Received:
26 August 2018

Revised:
08 October 2018

Accepted:
13 October 2018

<https://doi.org/10.1259/bjr.20180743>

Cite this article as:

Beeksmas B, Lehmann J. Excessive applicator radiation leakage for a common therapeutic kilovoltage system. *Br J Radiol* 2018; **91**: 20180743.

FULL PAPER

Excessive applicator radiation leakage for a common therapeutic kilovoltage system

¹BRAD BEEKSMA, MSc and ^{1,2,3}JOERG LEHMANN, PhD, FAAPM

¹Department of Radiation Oncology, Calvary Mater Newcastle, Newcastle, NSW, Australia

²Institute of Medical Physics, School of Physics, University of Sydney, Sydney, NSW, Australia

³School of Mathematical and Physical Sciences, The University of Newcastle, Newcastle, NSW, Australia

Address correspondence to: Mr Brad Beeksmas
E-mail: bradley.beeksmas@calvarymater.org.au

Objective: The objective of this work is to characterise out-of-field leakage radiation emanating from clinical applicators of the Womed T-200 kilovoltage therapy machine.

Methods: To identify points of leakage, radiosensitive film was affixed to the walls and base plate of each applicator. Quantitative assessment of leakage radiation was conducted with a 0.23 cm³ ionisation chamber following the International Electrotechnical Commission standard. Film was also used to illustrate leakage distribution in the patient plane. Angular and energy dependences of the leakage radiation were quantified as well as a two-dimensional leakage profile in the plane parallel to one applicator.

Results: Leakage was found when the diameter of primary collimator of the kV tube exceeded the external dimension of the applicator wall. In the patient plane

all applicators showed similar leakage rates with the leakage distribution dependent upon applicator design. Mean patient plane leakage was 1.37% of central axis air kerma rate, exceeding the 0.5% limit specified in the standard. Leakage was shown to be profoundly energy dependent with maximum leakage of 11.8% for the 200 kV beam, 1.3% for 150 kV and 0.2% for 100 kV. Angular dependence measurements showed a 10.3% change in leakage between the minimum and maximum positions.

Conclusion The combination of shielding thickness, primary collimator design and applicator dimensions permits unwanted radiation to contribute dose outside the treatment field when energies ≥ 150 kV are used.

Advances in knowledge: Even carefully designed modern kV therapy systems can exhibit leakage in some areas. Thorough assessment of leakage is needed prior to release for clinical use.

INTRODUCTION

Kilovoltage X-ray systems are often used in radiotherapy departments for the therapeutic treatment of skin cancers,^{1,2} benign diseases and other conditions.^{3–5} Typically, these units operate with peak accelerating voltages ranging from 10 to 400 kVp.⁶ For a kilovoltage therapy machine, leakage radiation can emanate from radiation penetrating through the head shielding or through any part of the applicator other than the dedicated aperture. Thus leakage radiation can be defined as ionising radiation transmitted through the protective shielding of a radiation source other than the primary beam.⁷ Flaws in head/applicator shielding, lack of head/applicator shielding, or an incorrectly positioned X-ray tube insert can lead to increased leakage radiation and consequently increased out-of-field patient dose. Following the installation of a new kilovoltage X-ray system, it is common for the medical physicist to quantify unwanted out-of-field, or leakage radiation emitted from the X-ray tube.⁸ As quality control guidance documents^{9–12}

do not recommend checking out-of-field doses as an ongoing quality assurance procedure, leakage measurements are regularly performed at time of acceptance or commissioning and often not checked again throughout the lifetime of the machine. It is therefore imperative that radiation leakage tests be performed correctly at time of acceptance/commissioning and if excessive leakage radiation is found, that the issue is remediated prior to clinical treatment as it is unlikely that ongoing routine QA would detect such an issue.

In the diagnostic and therapeutic setting, guidelines and national standards^{7,13,14} suffice as a best practice compliance document which provides recommendations on methodologies to quantify leakage radiation and its permissible limit. Although there are many publications in the literature which assess out-of-field radiation doses for therapeutic high energy photons,^{15–18} electrons,^{19–21} protons^{22–25} or neutrons^{26,27} very few publications assess the issue within

the kilovoltage energy range for therapeutic purposes. In a publication on kilovoltage therapy machine commissioning, Aspradakis and Zucchetti²⁸ reported applicator leakage for the 200 kV (1.78 mm Cu Half Value Layer (HVL)) beam of a Womed T-200 unit (Wolf Medical Systems, St Gangloff, Germany) with a Varian HPX-226 tube (Varian Medical Systems, Palo Alto, CA) for both 6 × 8 cm and 5 cm diameter applicators. Maximum reported leakage was 3.6 and 1.9% of central axis dose measured at 1 cm in water, 6 cm and 4 cm from central axis for each applicator respectively. The authors reported retrospectively installing thicker screws and retrofitting 2 mm thick sheets of lead to the applicator base plate to reduce this leakage radiation.

This work outlines investigations carried out in quantifying out-of-field dose caused by leakage radiation on a newly installed Womed T-200 kilovoltage therapeutic X-ray (Wolf Medizintechnik GmbH, St Gangloff Germany) with a Comet MXR-226 tube (COMET AG, Flamatt, Switzerland).

METHODS AND MATERIALS

To identify any insufficiencies in the shielding of the T-200 unit and its applicators, Gafchromic RTQA-2 film (Ashland Advanced Materials, Bridgewater NJ) was affixed to the head of the treatment unit, the entirety of each applicator and the applicator base plate. As RTQA-2 film does not require post-processing, a change in its optical density (OD) was used to act as a binary indicator for leakage radiation (hot spots) caused by gaps in shielding or reduced shielding thickness. The sensitive side of the film was directed outwards such that a visual assessment of any hotspots could be performed whilst the film was still on the applicator. This is advantageous in giving accurate geometric location of hotspots relative to the applicator.

Film measurements were also performed in the patient plane, perpendicular to the applicator axis. Here, Solid Water (Gammex-RMI, Middleton, WI), was used as backscatter material and lead blocks (as shown in Table 1) were attached to the end of the applicator to attenuate the primary beam such that only leakage radiation was detected on the films. Thin strips of lead were placed on the films in the patient plane to provide contrast between background OD and change in OD due to leakage radiation. This is illustrated in Figure 1. Measurements were performed with the highest energy beam available (200 kV, 1.8 mm Cu HVL). Irradiation times for the films attached to the base plate and applicator walls were 15 min and for the films in the patient plane 60 min, based on observation of film

Figure 1. Experimental setup for films taken in the patient plane. 6 × 8 cm² shown here with lead attenuating plate and lead strips for OD contrast.

darkening. The indication of hot spots on these films was used to guide further investigations.

Quantitative assessment of leakage radiation in the patient plane was conducted following the methodology specified in the International Electrotechnical Commission (IEC) standard IEC 60601-2-8:2010¹⁴ as adopted by the Australian/New Zealand Standard AS/NZS IEC 60601.2.8:2015.¹³ As per the standard, a 1 cm thick lead block was secured to the end of each applicator tested. This lead provided sufficient thickness to attenuate the primary beam air kerma rate of the radiation field by a factor of $>10^4$. Measurements were conducted at the maximum energy available (200 kV, 1.8 mm Cu HVL), at varying distances laterally from the edge of the lead block, in the plane of the distal surface of the applicator. In accordance with the standard, the measurement location was chosen at the location of maximum air kerma rate, at a distance ≥ 20 mm from the edge of the lead block.

For each applicator, measured leakage air kerma rate was evaluated as a percentage of the un-attenuated air kerma rate on central axis of that applicator. Table 1 illustrates the dimensions of the applicators and lead blocks which were used during the assessment of the leakage radiation. All measurements were conducted using a Scanditronix / Wellhofer 0.23 cm³ FC23-C farmer type ionisation chamber (IBA Dosimetry GmbH, Schwarzenbruck, Germany). Although a larger volume chamber would have provided a better signal to noise

Table 1. Applicator and lead block dimensions used in leakage investigation

Applicator code	Source to end of applicator distance	Applicator dimension	Dimension of lead block
D3/40	40 cm	3 cm diameter	4.5 cm diameter
D4/40	40 cm	4 cm diameter	6.0 cm diameter
6 × 8/30	30 cm	6 × 8 cm	9.0 × 12.0 cm
8 × 10/40	40 cm	8 × 10 cm	12.0 × 15.0 cm
10 × 15/40	40 cm	10 × 15 cm	15.0 × 22.5 cm

ratio, the smaller 0.23 cm^3 volume chamber was chosen for spatial resolution reasons. Due to the design of the applicators, and as found with the film measurements, a narrow but intense beam of leakage radiation was produced in some cases. Measurements with a larger ionisation chamber would have involved partial irradiation of the chamber, failing to ionise the entire volume and therefore lead to an underestimation of the true leakage dose rate. As there are differences in beam quality and dose rate between leakage and primary radiation, the spectral response and the dose rate response of the chamber have been considered prior to its application for these measurements. Specifically, air kerma calibration of this chamber at a primary standards laboratory showed that the chamber response exhibits minimal energy dependence with a maximum air kerma rate deviation of 0.5% relative to the mean for a range of 22 beam qualities between 150 kV and 300 kV. This includes air kerma calibration factors for beams with the same kV and different levels of filtration, as is relevant for this work of relative measurements of primary and leakage radiation. Thus the chamber was determined to be suitable dosimeter for determining applicator leakage rates.

Further measurements were conducted to assess the energy dependence of the leakage radiation. In a similar method to the patient plane testing, the 0.23 cm^3 farmer type ionisation chamber was placed at a distance of 12 mm from the base plate of the D3/40 applicator, with the tip of the chamber positioned 1 mm from the applicator wall. The dose rate at this location

Figure 2. Experimental setup showing custom 3D printed jig used in determination of leakage radiation angular dependence. 3D, three-dimensional.

Figure 3. Schematic of experimental setup used to determine the 2D planar leakage radiation parallel to the length of the applicator. Crosses indicate the chamber tip position used in the measurement at that location. Figure is to scale overlaid on 1cm grid spacing.

was compared to the in-field central axis dose rate at the distal end of the applicator. This was conducted for the following beams: 200 kV (1.8 mm Cu HVL), 150 kV (0.7 mm Cu HVL), 100 kV (4.8 mm Al HVL), 80 kV (3.9 mm Al HVL) and 60 kV (2.3 mm Al HVL).

The leakage dose rate angular dependence of the D3/40 applicator was assessed. For a 200 kV (1.8 mm Cu HVL) beam, measurements were performed by placing the 0.23 cm^3 farmer type ionisation chamber at fixed positions in 45 degree increments, equally spaced 40 mm from the distal end on the anode side of the applicator. As shown in Figure 2, a custom three-dimensional (3D) printed chamber holder was affixed to the exterior perimeter of the applicator which ensured the chamber stayed at a fixed distance of 50 mm from the exterior wall of the applicator. The measured air kerma rate at each angular position was compared to the maximum air kerma rate of all the positions.

The dose rate at various locations in the plane parallel to the D3/40 applicator was also assessed. Measurements were performed at 50 mm increments parallel to the applicator from the applicator base plate up to 200 mm and also in the plane of the distal surface of the applicator (240 mm from the base plate) on the anode side of the tube. These measurements were also conducted with the ionisation chamber tip incrementally moved in 25 mm increments perpendicular to the applicator from the applicator wall to 75 mm. A schematic of this is shown in Figure 3. All measurements were conducted using a 200 kV (1.8 mm Cu HVL) beam with a 0.23 cm^3 farmer type ionisation chamber. At each location, three measurements

Figure 4. Film wrap of the D3/40 applicator indicating the location of hotspots from leakage radiation.

were performed and the mean reported. Measured leakage radiation air kerma rates were compared to the in-field central axis air kerma rate.

RESULTS AND DISCUSSION

No change in OD and hence no leakage was detected from the housing of the kV tube. As shown in Figure 4, a notable change in OD was observed on the Gafchromic RTQA-2 film affixed to the base plate and outer wall of each applicator. The source of these hot spots was determined to be two-fold. The first source was radiation penetrating each of the screws which affix the applicator to the base plate, and second from radiation penetrating through the base plate itself.

A symmetric ring-shaped hot spot extending 1.5 cm from the applicator wall was identified on the metal base plate of the D3/40 applicator. A similar symmetric ring-shaped hotspot was seen on the base plate of the D4/40 applicator which extended 1 cm from the applicator wall. Hotspots with the same outer diameter were also identified on the 6 × 8/30, 8 × 10/40 and 10 × 15/40 applicators.

Upon investigation, the cause of this hotspot is due to the diameter of primary collimator of the kV tube (8 cm in diameter) exceeding the external dimension of the applicator wall. Consequently, primary beam radiation is able to penetrate the metal base plate of the applicator outside the external dimension of the applicator wall, causing excessive leakage radiation. This principle is schematically illustrated for the D3/40 applicator in Figure 5.

Assessment of the dose rate in the patient plane found that the leakage radiation exceeded the 0.5% central axis dose limit specified in the standard.¹³ Table 2 indicates the maximum measured

Table 2. Maximum measured dose at the plane of the distal surface of the applicator

Applicator	Distance to edge of lead block	Leakage dose relative to open Central Axis(CAX) of beam
D3/40	45 mm	1.42%
D4/40	45 mm	1.36%
6 × 8/30	22 mm	1.34%
8 × 10/40	30 mm	1.35%
10 × 15/40	20 mm	1.03%

CAX, Central Axis;

dose in the patient plane relative to CAX for each applicator. The 10 × 15/40 applicator saw reduced radiation leakage due to the geometrical size of the applicator.

As demonstrated in Figure 5, the width of the leakage radiation profile is dependent upon the geometrical difference between the primary collimator and the edge of the applicator wall.

Figure 5. Schematic identifying the cause of the excessive leakage radiation.

Figure 6. Films taken in the patient plane with a 60 min exposure. Black lines indicate the external applicator wall for (A) D30/40 (B) $6 \times 8/30$ (C) $8 \times 10/40$ (D) $10 \times 15/40$ (applicator wall not shown). Lead strips were placed on the films in (A), (C) and (D) for OD contrast. OD, optical density.

Table 3. Energy dependence of leakage radiation measured at a distance of 12 mm from the applicator base plate

Beam energy (HVL)	Percentage of CAX dose
200 kV (1.8 mm Cu)	11.8%
150 kV (0.7 mm Cu)	1.3%
100 kV (4.8 mm Al)	0.2%
80 kV (3.9 mm Al)	0.0%
60 kV (2.3 mm Al)	0.0%

HVL, Half Value Layer; CAX, Central Axis;

The mean leakage radiation across all applicators excluding $10 \times 15/40$ is 1.37%. Since the source of the leakage radiation is independent of the applicator, the constancy of the measured leakage across all applicators is expected. This result is lower than the 1.9–3.6% maximum doses reported by Aspradakis

Figure 7. Leakage radiation angular dependence about the D3/40 applicator.

and Zucchetti.²⁸ In saying this, measurement conditions were not identical as Aspradakis and Zucchetti's measurements were conducted at 1 cm depth in water and did not block the CAX of the field with lead. The $10 \times 15/40$ applicator has a larger applicator wall, so the space between the wall and the primary collimator is reduced. Consequently, a smaller leakage radiation beam profile is permissible, thus reducing the measured dose. This is evident from the patient plane films shown in Figure 6.

As shown in Table 3, the measured leakage radiation was shown to be profoundly energy dependent. The base plate of the applicator has an approximately 2 mm thick lead sheet imbedded in a steel housing. Evidently, this lead is thick enough to completely attenuate the radiation for the lower energy 60 kV and 80 kV beams. As energy increases, the 100 kV, 150 kV and 200 kV beams are energetic enough to penetrate this shielding, giving rise to increased out-of-field leakage radiation with increasing energy.

Evaluation of the angular dependence about the plane of the distal end of the applicator showed a large variation in the leakage radiation dependent upon the angular position relative to the target. Figure 7 demonstrates that the leakage radiation is asymmetric in nature with a maximum variation of 10.3% seen between the 90° location and location maximum leakage. The asymmetry is attributed to self-attenuation of photons within the

Table 4. Dose relative to CAX at various distances (as shown in Figure 3) from the D3/40 applicator

Distance from base plate (mm)	Distance of chamber tip from applicator wall (mm)			
	0	25	50	75
12	11.79%	0.50%	0.10%	0.00%
50	3.98%	1.36%	0.20%	0.02%
100	0.93%	3.56%	0.22%	0.05%
150	0.23%	2.46%	0.32%	0.07%
200	0.16%	1.16%	1.61%	0.10%
240	0.10%	0.60%	1.41%	0.13%

CAX, Central Axis;

target and due to the shift in focal spot from CAX as reported by Aspradakis and Zucchetti.²⁸

Table 4 shows the measured dose relative to central axis at various distances surrounding the D3/40 applicator. The maximum measured leakage was 11.79% at the location as close as physically possible to the base plate (12 mm) at the applicator wall. The two-dimensional (2D) dose distribution follows the beam lines outlined in Figure 5 and, where not shielded by the applicator wall, decreased as a function of distance from the source.

CONCLUSION

Due to the manufacturer's design of the Womed T-200 kilovoltage unit, the diameter of primary collimator of the kV tube exceeds the external dimension of each of the tested applicator walls. This design permits unwanted radiation to contribute dose outside the treatment field. This leakage radiation was shown to be highly energy dependent. Beam energies <100 kV (4.8 mm Al HVL) were found not to be energetic enough to give rise to any leakage radiation. In a worst case scenario, the highest energy, 200 kV (1.8 mm Cu HVL) gave a maximum

dose of 11.8% compared to the open non-attenuated central axis dose.

All applicators were shown to exceed the IEC (and Australian Standard) tolerance for leakage radiation in the plane of the distal end of the applicator. The mean leakage radiation across all applicators (excluding the 10 × 15/40) in this plane was 1.37%. The leakage radiation around the D3/40 applicator was shown to exhibit an asymmetric angular dependence varying by up to 10.3% depending upon its angular position with the greatest attenuation occurring on the side in line with the cathode. The 2D leakage dose distribution was mapped in the plane parallel to the D3/40 applicator. The measured dose showed good agreement with the expected dose distribution when considering the geometric difference between the applicator wall and the primary collimator.

ACKNOWLEDGMENT

The authors would like to thank Joshua Wolf for his help in creating the schematics shown in this paper and for his assistance in 3D printing.

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