# A preliminary clinical dosimetry study for synchrotron radiation therapy at SSRF (Postprint)

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## Abstract

Synchrotron radiation (SR) represents a unique and innovative anti-cancer treatment due to its unique physical features, including high flux density, and tunable and collimated radiation generation. The aim of this work is to assess the dosimetric properties of SR in Shanghai Synchrotron Radiation Facility (SSRF) for potential applications to clinical radiation oncology. The experiments were performed with 34 and 50 keV X-rays on the BL13W biomedical beamline of SSRF and the 6 MV X-rays from ARTISTE linac for the dosimetry study. The percentage depth dose (PDD) and the surface dose of the SR X-rays and the 6 MV photon beams were performed in solid water phantom with Gafchromic EBT3 films. All curves are normalized to the maximum calculated dose. The depth of full dose buildup is about 10 µm deeper for the monoenergetic X-ray beams of 34 and 50 keV. The beam transmits through the phantom, with a linear attenuation coefficient. The profile in the horizontal plane shows that the dose distribution is uniform within the facula, while the vertical profile shows a Gaussian distribution of the dose. The penumbra is less than 0.2 mm in the horizontal profile. Gafchromic EBT film may be a useful and convenient tool for dose measurement and quality control for the high space and density resolution. It is therefore important to gain a thorough understanding about the physical features of SR before this novel technology can be applied to clinical practice.

## Full Text

## Preamble

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### A Preliminary Clinical Dosimetry Study for Synchrotron Radiation Therapy at SSRF

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**Abstract:** Synchrotron radiation (SR) represents a unique and innovative anti-cancer treatment modality due to its distinctive physical features, including high flux density, tunable energy, and highly collimated beam generation. The aim of this work is to assess the dosimetric properties of SR at the Shanghai Synchrotron Radiation Facility (SSRF) for potential applications in clinical radiation oncology. Experiments were performed with 34 and 50 keV X-rays on the BL13W biomedical beamline of SSRF, with 6 MV X-rays from an ARTISTE linac used for comparative dosimetry studies. Percentage depth dose (PDD) and surface dose measurements for both the SR X-rays and 6 MV photon beams were conducted in a solid water phantom using Gafchromic EBT3 films. All curves were normalized to the maximum calculated dose. The depth of full dose buildup is approximately 10 µm for the monoenergetic 34 and 50 keV X-ray beams. The beam transmits through the phantom with a linear attenuation coefficient. The horizontal plane profile shows uniform dose distribution within the facula, while the vertical profile exhibits a Gaussian dose distribution. The penumbra is less than 0.2 mm in the horizontal profile. Gafchromic EBT film may serve as a useful and convenient tool for dose measurement and quality control given its high spatial and density resolution. It is therefore important to gain a thorough understanding of the physical characteristics of SR before this novel technology can be applied to clinical practice.

**Key words:** Radiation therapy, Synchrotron radiation, Physical features, Dosimetry

## Introduction

Radiation therapy, along with surgery and chemotherapy, represents a primary treatment option for cancer. Radiotherapy is used in the treatment of 60–70% of cancer patients. The fundamental goal of radiation therapy is to deliver the maximum possible dose to a tumor while minimizing radiation damage to surrounding normal tissues. However, existing radiotherapy techniques, including conventional MV X-ray radiation therapy, have certain limitations in both physical and radiobiological aspects. Therefore, it is imperative to develop new technologies that can maximize tumor dose while minimizing damage to surrounding normal tissues. Recent advances in synchrotron radiation have offered a promising new option.

The Shanghai Synchrotron Radiation Facility (SSRF), a third-generation synchrotron radiation light source available to users since 2009, provides an invaluable tool for cancer treatment. Two SR-based techniques (SRT) have been reported in the literature [1,2]: stereotactic synchrotron radiotherapy (SSRT) and microbeam radiation therapy (MRT). The first patient was admitted for SSRT in late June 2012 at the European Synchrotron Radiation Facility (ESRF), while MRT has been in pre-clinical radiosurgery trials dedicated initially to treating brain tumors [3]. As the biomedical beamline of SSRF is similar to the ESRF beamlines used for SSRT and MRT developments in terms of beam intensity and stability, it should be possible to deliver sufficient dose to a tumor target within a short period of time, enabling potential treatments of aggressive tumors with hypofractionated irradiations similar to SSRT at ESRF.

Therefore, it is necessary to gain a thorough understanding of the parameters related to radiation therapy on the SSRF beamline, including skin dose, dose rate, and X-ray spectrum, before this technology can be applied to clinical practice. The purpose of the present study was to investigate the physical features of SSRF-based synchrotron radiotherapy.

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## 2.1 General Data

The experiments were performed on the BL13W biomedical beamline of SSRF, which operates with 3.5 GeV electron beam bunches circulating in a 432-m circumference storage ring. Monoenergetic X-rays of 34 and 50 keV were selected from the synchrotron radiation generated by a wiggler. Photon beams from a 6 MV ARTISTE linac (Siemens Corp.) were also used for comparative dosimetry studies. Dosimetric verification of both the SR X-rays and 6-MV photon beams was performed at various depths in a solid water phantom (PTW Solid Water Phantom).

## 2.2 Film Dosimetry

Medical radiation dosimetry can be performed using radiochromic films capable of producing a permanent visible color change upon irradiation. In this work, Gafchromic EBT3 radiochromic film (International Specialty Products, NJ, USA) was used for radiation-induced auto-developing X-ray analysis. The film offers high spatial resolution (5 μm), high sensitivity, and good response uniformity (<1.5%). It can be used for dose measurements across a wide range (0.01 Gy to 40 Gy) with X-rays of various energies (from keV to MeV). All irradiated films were scanned using an EPSON 10000XL scanner (EPSON, Japan) and analyzed with FilmQA-PRO software (International Specialty Products, NJ, USA).

A calibration curve was established using the 6 MV X-rays. For calibration, a 13-mm thick PMMA plate was used to cover the films, which were backed by 5-cm thick solid water phantom material.

## 3 Results and Discussion

For a feasibility study of clinical SSRT trials on the BL13W beamline at SSRF, it is essential to characterize its specific features, including the dosimetric characteristics of linearity, reproducibility, uniformity, penumbra, surface dose, and percentage depth dose (PDD). These parameters were investigated experimentally using radiochromic film. It was found that the film serves as a useful and convenient tool for dose measurement and quality control of SR X-rays.

### 3.1 PDD of SSRF

In radiotherapy, PDD is a key parameter for calculating the prescribed dose and the tissue or tumor absorption dose. A PDD curve relates the absorbed dose to medium depth along the beam axis. Doses are expressed as percentages of the maximum dose, referred to as Dmax. Measurements are typically performed in water or "water-equivalent" plastic using an ionization chamber, as water is similar to human tissue in terms of radiation scattering and absorption.

[Figure 1: see original paper] Central axis depth dose at the surface of the solid water phantom.

[Figure 2: see original paper] Absolute transmission of 34 keV SR X-rays and conventional 6 MV X-rays in the solid water phantom.

Low-energy X-rays exhibit a high surface dose with shallow buildup depth. Fig. 1 shows the central axis depth dose normalized to the maximum calculated dose at the surface of the solid water phantom, obtained from film measurements with 34 keV or 50 keV X-rays on the BL13W beamline. The depth of full dose buildup is approximately 10 µm for the monoenergetic 34 and 50 keV X-ray beams. These results are similar to those obtained at ESRF [4]. The beam transmits through the phantom with a linear attenuation coefficient [5], which is consistent with predicted results from simulations [6].

In Fig. 2, the PDD of 34 keV X-rays is compared with X-rays from the 6 MV linac. The dose attenuation with 34 keV X-rays in the phantom is much more rapid than that with the 6 MV X-rays.

### 3.2 Facula Features

Synchrotron radiation demonstrates excellent reproducibility and uniformity. Two films were irradiated at different times with 34 keV X-rays using identical parameters, and the difference in absorbed dose was less than 4%.

Fig. 3 shows the facula size, which is approximately 4 cm in length and 4 mm in height. The horizontal plane profile (Fig. 4) shows that the dose distribution is uniform within the facula, while the vertical profile (Fig. 5) shows a Gaussian dose distribution.

[Figure 3: see original paper] Very small facula of the 34 keV SR X-ray.

[Figure 4: see original paper] Profile in the horizontal plane, showing good uniformity of the 34 keV SR X-ray.

The center of the facula is the brightest region, indicating non-uniformity of dose in the radiation field and thus necessitating intensity-modulated radiation therapy techniques in the vertical plane.

[Figure 5: see original paper] Profile in the vertical plane, showing a maximum facula width of only 4 mm for the 34 keV X-ray.

In conventional X-ray therapy, metal or plastic blocks are used to improve dose distribution. As shown in Figs. 4 and 5, the dose curves are very sharp at the facula edges. The penumbra is less than 0.2 mm in the horizontal profile (Fig. 4). Penumbra has a major impact on the uniformity of isodose distributions in radiation therapy. For the 34 and 50 keV SR X-rays, the penumbra is so small that organs at risk (OAR) surrounding the tumor can be effectively protected. Synchrotron X-rays exhibit extraordinarily high flux density and small divergence, with sharply defined beam edges at depth within the body. Compared with conventional radiotherapy, SR-based radiotherapy can deliver a higher fraction dose to the target within a shorter time. In conventional radiotherapy, tumor movements during irradiation can result in missing the treated target. Because of the high flux density of synchrotron X-rays, the tolerance of tumor motion can be well within the limits of accuracy in SR-based radiotherapy, which ensures higher therapeutic effects than conventional irradiation.

## 3.3 Field Expansion

The X-ray beam available at the BL13W beamline has a maximum height of 4 mm, but tumors are typically larger than the facula. A scanning method can be employed to expand the irradiation field. A tumor volume can be outlined according to CT images, and plumbum masks are fabricated in the beam's eye view to conform the incoming beam to the tumor shape. Fig. 6 shows an expanded irradiation field, and Fig. 7 shows the corresponding profile. If two consecutive faculas are interlaced, the dose will overlap and the high-dose region may cause injury to normal tissues. If consecutive faculas are separated, the dose will be insufficient, and low-dose regions may increase the risk of tumor recurrence. How to properly adjoin the faculas is an important problem for SR-based radiation therapy at SSRF.

[Figure 6: see original paper] Field expansion.

[Figure 7: see original paper] Profile in the vertical plane for the expanded irradiation field.

## 3.6 Quality Assurance for SSRF

A treatment planning system for ESRF ID17 clinical trials is under development through collaboration with the CHU-INSERM team and the company

DOSIsoft [7] for SSRT applications only. Realistic dose distribution simulation is necessary for treatment planning and evaluating experimental results. In SRT, tumors are irradiated with very high doses. High-flux synchrotron X-rays enable extremely rapid irradiation, eliminating collimation errors due to micro-movement fluctuations of the target. The absolute dose to the target needs to be calculated and delivered accurately. Monte Carlo-based calculations have been carried out for SRT to determine dose distribution for treatment planning [8–10]. These data allow description of physical dose deposition, but reliable prediction of biological effects has not yet been achieved, particularly regarding treatment volume size, where knowledge is limited to small volumes in the brain. Accordingly, true optimization of treatment parameters is not yet feasible. To establish a treatment planning program for human patients, additional data for normal tissues and tumors are necessary [7].

## 3.5 Dose Profile Evaluation

For SRT, dosimetry tests should be performed before and/or after patient treatment using dosimetric films, TLDs, or gel dosimetry to ensure patient safety. Dosimetry of SRT beams should record the total absorbed dose to the tissue. Calculation results should be compared with dosimetric and microdosimetric measurements using ionization chambers, MOSFET detectors, TLD, or radiochromic films [11–15], as measurement readout ensures irradiation quality. To achieve better agreement with experimental data and predict dose distributions more accurately for therapeutic applications, it is necessary to further refine Monte Carlo simulations of SRT [4]. Additionally, systematic analysis of therapeutic gain for different microdosimetric patterns based on beam energy, beam shape, and overall field size is still evolving for SRT of targets in experimental animals.

In radiotherapy, quality assurance (QA) plays a crucial role in the clinical workflow. SRT is a technique designed to deliver radiation therapy with extreme precision to tumors. The technology used in SRT allows external beam radiation to be delivered with pinpoint accuracy. However, accurate and consistent treatment delivery is by no means easy to achieve, as the radiation therapy process involves a complex interweaving of numerous related tasks for designing and delivering radiation treatment. QA of radiation therapy equipment primarily involves ongoing evaluation of functional performance characteristics. Accurate radiotherapy determines therapeutic efficacy, and high precision is mandatory for prescribing an exact dose. QA is a prerequisite for treatment setup, ensuring consistency of the medical prescription and safe fulfillment of the radiotherapy prescription. For patient treatment, the accuracy of both location and dose should be checked frequently. Although the synchrotron accelerator has very high accuracy and precision, the mechanical isocenter should be checked aperiodically, as the center of the facula may shift after several years.

## 4 Conclusion

Synchrotron radiation offers numerous physical and biological advantages for radiation therapy, and related medical research plays an important role in advancing the field. SR therapy represents a radiation source with great potential for cancer treatment. The results of our trial demonstrate that the physical features of SSRF are similar to those of light sources abroad. We believe that SSRF will be applied in radiation oncology in the near future. However, the transition from animal experiments to clinical therapy in human patients appears to be more complex.

Further dosimetric studies are necessary to better predict dose distributions in clinical applications. Dose measurements within phantoms of different tissue densities using alternative methods are required. The film can measure continuous dose distribution in a plane with high spatial and density resolution, making it a useful and convenient tool for dose measurement and quality control. With such knowledge, it can be anticipated that advancements in conventional tools will lead to improvements in medical practice [16].

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**References**

2005, 548: 30–37.

8 Masami T, Yumiko O, Naoto Y, et al. Eur J Radiol, 2008, 68S: S114–S117. Orion I, Rosenfeld A B, Dilmanian, F A. et al. Phys Med Biol, 2000, 45: 2497–2508.

10 Stepanek J, Blattmann H, Laissue J A, et al. Med Phys, 2000, 27: 1664–1675.

11 Bräuer-Krisch E, Bravin A, Lerch M, et al. Med Phys, Curtis H J. Radiat Res Suppl, 1967, 7: 250–257. 2003, 30: 583–589.

Baker C P, Curtis H J, Zeman W, et al. Radiat Res, 1961,

12 Ptaszkiewicza M, Braurer-Kirsch E, Klosowski M, et al. 15: 489–495. Radiat Meas, 2008, 43: 990–993. Serduc R, Christen T, Laissue J, et al. Phys Med Biol,

13 Siegbahn EA, Bräuer-Krisch E, Bravin A, et al. Med Phys, 2008, 53: 3609–3622. 2009, 36: 1128–11137. Siegbahn E A, Bräuer-Krisch E, Stepanek J, et al. Nucl

14 Brauer-Krisch E, Bravin A, Lerch M, et al. Med Phys, Instrum Meth A, 2005, 548: 54–58. 2003, 30: 583–589.

Dilmanian F A, Romanelli P, Zhong Z, et al. Eur J Radiol, 15 Nariyama N, Ohigashi T, Umetani K, et al. Appl Radiat 2008, 68S: S129–S136. Isotopes, 2009, 67: 155–159.

Dilmanian F A, Zhong Z, Bacarian T, et al. Proc Natl

16 Suortti P and Thomlinson W. Phys Med Biol, 2003, 48: Acad Sci USA, 2006, 103: 9709–9714. R1–R35. Dilmaniana F A, Qu Y, Liu S, et al. Nucl Instrum Meth A,

*Note: Figure translations are in progress. See original paper for figures.*