response of Bcl-2 cells and decreased the difference in apoptotic incidence between Bcl-2 and Neo cells.[37] Flow cytometric analysis demonstrated

that, unlike the case for γ-rays, carbon-ion exposure prolonged G_2/M arrest, and it occurred more extensively in Bcl-2 cells than in Neo cells.[37] Our preliminary data obtained with the Western blot analysis illustrated that whereas exposure to either carbon ions or γ-rays fails to alter the amount of Bcl-2 proteins, the former augments Bcl-2 phosphorylation at serine 70 more effectively than the latter (unpublished data), warranting further studies to delineate the intermediate molecular events. Collectively, these results indicate that high-LET heavy ions overcome tumor radioresistance caused by *Bcl-2* overexpression, which might be potentially accounted for at least in part by the enhanced apoptotic response and prolonged G_2/M arrest. Thus, heavy-ion therapy may be a promising modality for *Bcl-2* overexpressing radioresistant tumors. Moreover, noteworthy is not merely the fact that *Bcl-2* overexpression (and *p53* mutations as reviewed in the previous section) arises in nearly half of human cancers and is related to radioresistance and chemoresistance,[99,100,104] but also that such radioresistance can be overcome with heavy ions.[36,37] Heavy ions thence appear to effectively inactivate a wide variety of radioresistant tumors, and possibly chemoresistant tumors as well.

Secondly, the combinational effect of Bcl-2 inhibitor and heavy ions was assessed.[41] Ethyl 2-amino-6-bromo-4-(1-cyano-2-ethoxy-2-oxoethyl)-4H-chromene-3-carboxylate (HA14-1) is a novel Bcl-2 inhibitor recently identified from *in silico* screening, and is a nonpeptidic small-molecule ligand (molecular weight = 409) of a Bcl-2 surface pocket.[105] Mounting evidence has indicated that HA14-1 selectively disturbs the interaction between Bcl-2 and Bax and sensitizes tumors to photons.[106,107] On the one hand, colony formation assay showed little difference in the cytotoxicity of HA14-1 to Bcl-2 cells and Neo cells, such that its 1-h treatment at 15 μM resulted in a surviving fraction of 58% for both cell types.[41] Compared with irradiation alone, pre-irradiation treatment for 1 h with 15 μM HA14-1 potentiated killing of Bcl-2 and Neo cells by carbon ions and γ-rays.[41] On the other hand, it would be desirable if a radiosensitizer could exert cytotoxic and sensitizing effects preferentially to tumors with minimal adverse effects to normal cells, and this was therefore tested with AG01522 primary normal human diploid fibroblasts. The surviving fraction of 15 μM HA14-1-treated AG01522 cells was 50%,[41] showing that the cytotoxicity of HA14-1 in AG01522 cells was almost identical to that in Bcl-2 and Neo cells. However, in contrast to the case for Bcl-2 cells and Neo cells, pre-irradiation HA14-1 treatment did not affect the sensitivity of AG01522 cells to carbon ions and γ-rays,[41] predicting that HA14-1 may produce preferential radiosensitization of tumor cells.

Altogether, these findings highlight the notion that Bcl-2 might be an attractive target for improving the efficacy of heavy-ion therapy. The underlying mechanisms and the *in vivo* validity need to be further examined.

EFFECTS OF HEAVY IONS AND PHOTONS ON THE PROCESSES OF METASTASIS AND ANGIOGENESIS

Background

In recent years, radiotherapy has attained excellent local control and reduction of the damage to normal tissues as a result of the development of highly precise irradiation techniques such as stereotactic irradiation, intensity-modulated radiation therapy and particle radiotherapy. However, radiotherapy has been basically regarded as a local cancer therapy like surgery; one of the next concerns would hence be whether it is able to inhibit distant metastasis, the main cause of mortality in cancer patients. The metastatic process of malignant tumor cells generally consists of (*i*) detachment of cells from the primary tumor, (*ii*) migration to extracellular matrix (ECM), (*iii*) degradation of basement membrane, (*iv*) invasion into blood vessels, (*v*) circulation in blood flow, (*vi*) escape to extravascular matrices and (*vii*) implantation to target organs. Angiogenesis is not only a prerequisite for tumor growth and development, but is also a major factor affecting the metastatic spread of malignant cells. Here we discuss the effects of heavy-ion and photon irradiation on the processes of metastasis and angiogenesis.

Radiation effects on the process of metastasis

The first study of the effects of local X-ray irradiation on metastasis has been reported by Kaplan and Murphy in 1949,[108] who showed that irradiated mice develop more frequent lung metastasis than untreated mice. Since then, a similar phenomenon has also been demonstrated by several investigators, but others have reported that the metastatic potential decreased after irradiation.[109] Such discrepancy might be due to differences in tumor types, tumor ages, radiation doses and experimental design (especially the timing factor). According to a review by von Essen,[109] four possible mechanisms that might influence the rate of metastasis following tumor irradiation can be considered: (*i*) direct alteration of tumor cells by irradiation, (*ii*) abscopal effect of local irradiation, (*iii*) local effect of irradiation facilitating entry of tumor cells into circulation and (*iv*) local effect of irradiation delaying tumor progression, thus allowing increased time for escape of tumor cells into circulation.

Recent progress in molecular biology has made it feasible to investigate the molecular mechanisms responsible for radiation effects on metastasis. Wild-Bode *et al.*[110] have reported that sublethal photon irradiation promotes the invasiveness of glioblastoma cells dose-dependently. The mechanism underlying this promotion of metastatic potential of cancer cells involved increased matrix metalloproteinase 2 (MMP-2) activity and upregulated expression of the cell-adhesion molecule integrin αVβ3. MMPs constitute a family of Zn^{2+}-dependent enzymes essential for ECM turnover

under normal and pathological conditions.[110] Especially, MMP-2 can degrade type IV collagen, one of the major components of the basement membrane, resulting in the promotion of tumor invasion and metastasis.[110] There have been many reports on the enhancement of MMP-2 activity by photon irradiation.[111] The integrin family of adhesion molecules is a class of ECM receptors consisting of multiple subtypes of α and β chains that, in combination, form various heterodimers with distinct cellular and adhesive characteristics.[112] Integrin-mediated adhesion to ECM triggers intracellular signaling that modulates cell proliferation, shape, migration, invasion and survival.[113] The vitronectin receptor, integrin αVβ3, also appears to be associated with increased invasiveness.[114] A monoclonal antibody against integrin αVβ3 abolishes such increased invasiveness, indicating that reduction of integrin αVβ3 can inhibit cell migration.[115] We have also confirmed that photon irradiation promotes cell migration capability concomitant with upregulation of integrin αVβ3 at a low dose.[34]

Qian *et al.*[116] reported that radiation increases the expression of hepatocyte growth factor (HGF) receptor/c-Met in pancreatic cancer cells *in vitro*. HGF is a stroma-derived cytokine that has multiple functions in various cell types including mitogenic, motogenic, morphogenic and antiapoptotic activities through a transmembrane tyrosine kinase receptor (c-Met). Radiation-enhanced expression of c-Met promotes HGF-mediated cell scattering and invasion.[116] A recombinant HGF antagonist can effectively inhibit photon-induced increases in invasive potential.[116] Overexpression of vascular endothelial growth factor (VEGF), an important growth factor in controlling angiogenesis, has been associated with tumor progression and metastasis. Photon irradiation enhanced the release/production of VEGF in human neuroblastoma cells, and these alterations have been associated with their increased metastatic potential.[117]

In many solid tumors, the stroma is increasingly being recognized for its importance in promoting tumor proliferation, invasion and metastasis. Ohuchida *et al.*[118] demonstrated that photon-irradiated stromal fibroblasts strongly promote the invasiveness of pancreatic cancer cells through increased activation of HGF/c-Met signals compared with non-irradiated fibroblasts. An HGF antagonist blocks the increased invasiveness of pancreatic cancer cells when co-cultured with photon-irradiated fibroblasts.[118] Paquette *et al.*[119] found that irradiation of the basement membrane enhances the invasiveness of breast cancer cells with upregulation of MMP-2 and membrane type 1-MMP from cancer cells. Consequently, tumor-stroma interactions, which play a significant role in tumor development and metastasis, should provide important therapeutic targets.

High-LET carbon ions have been shown to be more effective for cell killing than photons. Only a few studies have addressed the effects of particle irradiation on the functioning of cells with metastatic potential. We hypothesized that particle irradiation might inhibit the metastatic potential by ion beam–specific biological effects, and first focused on *in vitro* models including adhesion, migration, invasion, and the expression level and activity of molecules related to metastasis such as integrins αVβ3 and β1, and MMP-2.[34] Carbon-ion irradiation decreased cell migration and invasion in a dose-dependent manner and strongly inhibited MMP-2 activity.[34] In carbon ion–irradiated cancer cells, the number of pulmonary metastases was decreased significantly *in vivo*.[34] We further investigated the effect of carbon-ion irradiation on gene expression associated with metastasis and angiogenesis of non-small-cell lung cancer cells using microarray.[120] Carbon-ion irradiation inhibited the gene expression of *ANLN* (anillin), which is involved in the activation of Rho and the phosphatidylinositol 3-kinase/Akt signaling pathway associated with cell migration.[120] Goetze *et al.*[121] demonstrated that carbon-ion irradiation inhibited integrin expression, thus leading to the inhibition of migration ability *in vitro*.

Radiation effects on the process of angiogenesis

The process of tumor development requires adequate nutrition and oxygen. Usually, tumor mass cannot exceed a size limit of 1–2 mm diameter without blood vessel formation. Angiogenesis, the formation of new capillaries from pre-existing vessels, is a complex process of ECM degradation, migration and proliferation of endothelial cells and, finally, tube formation.[122] Tumor vasculature is often structurally and functionally abnormal, and tortuous and leaky vasculature leads to interstitial hypertension, hypoxia and acidosis. Therefore, angiogenesis plays a key role in cancer cell survival, local tumor growth, and development of distant metastases. The combination of antiangiogenic agents and radiotherapy has been extensively investigated with the aim of improving therapeutic gain in preclinical and clinical settings.

Some studies have shown that low-dose irradiation of endothelial cells induces angiogenic factors, promoting angiogenesis. Sonveaux *et al.*[123] reported that low-dose photons activate the nitric oxide pathway in endothelial cells, leading to phenotypic changes promoting tumor angiogenesis. A nitric oxide synthase inhibitor prevents photon-induced tube formation.[123] Abdollahi *et al.*[124] found that photons increase VEGF and basic fibroblast growth factor in prostate cancer cells and VEGF receptor in endothelial cells. In a co-culture invasion model of prostate cancer cells and endothelial cells, selective irradiation of cancer cells promotes endothelial cell invasion through the basement membrane.[124] Receptor tyrosine kinase inhibitors attenuate endothelial cell invasion in response to irradiated cancer cells in the co-culture model.[124]

The inhibition of further tumor growth by tumor mass is generally observed in some clinical and experimental malignancies due to the production of angiogenesis inhibitors by

the primary tumor. Therefore, removal of the primary tumor can be followed by the rapid growth of distant subclinical metastases.[125] These phenomena are similar to that reported by Camphausen *et al.*[126] in the eradication of photon-treated primary tumor. Administration of recombinant angiostatin, an angiogenesis inhibitor, suppresses the growth of the metastases after local control of the primary tumor with radiotherapy.[126] This means that combination treatment with angiogenesis inhibitor offers the promise of control of distant metastasis, thus improving the therapeutic gain.

It is well known that hypoxia contributes to radioresistance, i.e., a lack of oxygen to facilitate DNA damage. Therefore, there is concern that a reduction in tumor oxygenation resulting from inhibition of angiogenesis with destruction of the tumor vasculature could render the tumor hypoxic and thereby more radioresistant. Wachsberger *et al.*[127] observed that treatment with a tumor vasculature–damaging agent when given at an inappropriate time prior to irradiation results in less antitumor activity compared with radiotherapy alone. This result can be explained by tumor hypoxia induced by the agent. However, most researchers have shown that antiangiogenic agents can enhance the tumor response to radiation.[128] Jain[129] has proposed that the angiogenesis inhibitor can also transiently normalize the abnormal structure and function of tumor vasculature to make it more efficient for oxygen and drug delivery. Additional work is awaited to determine the optimal timing and duration of antiangiogenic therapy combined with radiotherapy for maximizing therapeutic gain.

Little is known about the effects of heavy ions on cell function associated with angiogenesis. We hypothesized that particle irradiation might inhibit angiogenesis as well as the metastatic potential of cancer cells. To confirm this hypothesis, we used *in vitro* models to observe the expression level and activity of molecules related to metastasis such as integrin $\alpha V\beta 3$ and MMP-2.[33] After carbon-ion irradiation, the adhesiveness and migration of cancer cells to vitronectin were inhibited and the capillary-like tube structures formed by cancer cells in three-dimensional culture were destroyed, concomitant with the inhibition of MMP-2 activity and downregulation of integrin $\alpha V\beta 3$.[33] Surprisingly, these structures could be destroyed even at a dose as low as 0.1 Gy.[33] Therefore, these results suggest that destruction of the vascular structure may not be induced by inhibition of endothelial cell growth but by other mechanisms such as inhibition of MMP-2 and downregulation of integrin $\alpha V\beta 3$.

Conclusion

Many investigators have shown that photon irradiation enhances the metastatic process of malignant tumor cells and angiogenesis at a sublethal dose. Although the molecular mechanisms underlying these phenomena seem complex, tumor-stroma interactions may play a significant role in tumor development and metastasis. Heavy-ion irradiation suppresses the metastatic potential of cancer cells and angiogenesis even at lower doses. Particle radiotherapy may be superior to conventional photon therapy in its possible effects for the prevention of metastasis of irradiated malignant tumor cells in addition to its physical dose distribution. Further intensive studies are also necessary to elucidate the relevant molecular mechanisms involved in angiogenesis- and invasion-related molecules specifically associated with particle irradiation.

BREAST CANCER INDUCTION BY LOW-DOSE HEAVY-ION RADIATION

Background of heavy ion–induced carcinogenesis

Based on many biological advantages as discussed in previous sections, continuing efforts to improve heavy-ion therapy have established more accurate control of cancer and longer patient survival than conventional photon therapy and, hence, its utilization has steadily spread. In turn, however, the potential risk for late adverse effects, especially for developing secondary cancers, is becoming a new matter of concern. Knowledge is therefore required concerning the secondary cancer risk from heavy-ion radiation; nevertheless, such information is still very scarce in both epidemiological and experimental aspects.

Breast (mammary gland) is one of the organs irradiated during radiotherapy for the chest area and is a susceptible organ to the cancer-inducing effect of low-LET radiation. Its high susceptibility to cancer after irradiation has been revealed by epidemiological studies on Japanese atomic bomb survivors and medically irradiated subjects.[130,131] Compared to the background breast cancer incidence, the risk of female breast cancer after low-LET irradiation increases as a linear function of dose by 0.87-fold per Gy (i.e., the excess relative risk is 0.87/Gy).[130] In contrast, there is no such information on human breast cancer risk from heavy ions. Nevertheless, it is of note that neutron radiation is reported to have a very high RBE of 13 to 100 at lower doses[132,133] for induction of rat mammary cancer, a widely used animal model of human breast cancer.[134] The very high RBE of neutrons renders it an important subject to clarify whether the RBE of heavy ions is similarly high. However, there are only limited data available on mammary gland carcinogenesis by heavy ions from the BEVALAC synchrotron at the University of California, Berkeley, USA, the AGS synchrotron at the Brookhaven National Laboratory, USA, and the HIMAC synchrotron (Table 2).[135–137]

The SOBP carbon-ion beam (LET, 40–90 keV/μm) from HIMAC has been intensively used to treat cancers of various sites since 1994.[7] Several animal experiments have been conducted to determine the effect of carbon ions from HIMAC on the induction of tumors of the skin, kidney, stomach, adrenal, ovary and thymus,[138–142] and recent reviews have elegantly covered such information on carcino-

Table 2. Relative biological effectiveness (RBE) of high linear energy transfer radiation for induction of rat mammary cancer.

Particle	Energy	Strain	Dose (Gy)	RBE	Dose response curve
Neutron[132]	430 keV	Sprague-Dawley	0.001–0.06	13–100	Convex upward
Neutron[133]	0.5 MeV	WAG/Rij	0.05–0.2	9–14	Linear
Neon ion[135]	6.6 GeV	Sprague-Dawley	0.02	> 5	Linear
Iron ion[136]	1 GeV	Sprague-Dawley	0.05–0.16	< 10 *	Linear
Carbon ion[137]	290 MeV	Sprague-Dawley	0.05–1	2–10	Convex upward

* The end point of the experiment was the development of overall mammary tumors including both cancer and benign tumors.

genesis in experimental animal models.[2,143] In this section, we briefly summarize some features of experimental carcinogenesis by heavy ions, focusing on the rat mammary cancer model.

Dose-effect relationship and RBE

Shellabarger and colleagues[135] have investigated the induction of Sprague-Dawley rat mammary cancer after exposure to neon ions (0.02–0.54 Gy; LET, 33 keV/μm) from BEVALAC and to X-rays (0.57–1.71 Gy). The dose response for neon ions was linear up to 0.54 Gy, and the RBE was roughly estimated to be > 5 at the incidence of 20% (i.e., ~0.02 Gy of neon ions; Fig. 7*a*).[135] Imaoka *et al.*[137] also used the Sprague-Dawley rat to compare the carcinogenic effects of carbon ions (0.05–2 Gy; LET, 40–90 keV/μm) from HIMAC and γ-rays (0.5–2 Gy). Therein, the dose response for carbon ions was convex upward and well-fitted by a square-root function of dose (Fig. 7*b*).[137] As the dose response for γ-rays was linear, these fittings resulted in a dose-dependent RBE, which yielded 10 and 2 at 0.05 and 1 Gy, respectively.[137] In addition, an interim result has reported an RBE of < 10 for iron ions from AGS (0.05–2 Gy; LET, 155 keV/μm), although this analysis did not separate benign tumors and cancers.[136] Those three studies obtained similar RBE, suggesting that high-LET heavy ions (33 and 40–90 keV/μm) have high RBE for rat mammary cancer induction comparable to the reported high values of neutrons (Table 2).

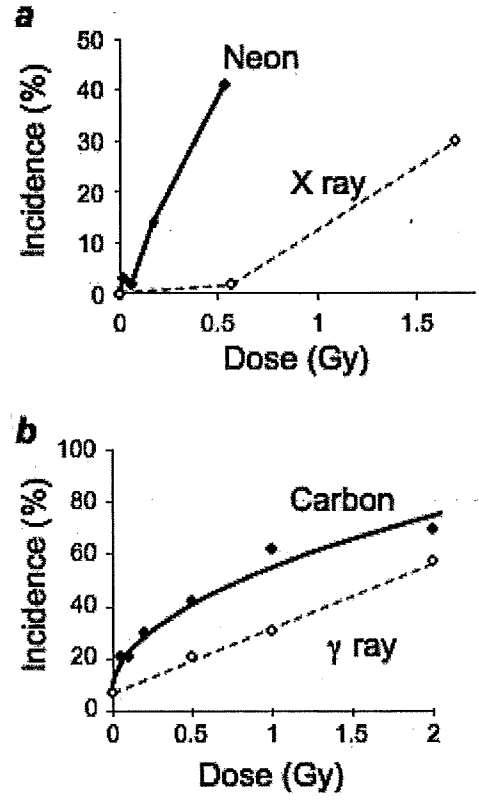

Fig. 7. Dose effect relationship of heavy ion– and low linear energy transfer radiation–induced rat mammary carcinogenesis. Shown is the incidence of mammary cancer after exposure to 6.6 GeV/u neon ions (*closed circles*) and X-rays (*open circles*) (Panel *a*) and 290 MeV/u carbon ions (*closed circles*) and γ-rays (*open circles*) (Panel *b*). Constructed from data presented in Shellabarger *et al.*[135] (*a*) and Imaoka *et al.*[137] (*b*).

Modulation by genetic factors

Genetic background is an important factor influencing cancer susceptibility, and in this respect rat strains with different genetic backgrounds have provided a good animal model.[134] For example, comparison of the susceptibility to chemically-induced mammary carcinogenesis among a series of rat strains has showed that the Sprague-Dawley, WF and Lewis strains have the highest susceptibility, whereas F344 and ACI strains have moderate-to-low susceptibility (Fig. 8*a*).[144] Regarding X-ray–induced mammary carcinogenesis, comparison of published data implies that susceptibility is high in Sprague-Dawley,[135,145,146] moderate in Lewis[146] and low in ACI[147] and F344[148] strains (Fig. 8*b*). Of note, X-rays show strong carcinogenicity when combined with estrogen treatment in ACI rats.[147] In the neutron induc-

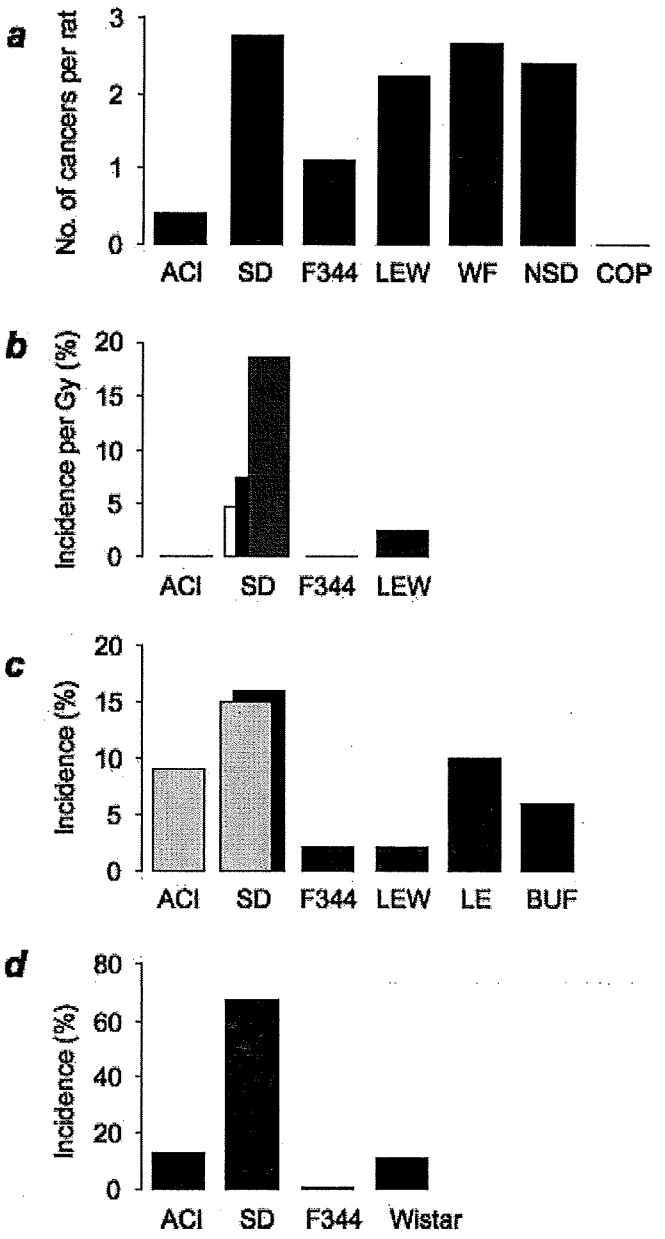

Fig. 8. Rat strain difference in susceptibility to mammary carcinogens. Panel *a*, The average number of cancers per rat after exposure to the chemical carcinogen 7,12-dimethylbenz(a)anthracene.[144] Panel *b*, Slope of linear equations fitted to dose-effect relationship for X-ray–induced mammary cancer incidence. Sprague-Dawley (data from three literatures are shown by *white*,[145] *black*[146] and *gray*[135] *columns*), F344[148] and Lewis[146] rats were observed for 300–350 days, and ACI rats for 190 days.[147] Panel *c*, Incidence of mammary cancer after exposure to 0.05 Gy of fission neutrons[150] (*black column*) and 0.004 Gy of 430 keV fast neutrons[149] (*gray column*). Panel *d*, Incidence of mammary cancer after exposure to 1 Gy of 290 MeV/u carbon ions with a spread-out Bragg peak.[137] All graphs were constructed from data in indicated literature. SD, Sprague-Dawley; LEW, Lewis; WF, Wistar-Furth; LE, Long-Evans; BUF, Buffalo.

tion models, the Sprague-Dawley strain has been identified as being highly susceptible in contrast to F344 and Lewis strains (Fig. 8*c*).[149,150] In addition, the Sprague-Dawley rat also has higher susceptibility to heavy ion–induced carcinogenesis than F344 and ACI strains (Fig. 8*d*).[137] The high susceptibility of the Sprague-Dawley strain thus seems to be independent of the carcinogen species. Given that variations in cancer susceptibility also exist for human populations, secondary cancer risk after heavy-ion therapy might well differ among individuals.

Biological characteristics of induced tumors

Although the biological characteristics of heavy ion–induced cancers are poorly understood, some insights are available from animal experiments. Data on neon ion–irradiated rats have indicated that the incidence of fibroadenoma (a benign tumor) of the mammary gland was higher than that of carcinoma (or cancer).[135] The same tendency has been observed in carbon ion–, X-ray– and γ-ray–irradiated rats.[135,137] Iron ion–induced mammary cancers have also been reported to contain fibroadenoma and carcinoma.[136] Such high prevalence of fibroadenoma is characteristic of radiation induction models, making a stark contrast to chemical induction, where carcinoma predominantly develops.[144] In addition, carbon ion–induced mammary cancer is reported to be highly metastatic to lung compared to γ-ray–induced one.[137] As metastasis has been observed after irradiation with a dose as low as 0.05 Gy,[137] it is unlikely that heavy ion–induced tissue reactions of the lung have promoted the metastatic process. The mechanism underlying the strong metastatic potential is currently unclear.

The ovarian hormone estrogen plays important roles in the development of most mammary cancers, and estrogen receptor expression is indicative of the hormone dependence of tumors. Because the majority (> 70%) of both carbon ion– and γ-ray–induced mammary cancers express estrogen receptor,[137] estrogen may play crucial roles in both models. The H-*ras* protooncogene is an estrogen-regulated gene, and its mutation, together with its induction by estrogen, plays a major role in chemically–induced rat mammary carcinogenesis.[151] Carbon ion–induced rat mammary cancer is, however, devoid of H-*ras* mutations, as is γ-ray–induced cancer, nor does it have *p53* mutation.[137] Thus, causative gene mutation for heavy-ion induction remains unidentified. Because comprehensive genetic analysis using microarray has revealed altered genes in γ-ray–induced rat mammary cancer,[152] such analysis on heavy ion–induced cancers is indeed warranted.

Implication for secondary cancer risk from medical exposure

Evidence suggests that heavy ions with LET of 33 and 40–90 keV/μm have high RBE for inducing mammary cancer in the Sprague-Dawley rat. Normal tissue in the close

vicinity of cancer may be exposed to the high-LET component of the SOBP beam during therapy and thus be at high risk of developing secondary cancer. In contrast, low-LET carbon ions (~13 keV/μm) have both low *in vitro* transformation efficiency[153] and weak tumorigenicity *in vivo*,[139] suggesting a relatively low risk from exposure of normal tissue to therapeutic heavy-ion beams. The variable sensitivity among rat strains implies that individual cancer susceptibility need to be taken into account, such as genetic polymorphisms related to breast cancer risk (e.g., *BRCA* genes). More information from experimental carcinogenesis study is awaited for a more concrete estimation of secondary cancer risk from heavy-ion therapy.

PERSPECTIVES

In spite of a series of studies, how heavy ions inactivate cells more effectively than photons continues to remain a fascinating question. The question concerning the LET dependence of induction of DNA DSBs and clustered DNA damage is still fully open.[11,12] Growing evidence now suggests that heavy ions kill cells via various modes of cell death (e.g., autophagy and premature senescence in addition to apoptosis) and overcome radioresistance, although the current evidence is still only phenomenological. A deeper understanding of the mechanism of action of heavy ions and the molecular underpinnings of heavy ion–induced cell death would be necessary, which may in turn lead to (*i*) mechanism-based designing of biological approaches that enhance tumor control without aggravating, or even with assuaging, normal tissue complications, (*ii*) prediction of both the heavy-ion responsiveness of tumors and normal tissue complications (including acute reactions and secondary cancers) prior to treatment and (*iii*) tailor-made therapy for individual patients. In this regard, recent studies have been conducted to molecularly profile the heavy-ion response of tumor cells irradiated *in vivo*,[154,155] and this encourages further investigation to clarify the genes responsible for susceptibility to heavy ions.

ACKNOWLEDGMENTS

N. H. and Y. K. are indebted to Drs. Takamitsu Hara, Sakura Hamada, Keiko Kataoka (Gunma Univ., Japan), Tetsuya Sakashita, Tomoo Funayama and Yuichiro Yokota (JAEA, Japan) for help with irradiation experiments; the work was supported in part by a Grant-in-Aid for the 21st Century Center-of-Excellence Program for Biomedical Research Using Accelerator Technology to Gunma University Graduate School of Medicine from the Ministry of Education, Culture Sports, Science and Technology (MEXT) of Japan, and by the budget of Nuclear Research of MEXT based on screening and counseling by the Atomic Energy Commission of Japan. T. I. and Y. S. acknowledge Drs. Mayumi Nishimura, Shizuko Kakinuma, Takashi Takabatake, Kazuhiko Daino (NIRS, Japan) and Daisuke Iizuka (Hiroshima Univ., Japan) for kind collaboration and critical reading of the manuscript; the work was supported in part by a research grant from the Takeda Science Foundation, and Grants-in-Aid for Young Scientists (B) (No. 20710049) from MEXT and for Scientific Research (A and C) (No. 19201011 and 21610029) from the Japan Society for the Promotion of Science (JSPS), and Health and Labor Sciences Research Grants (No. 19141201 and 19S-1) from the Ministry of Health, Labor and Welfare of Japan. S. M. and K. O. acknowledge Drs. Ryoichi Hirayama and Akiko Uzawa (NIRS, Japan) for dedicated support for animal experiments; the work was supported in part by Grants-in-Aid for Scientific Research (C) (No. 18591380 and 20591493) from JSPS. T. Ogata and T. T. acknowledge Drs. Nariaki Matsuura, Yutaka Takahashi (Osaka Univ., Japan) and Yoshiya Furusawa (NIRS, Japan). R. O. and T. K. greatly appreciate Drs. Akira Fujimori, Miho Noguchi, Mr. Kentaro Seo and Mr. Yoshihiro Fujii (NIRS, Japan) for invaluable help in preparing the manuscript; the work was supported by a Grant-in-Aid for Scientific Research (A) (No. 16209036) from JSPS. A. T. and T. Ohnishi acknowledge Drs. Tadaaki Kirita and Nobuhiro Yamakawa (Nara Medical Univ., Japan); the work was supported by Grants-in-Aid for Scientific Research from MEXT, a grant from the Central Research Institute of Electric Power Industry, and a grant for Exploratory Research for Space Utilization from the Japan Space Forum. Some works herein were conducted as part of the Research Project with Heavy Ions at NIRS-HIMAC. The cost for the English editing of the manuscript was supported by Space Radiation Research Unit, International Open Laboratory, NIRS, Japan, and the authors are grateful to Dr. Yukio Uchihori (NIRS, Japan).

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