Study on the Tongue and Groove Effect of the Elekta Multileaf Collimator Using Monte Carlo Simulation and Film Dosimetry

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Background: Nowadays, multileaf collimation of the treatment fields from medical linear accelerators is a common option. Due to the design of the leaf sides, the tongue and groove effect occurs for certain multileaf collimator applications such as the abutment of fields where the beam edges are defined by the sides of the leaves.
Material and Methods: In this study, the tongue and groove effect was measured for two pairs of irregular multileaf collimator fields that were matched along leaf sides in two steps. Measurements were made at 10 cm depth in a polystyrene phantom using Kodak EDR2 films for a photon beam energy of 6 MV on an Elekta Sl*i*-plus accelerator. To verify the measurements, full Monte Carlo simulations were done. In the simulations, the design of the leaf sides was taken into account and one component module of BEAM code was modified to correctly simulate the Elekta multileaf collimator.
Results and Conclusion: The results of measurements and simulations are in good agreement and within the tolerance of film dosimetry.

Key Words: Tongue and groove effect · Multileaf collimator · Monte Carlo simulation

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Untersuchung des Nut- und Feder-Effekts des Elekta-Lamellenkollimators mittels Monte-Carlo-Simulation und Filmdosimetrie

Hintergrund: Heutzutage werden zunehmend Lamellenkollimatoren für die Kollimierung von Strahlenfeldern eingesetzt. Zwar erreicht man mit Lamellenkollimatoren eine bessere Anpassung der Dosisverteilung an die Form des Zielvolumens, jedoch ist ihre Verwendung auch mit einigen Problemen bei der Dosisberechnung verbunden. Eines dieser Probleme, der Nut-und-Feder-Effekt, wird in dieser Arbeit untersucht. Dieser Effekt ist besonders bedeutsam, wenn Feldanschlüsse zweier Felder bei einer Bestrahlung vorgesehen sind.
Material und Methodik: Zur Untersuchung dieses Effekts wurden zwei Konfigurationen mit unregelmäßigen Paarfeldern eingesetzt. Die Messungen erfolgten in einem Polystyrol-Phantom mit Kodak-EDR2-Filmen bei 6-MV-Photonenstrahlung an einem Elekta-Linearbeschleuniger (Sl*i*-plus). Um die Messungen zu verifizieren, wurde der Beschleunigerkopf mit Hilfe des BEAM-Programms modelliert. Zur Berücksichtigung des Nut-und-Feder-Effekts wurde das BEAM-Programm entsprechend der Bauart des Elekta-Kollimators modifiziert.
Ergebnisse und Schlussfolgerung: Messungen und Dosisberechnungen der Monte-Carlo-Simulation ergaben eine gute Übereinstimmung.

Schlüsselwörter: Nut-und-Feder-Effekt · Lamellenkollimatoren · Monte-Carlo-Simulation

Introduction

For several years, the computer-controlled multileaf collimator has replaced compensators for conformal radiation therapy. Step-and-shoot and the dynamic multileaf collimator are two well-known techniques based on the multileaf collimator and are used to deliver intensity-modulated radiotherapy [3, 12]. At the Tübingen University Hospital, Germany, the former of these techniques (step-and-shoot) is used with an Elekta Sl*i*-plus Linac equipped with the Elekta multileaf collimator. Many researchers have investigated the aspects of

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dosimetric characteristic of a multileaf collimator [1, 2, 6, 7, 15]. One of these aspects, the tongue and groove effect, may become a significant issue when underdosage occurs in the region of overlap of two leaf pairs of a multileaf collimator [10, 13, 16]. The results of several investigations show that synchronization of the leaves can avoid the tongue and groove effect [11, 14], but increases the total number of monitor units needed to deliver the required dose. In this study, we concentrate on a comparison of measurements of the tongue and groove effect and Monte Carlo simulations.

Dose calculation distributions influenced by the tongue and groove effect can only be predicted accurately using the Monte Carlo method. With this method a detailed design of the multileaf collimator can be taken into account for the dose calculation. For this investigation, the BEAM packages [9] were used to simulate the accelerator head. In the new version of the BEAM packages, only the component module VARMLC is available to model the multileaf collimator based on the design for Varian multileaf collimator. Therefore, this component module was modified, so that it can be used to simulate the Elekta multileaf collimator.

Material and Methods

The Elekta Multileaf Collimator

The Elekta multileaf collimator consists of 80 independent leaves which are divided into two banks. The material of the leaves is tungsten alloy with a density of 18.0 g/cm^3. The Elekta multileaf collimator has curved leaf ends and a stepped design for the leaf sides. The projection of the leaf pitch in the isocentric plane is 1.0 cm, but the projection of an individual leaf is 1.1 cm. The Elekta multileaf collimator is placed 29.8 cm below the target and has a thickness of 7.5 cm. More detailed information of the Elekta multileaf collimator can be found in the papers by Jordan & Williams [7] and Sykes & Williams [10].

The modified component module that was used to model the Elekta multileaf collimator is based on the component module VARMLC. Some modifications have been made regarding the stepped design of the leaf sides. The parameters required to describe the leaf are: the width of leaves (LW), the dimensions of the leaf gap (LG), and the tongue and groove mechanism (WG and WT; Figure 1). All parameters are given at the top surface of the multileaf collimator (ZMIN), and the leaf sides are focused to the target.

Monte Carlo Simulation

The 6-MV photon beam of the Elekta Sl*i*-plus was modeled using the BEAM program. A detailed model of this beam can be found in previous papers [4, 5]. Basic modification was made to the multileaf collimator geometry, since the stepped design of the leaf sides was taken into account for the simulations. The treatment head was divided into two stages. The first stage consists of the target, primary collimator, low secondary filter, monitor chamber, mirror, and anti-backscattering plate. The setting of these components is independent of the field size. The components of the second stage that are dependent on the setting of field include the multileaf collimator, the backup jaws, and the lower jaws. The multileaf collimator and the backup jaws can move along the y-axis and the lower jaws along the x-axis according to the Elekta convention. In this convention, the coordinate system is based on the collimator's coordinate system.

In a first stage, the electron beam was modeled as a point source with 2 mm diameter at the surface of the target, and its energy has a spectrum with normal distribution. This spectrum has a mean energy of 6.8 MeV and a full-width at half-maximum of 1 MeV. A trial-and-error method was used to obtain the mean energy, until good agreement between calculated and measured depth dose was achieved. To increase the speed of the simulation, bremsstrahlung splitting and range rejection were enabled in this stage. Each bremsstrahlung photon was split into 25 photons with reduced weight. The phase space file was scored in the region below the mirror and was employed as a particle source for the second stage. This phase space file contains information of about 1.0×10^7 particles. From the second stage, a second phase space file was generated at the front surface of phantom (90 cm below the target). The number of particles in this file depends on the field shape.

The DOSXYZ [8] code was employed to simulate the measurements which were done in a polystyrene phantom. The second phase space file was used as input for this simu-

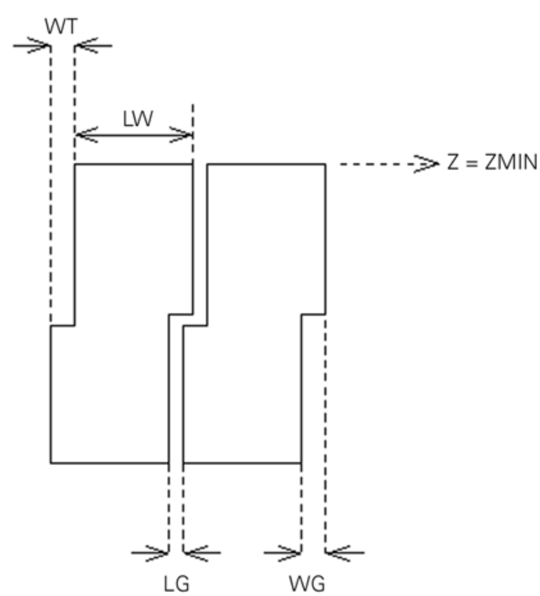

Figure 1. Design of the Elekta multileaf collimator, described by the parameters: tongue width (WT), groove width (WG), leaf gap (LG), and leaf width (LW).

Abbildung 1. Aufbau der Elekta-Multilamellenkollimatoren und ihre Eigenschaften: Nutbreite (WT), Federbreite (WG), Luftspaltbreite (LG) und Lamellenbreite (LW).

lation. The voxel size was 0.2 cm perpendicular to the leaf motion direction for overlap regions and 0.5 cm for other regions, 1 cm in direction of the leaf motions, and 1 cm high. The medium of voxels was set to the medium of polystyrene phantom.

Measurement of the Tongue and Groove Effect

To reproduce the tongue and groove effect, two pairs of irregular fields were generated. All irregular fields were created by the multileaf collimator only. Figure 2 shows the leaf prescriptions of the first pair of irregular fields. The first irregular field of this pair is the half of a 20 × 20 cm area that was blocked with the leaves of the left leaf bank, with the leaf ends at overtravel position of 10 cm. The leaf ends of the leaves of the right leaf bank were set at 11 cm from the central axis. In the second field, only the leaf positions of the left leaf bank were changed. All leaves of the left leaf bank which were opened in the first field are closed in the second field and vice versa. Therefore, the tongue and groove effect was measured for only one overlap region between leaves 20 and 21. Another pair of irregular fields can be seen in Figure 3. The size of the open area for these fields was similar to the fields of the first pair. In the first field, every alternate group of two leaves from the left bank was set to cross the central axis by 10 cm and the other leaves were set 11 cm from the central axis. The second field is the complement of the leaf configuration of the first field. Using this pair of irregular fields, the tongue and groove effect was investigated for nine overlap regions between leaves 12–13, 14–15, 16–17, 18–19, 20–21, 22–23, 24–25, 26–27, and 28–29.

The tongue and groove effect was investigated by measurements with Kodak EDR2 films in a polystyrene phantom. Measurements were performed at an Elekta Sl*i*-plus with a 6-MV photon beam. The films were placed at a depth of 10 cm below the phantom surface with a source-to-phantom-surface distance of 90 cm. All films were exposed to the same number of monitor units for each irregular subfield of the pair leaf configurations. The films were developed with a PROTEC M45 film processor and scanned using the Vidar VXR-12 film digitizer with a pixel size of approximately 0.339 mm.

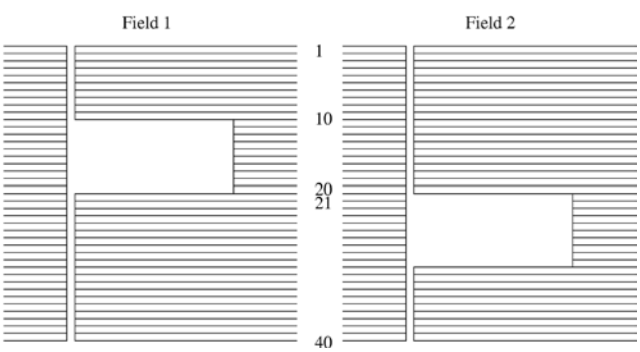

Figure 2. Leaf prescription for the first pair of irregular fields.

Abbildung 2. Konfiguration der Multilamellenkollimatoren beim ersten Paar unregelmäßiger Felder.

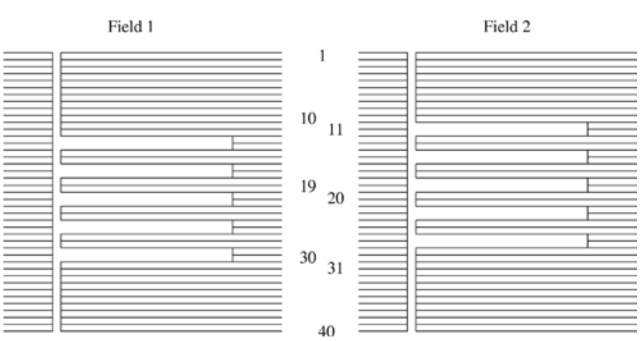

Figure 3. Leaf prescription for the second pair of irregular fields.

Abbildung 3. Konfiguration der Multilamellenkollimatoren beim zweiten Paar unregelmäßiger Felder.

Results and Discussion

Figure 4 shows a comparison of measured and simulated profiles for the first pair of irregular subfields. The measured and simulated profiles were normalized to the maximum dose. In this comparison, an agreement within 1% was found. The statistical uncertainties of the simulated profile were kept within 1%. At the overlap region by both profiles, a large deficit in dose was seen. A peak deficit of the measured profile of 27.4% with a full-width at half-maximum of 3.9 mm appeared. The peak deficit of the simulated profile happened to be 28.0% with a full-width at half-maximum of 4.6 mm. The difference between the pixel size and the voxel size causes the difference between measured and simulated peak deficit and its full-width at half-maximum.

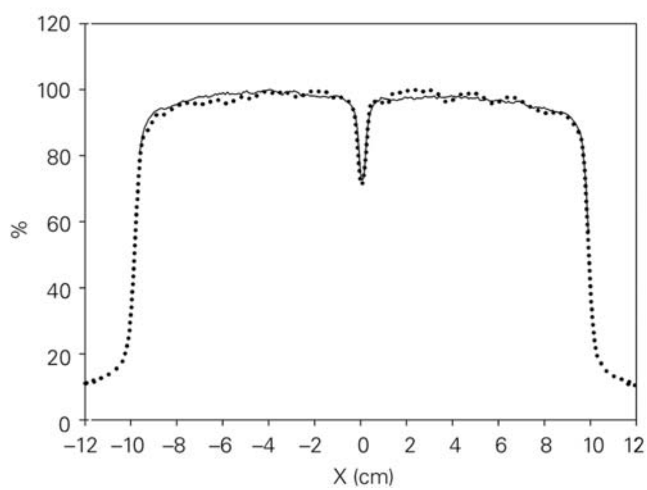

Figure 4. Comparison of the measured (solid line) and simulated (dotted line) profile for the first pair of irregular field.

Abbildung 4. Gemessene (durchgezogene Linie) und simulierte (punktierte Linie) Querprofile für die erste Feldkonfiguration.

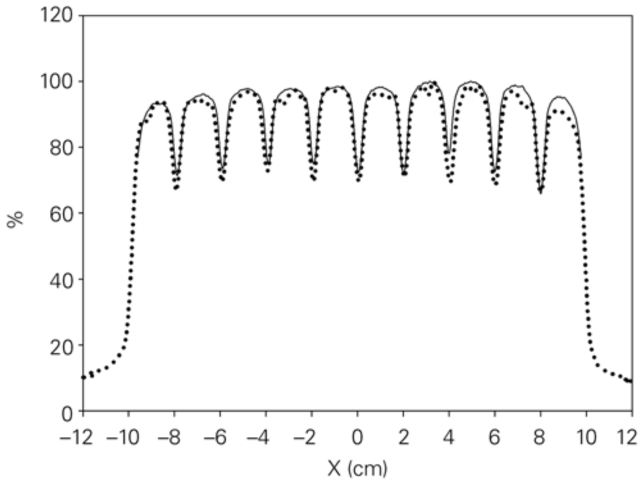

Figure 5. Comparison of the measured (solid line) and simulated (dotted line) profile for the second pair of irregular field.

Abbildung 5. Gemessene (durchgezogene Linie) und simulierte (punktierte Linie) Querprofile für die zweite Feldkonfiguration.

The measured and simulated profiles from the second pair of the irregular subfields can be seen in Figure 5, where variation of the peak deficits at the nine overlap regions for both profiles appeared. As for the first pair of the irregular fields, the measured and simulated profiles of the second pair were normalized to the maximum dose. In Figure 5, a good agreement between measured and simulated profiles was found. Yet, there are still differences at the overlap region near the edge of profile. The largest difference between measured and simulated profile is still < 5%, while the statistical uncertainties of the Monte Carlo simulation are in the order of 1%.

Table 1 gives more detailed information on these variations. For the measured profile, the peak deficits vary from 21.9% to 34.0% and their full-width at half-maximum from 3.3 to 4.6 mm. Table 1 shows that the variation of the peak deficits for the measurement is independent of the position of the overlap regions. This variation may be caused by small deviations of the dimension of the leaf parameters within machining tolerance. For simulation, the variation of the peak deficits shows a pattern of underdosage which depends on the location of the overlap region. The peak deficit increases with the increment of the distance of the leaves from the central axis. The peak deficit of the overlap region at the central beam axis is lower than the peak at the edge of the profile.

Table 1. Results of measured and simulated underdoses for the second pair of the irregular fields. FWHM: full-width at half-maximum.

Tabelle 1. Ergebnisse der gemessenen und simulierten Dosiseinbrüche beim zweiten Paar unregelmäßiger Felder. FWHM: Halbwertsbreite.

Position of overlap region	Measurement Peak deficit (%)	FWHM (mm)	Simulation Peak deficit (%)	FWHM (mm)
1	34.0	4.4	33.3	4.5
2	27.3	3.9	30.5	4.0
3	21.9	3.3	26.8	4.0
4	28.1	4.1	29.2	4.0
5	27.6	4.1	30.1	4.5
6	25.0	3.8	28.2	4.0
7	25.0	3.9	29.6	4.0
8	26.5	4.1	29.2	4.5
9	28.5	4.6	30.8	4.5

There are no obvious differences in measurements and simulations of the peak deficit and its full-width at half-maximum at the same overlap region between the two pairs of the irregular fields. This proves that the tongue and groove effect is independent of the configuration of the leaf position, but only depends on the location of the overlap region. The measurements and simulations have shown that the full-width at half-maximum is wider than that expected using an idealized model. This means that the focal spot has a finite size and the leaf edge may not be perfectly aligned. There will also be photon scattering and electron effects within the irradiated medium.

Conclusion

In this study, the Monte Carlo simulation accurately reproduces the measured underdosage at overlap regions due to tongue and groove effect, if detailed information of the leaf side design is taken into account. The differences between measured and simulated underdosage were found to be still below the maximum allowed discrepancy of measurements with film dosimetry.

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