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FULL PAPER

Acceptance, commissioning and clinical use of the WOmed T-200 kilovoltage X-ray therapy unit

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Objective: The objective of this work was to characterize the performance of the WOmed T-200-kilovoltage (kV) therapy machine.

Methods: Mechanical functionality, radiation leakage, alignment and interlocks were investigated. Half-value layers (HVLs) (first and second HVLs) from X-ray beams generated from tube potentials between 30 and 200 kV were measured. Reference dose was determined in water. Beam start-up characteristics, dose linearity and reproducibility, beam flatness, and uniformity as well as deviations from inverse square law were assessed. Relative depth doses (RDDs) were determined in water and water-equivalent plastic. The quality assurance program included a dosimetry audit with thermoluminescent dosimeters.

Results: All checks on machine performance were satisfactory. HVLs ranged between 0.45–4.52 mmAl and 0.69–1.78 mmCu. Dose rates varied between 0.2 and

3 Gy min⁻¹ with negligible time-end errors. There were differences in measured RDDs from published data. Beam outputs were confirmed with the dosimetry audit. The use of published backscatter factors was implemented to account for changes in phantom scatter for treatments with irregularly shaped fields.

Conclusion: Guidance on the determination of HVL and RDD in kV beams can be contradictory. RDDs were determined through measurement and curve fitting. These differed from published RDD data, and the differences observed were larger in the low-kV energy range.

Advances in knowledge: This article reports on the comprehensive and novel approach to the acceptance, commissioning and clinical use of a modern kV therapy machine. The challenges in the dosimetry of kV beams faced by the medical physicist in the clinic are highlighted.

INTRODUCTION

The treatment of superficial cancerous or benign lesions with radiation therapy has been carried out for many years using X-ray beams generated from peak potentials ranging from 6 up to 300 kilovoltage (kVp).¹ The availability of electron beams on linear accelerators appears not to have made kilovoltage (kV) beams redundant. kV treatment machines still feature in radiotherapy departments, and one can argue that there is a revived interest in their development and the improvement of dosimetry in these beams.² With kV treatments, despite the apparent simplicity in dose delivery, the determination of beam quality index, and reference and relative dose is not straightforward. There is somewhat conflicting guidance on the irradiation geometry that should be used for the determination of the beam quality index in the low energy region (energies from tube potentials ≤ 100 kV).^{3,4} The beam quality index for these beams is the half-value layer (HVL), defined as the thickness of an absorber, which reduces the air kerma rate of a narrow X-ray beam at a reference point distant from the absorbing layer to 50%

compared with the air kerma rate for the non-attenuated beam.³ Most dosimetry codes of practice and radiotherapy physics textbooks make no distinction between low and medium energies (at $100 \text{ kV} \leq \text{tube potential} \leq 300 \text{ kV}$) and recommend that HVLs are measured under a scatter-free narrow-beam geometry with a chamber at about 1 m from the X-ray source and with the beam attenuators placed halfway in between.^{5–8} In the International Atomic Energy Agency (IAEA) TRS-398 dosimetry protocol,³ it is recommended that for the measurement of HVL in the low energy range, the chamber is placed at a source-to-chamber distance (SCD) equal to that used for the measurement of reference absorbed dose, a geometry which differs from the standard narrow-beam geometry mentioned above.

In dosimetry codes of practice, the determination of reference dose and the calibration of kV beams are carried out using different types of chambers and phantoms depending on beam energy.^{3,5,6} Liquid water is the medium of choice for reference dosimetry apart from measurements in the

low energy range (<100 kV) where solid phantoms, such as water-equivalent plastics or polymethyl methacrylate (PMMA) and polystyrene can be used instead.⁹ Guidance in dosimetry codes of practice is less specific when it comes to relative dosimetry and in particular the measurement of relative depth doses (RDDs). The challenge with the determination of RDDs in the kV range lies in the choice of detector and phantom material.^{9,10} An ionization chamber with a flat energy response (better than $\pm 5\%$ between 40 and 300 kV) and suitable size which allows measurement at shallow depths is recommended.^{3,6,11,12} Some dosimetry protocols recommend only liquid water for relative dosimetry,^{6,12} whereas others do not discourage the use of non-water-equivalent plastics in the low-kV energy region.^{3,4,13} Based on the findings by Hill et al,⁹ some, but not all commercially available solid phantoms, are water-equivalent within $\pm 2\%$ in kV beams and data measured in some plastics can differ from those measured in water by up to 7%, and this depends on beam quality and field size. If it is not possible to directly measure RDDs, Ma et al⁶ recommend interpolating from the data in Supplement 25 of the *British Journal of Radiology* (BJR-25).¹ The BJR-25 report includes data from beams from a wide range of kV beam qualities, a large range of source-to-surface distances (SSDs) (from 2 up to 50 cm), and collimated by open or diaphragm-defined applicators. These were compiled from an average of measurements carried out on older treatment units installed at various hospitals using a variety of (cylindrical or plane-parallel) ionization chambers and phantom materials including water and plastics. It is important that data used for treatment are determined in water or in a water-equivalent medium or that the irradiated medium is stated for data given in publications.^{14,15}

This article reports on the acceptance and commissioning work carried out on the T-200 X-ray therapy system manufactured by Wolf-Medizintechnik (WOMed) GmbH (WOMed, St Gangloff, Germany) installed at our clinic. The intended use of this machine is for superficial X-ray therapy using beams from tube potentials between 30 and 200 kV. Existing publications^{14,16–18} report on performance characteristics and dose determination from kV units by other manufacturers. The T-200 system by WOMed differs from other systems, because of its design using interchangeable filters on a carousel, the design of its applicators and the integrated software for machine control and clinical use. The latter incorporates information on patient demographics, enables treatment time calculations and manages treatment

delivery. Dose determination was carried out following recommendation number 9 of the Swiss Society of Radiobiology and Medical Physics (SSRMP).⁸ The determination of RDDs was investigated in some detail, with measurements carried out both in water and plastic using different detectors and also compared against data from the BJR-25.¹ Finally, the article also describes the comprehensive quality assurance (QA) programme put in place for this machine and its clinical use for the treatment of patients under non-reference irradiation conditions.

METHODS AND MATERIALS

The WOMed T-200 machine

The T-200 machine has a unipolar metal ceramic stationary anode X-ray tube (model Varian HPX-226; Varian® Medical Systems, Palo Alto, CA) with an integral high-voltage receptacle and water cooling system. The X-ray generator is powered to a maximum of 3 kW with a maximum peak voltage reached at 225 kVp. This machine is set to deliver beams from accelerating potentials ranging between 30 and 200 kV and tube currents ranging between 10 mA at 30 kV, 13 mA at 200 kV and 20 mA at the remaining accelerating potentials. According to specification, the X-ray target is made of tungsten, which is at an angle of 30° and has a focal spot of 7.5 mm. The tube has inherent permanent filtration of 0.8 mm of beryllium (Be) and a maximum coverage of the radiation field of 40° .

The machine warm-up procedure is initiated by the X-ray controller when the system is powered on. The T-200 X-ray control is a dual programmable logic microprocessor controller (PLC) with a time-based control system with an independent back-up timer. A maximum treatment time of 900 s can be set on the primary timer. The back-up timer is set to run 8 s behind the primary. At the end of each treatment, an automatic test procedure completes the countdown of the secondary timer. The values of kV and mA are being continually monitored during irradiation, and radiation is interrupted if any of these deviate more than $\pm 3\%$ from nominal. Integrated to the treatment unit is a non-sealed and non-calibrated ionization chamber (by VacuTec Messtechnik GmbH, Dresden, Germany) serving as an additional system for safety and QA. A maximum of seven treatment filters are available on a carousel mounted within the treatment head and selected through an automatic filter changer (Figure 1). Eight beams were specified and commissioned in our current

Figure 1. Carousel with filters: (a) view from the end of the applicator towards the X-ray source; (b) view from the X-ray source towards the applicator distal end. Al, aluminium; Cu, copper.

Table 1. Beams and applicators available on the T-200 kilovoltage (kV) treatment machine (by Womed GmbH, St Gangloff, Germany)

Beams									
Tube potential (kV)		30	40	50	60	80	100	150	200
Current (mA)		10	20	20	20	20	20	20	13
Filter	(mmAl)	0.3	0.7	1.0	2.6	4.5	4.5	1.0	1.0
	(mmCu)	–	–	–	–	–	–	0.4	1.3
Applicators									
Applicator type	Applicator SSD (cm)	Field size at nominal SSD (cm)							
Circular with open ends	20	2 Ø		3 Ø			5 Ø		
	30	2 Ø		3 Ø			5 Ø		
Rectangular with closed ends (1-mm plastic)	40	6 × 8		10 × 10			10 × 15		

Al, aluminium; Cu, copper; SSD, source-to-surface distance.

configuration of kV/mA and filter combination (Table 1). For warm-up, a lead plate of 6-mm thickness is placed at the position of the applicator. Applicators with open ends define circular fields with diameters of 2, 3 and 5 cm at SSDs of either 20 or 30 cm. Rectangular applicators define rectangular fields with sizes of 6 × 8 cm, 10 × 10 cm and 10 × 15 cm at an SSD of 40 cm. The ends of the rectangular applicators are closed with a sheet of 1 mm Macrolon®, a type of polycarbonate with mass density close to unity and a small cross at its centre indicating the applicator axis. The base of all applicators is made of stainless steel and lead. The body of the applicators is made of 10-mm thick Kyowaglas-XA, which according to specification has an inherent shielding of 0.5 mm lead. According to the manufacturers' specification, the alignment of the focal spot with the applicator axis is within ±5 mm. The applicators commissioned for patient treatment are summarized in Table 1. A special "QA applicator", purchased as an optional, allows for measurements in PMMA at two distances from the source using a 0.6 cm³ cylindrical ionization chamber.

The treatment unit operates through an integrated software suite (known as RadControl-II, also by Womed GmbH) serving as

treatment console as well as patient management, treatment time calculator and treatment verification system.

Tube leakage

Tube leakage was examined using Gafchromic RTQA-2 film by Ashland Advanced Materials (Bridgewater, NJ). According to the findings of Butson et al,¹⁹ this film exhibits a higher energy response at lower photon energies than that of other types of radiochromic films with a net optical density (OD) of 0.3 producing significant visual colour change on the film. With the lead beam stopper at the position of the applicator and the tube wrapped with film, exposures of 10 min were delivered using the 100-, 150- and 200-kV beams.

Applicator assessment

Each applicator was assessed in terms of distortion in its construction. With a spirit level, it was checked whether the end surface of the applicator was flat. The position of the applicator axis on rotation of the applicator was investigated by noting the movement of the marked centre of the applicator aperture on a graph paper. The alignment of the applicator axis with the beam axis was investigated with RTQA film. Leakage through the

Figure 2. The special jig constructed for checking the size and shape of the focal spot and the set-up for taking an image of this. (a) The device in the applicator. (b) The experimental set-up where a piece of film on top 5 cm of polymethyl methacrylate (PMMA) and with the end of the special jig on the film.

walls of applicators was investigated with films wrapped around the applicator walls.

Focal spot

The purpose of this task was to record an image of the source at the time of commissioning, which would serve as reference for routine QA on the condition of the tube and for checks following any major repair. For this, a purpose-built jig was constructed in-house to enable the irradiation of RTQA film under pinhole geometry. The cylindrical jig, shown in Figure 2, is made of white polystyrene and fits tightly in the applicator with 5-cm diameter. At one end, the jig contains a 4-mm thick disk made of steel with a 1-mm diameter hole drilled at its centre and aligned to the axis of the applicator. At its other end, thin orthogonal wires were imbedded in the walls with their intersection aligned with the 1-mm hole at the other end. The precision in manufacturing this jig was better than 0.1 mm. With the jig inserted in the applicator, the pinhole on the disk is at 140 mm from the focal spot, the source-to-applicator end distance is 300 mm and the source-to-film distance is 362 mm. This geometry allows a magnification ratio >2 , as recommended for experiments designed to determine focal spot sizes from radiographs.⁷

Films were exposed at each tube voltage for 3 min and with the applicator/jig at 0° and at 180° rotation (applicator at 0° was the standard orientation with which applicators were inserted to the machine for all measurements carried out during commissioning).

From these exposures, the size and position of the focal spot with respect to the applicator axis and applicator rotation was evaluated.

Effective source-to-surface distance

The SSD as defined by each applicator may differ from the effective SSD (SSD_{eff}), which is the SSD at which the inverse square law (ISL) holds.²⁰ SSD_{eff} can be used instead of the nominal value to more accurately account for the effect of ISL in treatments with stand-offs, and this has been reported to be more important in the case of applicators closed with PMMA plates which were 3–4 mm thick.^{21,22}

In this work, the end plates of closed applicators had a thickness of 1 mm, and SSD_{eff} were determined for each applicator at 30, 50, 100 and 200 kV using cylindrical ionization chambers: depending on the field size, either a TW30013 (0.6 cm^3) or TM31010 (0.125 cm^3) chamber was used (both by PTW-Freiburg, Freiburg, Germany). For each measurement, the effective point of measurement of the chamber in air was placed on axis and at the required distance from the applicator end. Ionization readings for 2 min were recorded as close as possible to the applicator and in steps of 2 cm at distances from 1 to 12 cm from the end of the applicator. For each combination of tube voltage and applicator, the inverse of the square root of the mean ionization measured was plotted against the distance from the focal spot, and a linear regression analysis was carried out to determine SSD_{eff} .²⁰

Figure 3. Experimental set-up for the measurement of half-value layers: ionization chamber at 100 cm from the X-ray source and with attenuating plates positioned halfway at 50 cm.

Machine timer

The machine internal timer was checked with an external timer (stopwatch). For this, the methodology recommended in the Institute of Physics and Engineering in Medicine (IPeM) report 81²³ was followed. For each tube voltage combination, exposures for 0.1, 1 and 3 min were measured from times of 0.15, 1.05 and 3.05 min set on RadControl-II, respectively. For each exposure, the external timer was started 0.05 min (3 s) after the start of the machine timer. This delay of 3 s in starting the external timer was introduced to ensure that both timers started together.

Following termination of a range of exposures, it was checked that the secondary timer of the machine always lagged 8 s behind as per system configuration. It was also checked that no exposure was possible without specifying a treatment time in RadControl-II.

The case of treatment interruption was simulated using the STOP irradiation button on the treatment console or by turning off the power mains to the whole unit. At treatment interruptions, the control software is expected to automatically create a new treatment plan with the remaining treatment time to be given to complete the prescribed dose fraction.

Determination of beam quality index

The irradiation geometry used for the determination of the HVL was a narrow-beam geometry, where the ionization chamber was positioned at about 1 m from the position of the X-ray source and at least 1 m from the floor and surrounding walls. The PTW TW30013 (0.6 cm³) cylindrical ionization chamber was used for the measurements. The X-ray beam with the 2-cm applicator was collimated using a narrow aperture made of lead which was placed halfway between the source and chamber. This collimation was large enough to ensure that the ionization chamber was fully exposed to the beam at 1 m.⁷ The position of the chamber with respect to the lead aperture was checked with RTQA film placed behind the chamber. Measurements (exposures of 2 min) were carried out under this irradiation geometry using filters of aluminium (Al) or copper (Cu) (99.99% high-purity materials obtained from PTW-Freiburg GmbH together with a HVL measuring stand) placed halfway between the source and the chamber (Figure 3). From the measurement of the first and second HVLs, the homogeneity coefficient was determined for each beam. The second HVL is the additional thickness of filtering required to reduce the beam intensity to 25% of that without any filtering. The homogeneity coefficient is defined as the ratio of the first to the second HVL and is a measure of the polyenergetic nature of the beam. The maximum value of one indicates a monoenergetic beam, and high values of the homogeneity coefficient indicate that the beams do not contain a large component of low-energy photons, whose presence is not desirable as these contribute little to dose beyond the surface. Using the measured HVL, the corresponding effective photon energy, which is the energy of a monoenergetic beam with the same HVL in Al or Cu as the clinical beam, was derived from tables of mass attenuation coefficients provided by the National Institute of Standards and Technology (NIST).²⁴

Measured HVLs were compared with the values calculated using the SpekCalc spectrum generation software.²⁵ This software tool

for calculating photon spectra from tungsten anode X-ray tubes owned jointly by the Institute of Cancer Research (London, UK) and McGill University (Montreal, CA), has been extensively validated and is known to give good results when benchmarked against simulations with the Monte Carlo method.²⁵ For a given target angle (30° in the case of the T-200), tube potential, internal (0.8 mm Be) and external filtration and distance from the target (1 m), the software calculates the photon spectrum at that distance, the first and second HVLs in mmAl and mmCu, the respective homogeneity indexes, the mean and effective energies and the bremsstrahlung output.

Time-end effect

The time-end effect or error δt is the amount of time not accounted for by the machine timer mechanism during the X-ray beam delivery. It is the difference between the elapsed time indicated by the machine timer and the time when the desired kVp and mA have been reached.^{6,26} At a negative δt , the timer starts early, resulting in a dose deficit, and thus $|\delta t|$ would need to be added to the treatment time, whereas for positive value indicates, the timer starts late, and thus $|\delta t|$ would need to be subtracted from the treatment time. Ma et al⁶ recommended that at commissioning of a new machine, and for accurate determination of δt , a graphical extrapolation method is used. For routine QA, the mathematical method proposed by Attix²⁷ would suffice:

$$\delta t = \frac{M_2 \Delta t_1 - M_1 \Delta t_2}{M_1 - M_2} \quad (1)$$

where M_1 and M_2 are the ionization chamber readings at exposure times Δt_1 and Δt_2 , respectively and $\Delta t_2 = 4 \times \Delta t_1$. In this work, for the graphical extrapolation method, a regression analysis of measurements for treatment times ranging between 0.05 and 3.2 min was performed to calculate the time at zero dose. Measurements were carried out with a cylindrical ionization chamber at 2-cm depth in water with the 10 × 10-cm applicator at all tube potentials above 100 kV. Below 100 kV and for the smallest applicator (2 cm diameter), these measurements were carried out with the PTW M23342 in the PTW Soft X-ray Slab phantom type 2969. Equation (1) was used for all combinations of tube potential and applicator. The extrapolation method is time consuming, and one does not expect time-end errors to vary with applicator. Following a pragmatic approach, we examined both the agreement between results from a more accurate regression analysis and Equation (1) and checked the time-end error for the whole range of tube potential and applicator available on the treatment unit.

Reference dosimetry: beam outputs

Reference dose determination was carried out according to recommendations number 9 of the SSRMP.⁸

In the low-kV energy range, reference dose determination was carried out at the surface of the PTW Soft X-ray Slab phantom type 2969, which consists of several plates (13 × 13 cm) of variable thickness (1, 2, 5, 10 mm) and is made of Plexiglas® GS (Evonik Industries AG, Darmstadt, Germany). The secondary standard instrument was a UNIDOS® T10001 electrometer (PTW-Freiburg, Freiburg, Germany) together with a PTW

M23342 (0.02 cm^3) plane-parallel ionization chamber. This instrument was calibrated together with the slab phantom in terms of absorbed dose to water at the Federal Institute of Metrology METAS. This calibration is traceable to the absorbed dose-to-water calibration service of the National Metrology Institute of Germany (PTB), which is valid for beam energies between 20 kV/0.11 mmAl HVL and 100 kV/4.74 mmAl HVL and was carried out at a SSD of 30 cm and in a radiation field diameter of 3 cm at this distance.⁴ Although it is recommended that thin build-up foils or plates to be added on the entrance window of the PTW M23342 to provide full build-up and shield from electron contamination,^{3,4,6} our chamber was calibrated by the standard laboratory without such foils, and thus, the chamber was used without these in the clinic.

In the medium energy range, reference dose determination was carried out at the depth of 2 cm in liquid water. The secondary standard instrument was a UNIDOS® E T10009 electrometer (PTW-Freiburg) together with a PTW TW30013 (0.6 cm^3) cylindrical Farmer-type ionization chamber. This secondary standard instrument was calibrated in terms of absorbed dose to water at the Institut de Radiophysique Appliquée (IRA) at the University Hospital of Vaud. This calibration is traceable to the absorbed dose to water calibration service of the PTB, which is valid for beam energies between 100 kV/0.151 mmCu HVL and 280 kV/4.01 mmCu HVL and was carried out at a SSD of 100 cm and in a radiation field with diameter of 11 cm at the position of the chamber.¹³

In both the low and medium energy ranges, the readings of the detector were corrected for changes from reference environmental conditions (pressure and temperature), and no additional corrections were applied to the calibration coefficient when measuring at other SSD and field sizes, as defined by the applicators on T-200.⁸ Absorbed dose to water calibration coefficients for the two reference instruments for the beams on the T-200 were interpolated from those listed on the certificates. Ion recombination and polarity corrections were set to one as these corrections were not considered in the determination of the calibration coefficient at the standard laboratories.

Relative dosimetry: depth doses

The measurement of RDDs in water was carried out in the large water tank (Welhöfner/IBA Dosimetry GmbH, Schwarzenbruck, Germany) for all beam and applicator combinations.

Initial investigations on the measurement of RDDs were carried out with waterproof Farmer-type and thimble-type cylindrical ionization chambers: PTW TW30013 (0.6 cm^3) and a Wellhöfner/IBA IC-15 (0.13 cm^3), respectively. According to Hill et al¹⁰ and Snow et al,²⁸ these chambers exhibit a relatively flat energy response in kV beams ranging between 20 kV/0.148 mmAl HVL and 250 kV/18.5 mmAl HVL. Owing to the excellent agreement observed between the measurements carried out with these two ionization chambers in the large fields, the definitive data set of RDDs in liquid water for all fields was based solely on the measurements with the Wellhöfner/IBA IC-15 (0.13 cm^3) ionization chamber. Owing to its cylindrical geometry, it was not possible to measure at and just below the surface of the water (within the first 10 mm of depth). Values at shallow depths were determined from curve fitting (fifth-order polynomials) to data measured at greater depths.

To validate the RDDs determined as described above and most importantly to check the relative dose values at the surface and within the first 10 mm, RDDs were also measured with a PTW Advanced Markus® (0.02 cm^3) plane-parallel ionization chamber (PTW-Freiburg) and with radiochromic EBT3 film (by Ashland Advanced Materials) in a water-equivalent plastic phantom. Measured RDDs were also compared against values interpolated from BJR-25.¹

Plastic water DT® (PWDT), manufactured by CIRS (Norfolk, VA), has been shown to be water-equivalent at low-energy photon beams in the range of 50 kV/1.6 mmAl HVL to 280 kV/3.3 mmCu HVL.^{29,30} Verification of RDDs at shallow depths at the higher energies was particularly of interest because polynomial curve fitting to data measured at greater depths could erroneously model the depth dose within the first millimetres below the surface.

The suitability of the PTW Advanced Markus plane-parallel ionization chamber for relative dosimetry in kV beams has been investigated in detail by Hill et al,¹⁰ and this chamber has been recommended for relative dose measurements in the range of 50 kV/1.6 mmAl HVL to 280 kV/3.3 mmCu HVL.

There is limited information in the literature on the energy response and suitability of EBT3 film for dosimetric measurements in the kV range. Brown et al³¹ reported small energy dependence in low-energy monoenergetic photon beams (25–35 keV), whereas by contrast, Villarreal-Barajas and Khan³² reported under-response of

Figure 4. Set-up for the measurement of profiles and inspection of field sizes. The detector array was placed on top of a polymethyl methacrylate (PMMA) block which was 5-cm thick. For irradiations with round applicators, a 1-mm thick sheet of PMMA was placed on top of the detector; this was not used with rectangular applicators as these are closed with 1-mm PMMA. SSD, source-to-surface distance.

Figure 5. Top row: images of the focal spot from 3-min exposures at 100 kV at applicator angles of 0° and 180°. Second row: analysis of the images.

the order of 20% at beams of 3.0 mmAl HVL and of the order of 5% at 4 mmCu HVL. Based on our findings from a previous investigation on the dependence of the calibration of EBT3 film on irradiation conditions in kV beams (energy and depths of irradiation in PWDT) and on the choice of irradiation geometry (orientation of the film with respect to the beam central axis),³³ for this work, calibration curves were determined at each kV beam. Films were calibrated at the surface for low-energy beams (<100 kV) and at the depth of 2 cm in PWDT for medium-energy beams (≥ 100 kV), as these are the depths used for the determination of reference dose in the respective energy ranges. RDDs were measured in PWDT with films positioned at different depths vertically to the beam central axis. The films were scanned with an Epson Expression 10000XL (Epson America, Inc., Long Beach, CA) flat-bed scanner, and the film analysis was carried out with the FilmQA™ Pro software by Ashland Advanced Materials. Only the signal from the red channel was used in the evaluation and comparison of RDDs.

Relative dosimetry: beam profiles

Field sizes from all applicators were examined from exposures at 150 kV with RTQA film placed on a 5-cm thick plastic block at the end of the applicator. The width of the exposed image was visually compared against the nominal field size as defined by the applicator aperture.

Orthogonal ionization profiles were measured at nominal SSDs from all applicators and tube voltage combinations with the two-dimensional (2D) ionization chamber array (array729, PTW-Freiburg). All profiles were measured below 1 mm of

plastic (PMMA) so that any contaminant electrons from applicator walls were removed from the beam. The set-up for the measurement of ionization profiles is shown in Figure 4. This ionization chamber array has a resolution of 1 cm between chamber centres. Measurements with this device adequately resolve the field shape within the central 80% of the field for the field sizes examined here (for fields with dimensions >5 cm). Owing to the coarse resolution of this detector matrix, the penumbra width of the profiles will be overestimated when assessed with this device as it can be confirmed with measurements using film. The main purpose of these profiles was to aid clinicians in their choice of field size for treatment.

The assessment of beam flatness (homogeneity) and symmetry was carried out from orthogonal ionization profiles measured at the field sizes down to a diameter of 5 cm and at all beam potentials using the array729. Following the definitions by the International Electrotechnical Commission (IEC 60976),³⁴ flatness was evaluated as:

$$\text{Flatness} = \frac{(M_{\max} - M_{\min})}{(M_{\max} + M_{\min})} \cdot 100\% \quad (2)$$

and symmetry as:

$$\text{Symmetry} = \left[\frac{M(x)}{M(-x)} \right]_{\max} \cdot 100\% \quad (3)$$

where $M_{\max}$ and $M_{\min}$ are the maximum and minimum ionization readings within 80% of the field size, which is

Table 2. Measured effective source-to-surface distance (SSD_{eff}) at tube potentials of 30, 50, 100 and 200 kV. The values for the rest of the beams and field sizes were interpolated. The last column gives the average SSD_{eff} assigned to each applicator

Tube potential (kV)		30	40	50	60	80	100	150	200		
Filter	(mmAl)	0.3	0.7	1.0	2.6	4.5	4.5	1.0	1.0		
	(mmCu)	–	–	–	–	–	–	0.4	1.3		
Applicator SSD (cm)	Field size at nominal SSD (cm)	Effective SSD (cm)								Average SSD_{eff} (cm) (all beams)	
20	2 Ø	19	19	19	19	19	18	–	–	19	
	3 Ø	19	18	18	18	18	18	–	–	18	
	5 Ø	18	18	19	18	18	18	–	–	18	
30	2 Ø	28	29	29	29	29	29	–	–	29	
	3 Ø	28	28	28	28	28	28	28	28	28	
	5 Ø	28	28	28	28	28	28	28	28	28	
40	6 × 8	36	36	37	37	37	37	37	37	37	
	10 × 10	36	36	36	36	36	37	37	37	36	
	10 × 15	35	36	36	36	36	37	37	37	36	

Al, aluminium; Cu, copper; SSD, source-to-surface distance.

defined at 50% of the value on the beam axis. $M(+x)$ and $M(-x)$ are the ionization readings at off-axis positions symmetrical to the centre of the beam and within the flattened region of the ionization profile. The measurements with the largest applicator served as reference of flatness and uniformity of the X-ray beam at commissioning from which one could periodically monitor possible changes in the X-ray target with time.

RESULTS

Tube head leakage

There was no evidence of radiation leakage from the X-ray tube on film wrapped around the head of the treatment machine (with the lead applicator in place).

Applicator assessment

All applicator ends were found to be flat to within $\pm 0.03^\circ$, which was comparable to the precision of the measurement instrument. At rotation of the two applicators (6 × 8 cm and 10 × 10 cm), it was noticed that the mechanical centre, as marked by the scribed cross on the end plate, had a walk-out of 4 mm at a worse case. This was communicated to the manufacturer, and as a result, these applicators were replaced. For all applicators, their axis exhibited a walk-out of less than 2 mm at rotation of the applicator.

The exposures with film wrapped around applicator walls indicated radiation leakage through the screws, which was visible on film placed at the end of the applicator. In an attempt to quantify this, measurements with a 0.6-cm³ ionization chamber at a depth of 1 cm in PMMA for 5-min exposures at a 200 kV below the 6 × 8-cm applicator on axis and at 6 and 9 cm off axis. These positions were chosen based on the position of darkening

seen on film. Ionization at these positions was 3.6% and 2.4% of the value on the axis, respectively. These values were considered acceptable, because the tolerances for leakage off axis at these positions as stated by the manufacturer are 2% and 0.5% with the aperture of the applicator closed by a lead shield. In our measurements, there was no lead shield present. Similar investigations with the applicator of 5 cm diameter showed that leakage through circular applicator walls at 4 and 5.5 cm off axis was 1.9% and 0.8%, respectively, of the ionization on axis. This was because the walls of the circular applicators are thicker than those of the rectangular applicators. As a result of these checks and in order to keep leakage through applicators as low as possible, the manufacturer replaced the screws on all applicators with thicker screws, and an additional sheet of 2 mm of lead was permanently added around the base of each applicator.

Focal spot

The size of the focal spot, as measured on film, was 7.5 × 7.5 mm at all tube potentials. At an applicator angle of 0°, the centre of the focal spot was off-set towards the anode by 1.5 mm from the applicator axis. With rotation of the applicator by 180°, the centre of the focal spot moved by 0.5 mm towards the direction of the cathode (Figure 5). A 1.5 mm off-set at source-to-film distance of 362 mm translates to a 0.7-mm off-set at the level of the pinhole (at 168 mm). The focal spot at a magnification at about 2 was estimated to be 15 × 15 mm. This is close to the dimensions quoted by the manufacturer (13.5 × 12.5 mm at a magnification of 2).

Effective source-to-surface distance

Table 2 summarises the data for SSD_{eff} for each applicator and beam. For the applicators which set a SSD of 30 cm, SSD_{eff} were

Table 3. Measured the first and second half-value layers (HVLs) on beams available on the T-200. Effective energies were interpolated from values in the National Institute of Standards and Technology (NIST) database. The last three columns contain data calculated with the SpekCalc software tool

Beam characteristics of kilovoltage beams on T200														
Beam			Measurements				From NIST data tables		Simulation with SpekCalc					
Tube potential	Current	Filter		First HVL	Second HVL	Homogeneity coefficient	Effective energy (Al)	Effective energy (Cu)	Effective energy (Al)	Effective energy (Cu)				
		(mmCu)	(mmAl)											
(kV)	(mA)		(mmAl)	(mmCu)	(mmAl)	(mmCu)		(keV)		(keV)				
30	10		0.3		0.45			0.64	0.70	17.5	16.8		19.9	
40	20		0.7		0.84			1.18	0.71	21.6	20.5		25.1	
50	20		1.0		1.20			1.75	0.69	25.7	23.1		29.5	
60	20		2.6		2.31			3.12	0.74	30.3	29.3		36.3	
80	20		4.5		3.75			5.12	0.73	37.9	38.4	36.6	37.4	46.1
100	20		4.5		4.52			0.18	0.55	40.0	42.8	40.0	41.6	52.3
150	20	0.4	1.0	10.42	0.69	1.10		0.63	0.63	71.4	64.9	68.3	74.4	74.4
200	13	1.3	1.0	15.34	1.78	2.46		0.72	0.72	104.8	97.5	101	103	103

Al, aluminium; Cu, copper.

at maximum 2 cm smaller from nominal SSDs. For the 6×8 -cm applicator, these were on average 3 cm smaller than the nominal and for the 10×10 -cm and 10×15 -cm applicators on average 4 cm smaller. In practice, a single value for SSD_{eff} was assigned per applicator. These values are used instead of the nominal SSD, for the calculation of treatment times in the presence of stand-offs.

Machine timer

The agreement between the machine timer and the stopwatch was within $\pm 2\%$. The secondary machine timer always lagged 8 s behind as per specification, and in case of treatment interruption, the RadControl II software always created a new plan with the remaining treatment time.

Beam quality indexes and beam spectrum parameters

The measured first and second HVLs of the beams available on the T-200 are shown in Table 3. The table also contains the corresponding effective photon energies derived from the measured HVL and those calculated by the SpekCalc software.

Calculated HVLs were lower than measured by 0.1–0.3 mmAl at tube potentials less than 100 kV and less than 0.1 mmCu at tube potentials greater than 100 kV. These differences were attributed to the ionization monitor chamber in the treatment head, whose presence cannot be directly modelled with SpekCalc. According to the specification of this chamber, its presence in an X-ray beam from a tube potential of 70 kV and an external filtration of 2.5 mmAl results in an equivalent filtration of 0.3 mmAl. The last three columns of Table 3 contain values of effective energies and spectrum mean energy as calculated by SpekCalc with the assumption that the monitor chamber introduced an additional filtration of 0.3 mmAl for all beams.

Time-end errors

Time-end errors are given in Table 4. There was almost no difference in the time-end errors determined with the graphical extrapolation method and with Equation (1), and errors were not more than 0.5 s. All values were negative, indicating that the machine starts before radiation comes on. These time-end errors were all less than 0.01 min; thus, errors on the determination of absorbed dose from their influence will be $<1\%$. For this reason, these were not considered in the determination of definitive beam outputs.

Reference dosimetry: beam outputs

Beam outputs under reference irradiation conditions are summarized in Table 5.

Relative depth doses

The tables in the Appendix provide discrete values of RDDs determined from measurements in water with the thimble (IC-15) cylindrical ionization chamber for field sizes defined by the applicators at nominal SSDs of 20, 30, and 40 cm and normalized at the surface. The polynomial regression coefficient was better than 0.9999 for all fits.

Table 4. Summary of measured time-end errors on the T-200 machine

Beam (kV)		30	40	50	60	80	100	150	200
Filter	mmAl	0.3	0.7	1.0	2.6	4.5	4.5	1.0	1.0
	mmCu	–	–	–	–	–	–	0.4	1.3
δt	(min)	–0.003	–0.008	–0.007	–0.007	–0.008	–0.007	–0.008	–0.005
	(s)	–0.18	–0.47	–0.44	–0.43	–0.47	–0.44	–0.47	–0.29

Al, aluminium; Cu, copper.

At medium beam energies (≥ 100 kV/4.52 mmAl HVL), measurements with IC-15 in water and with the Advanced Markus and radiochromic film in PWDT agreed within $\pm 2\%$. The differences from the data published in *BJR-25* were within $\pm 5\%$ at this energy range.

At beam energies between 50 kV/1.2 mmAl HVL and 100 kV/4.52 mmAl HVL, differences between data determined from measurements in liquid water and in PWDT increased with decreasing beam energy with deviations not exceeding 2.5% (at 50 kV). This confirms the findings of Hill et al⁹ who examined the water equivalence of PWDT down to 50 kV/1.6 mmAl HVL. The comparison with published data in *BJR-25*¹ however showed differences in RDDs $>10\%$. These data support the conclusions of Hill et al³⁵ who recommended that the *BJR-25* data below 75 kV/2.6 mmAl HVL should be used with caution.

Representative results are shown in Figure 6 with RDDs at 50 kV (a beam representative of the low range) and at 150 kV (a beam representative of the medium range) for one field size at the SSD of 40 cm. These data are normalized at the depth of 2 cm.

Finally, at the two lowest beam energies, namely at 40 kV/0.84 mmAl and 30 kV/0.45 mmAl, the differences between RDDs determined with the thimble chamber in water and the plane-parallel ionization chamber or film in PWDT were $>10\%$, with the RDDs from the thimble chamber overestimating relative dose at depth in water in relation to the dose measured with the plane-parallel chamber in PWDT. At these very low energies, the suitability of the detectors used in this work, in terms of energy dependence, and the water equivalence of PWDT are not known. In the IAEA TRS-398 dosimetry protocol, it is recommended that at such low energies, RDDs are to be measured in solid plastic with a suitable plane-parallel ionization chamber, such as the PTW M23342, because this detector is used for reference dosimetry, and it is not waterproof. The rationale for allowing the measurement of RDD in solid plastic at these very low energies is that typically only the dose at the surface is of clinical interest. With this in mind and for consistency in our clinic, for the 40-kV and 30-kV beams, the RDDs determined with the thimble chamber in water were included in the dosimetry tables (Appendix).

Table 5. Beam dose rates under reference conditions on the T-200

Tube potential (kV)		30	40	50	60	80	100	150	200
Filter	mmAl	0.3	0.7	1.0	2.6	4.5	4.5	1.0	1.0
	mmCu	–	–	–	–	–	–	0.4	1.3
Half-value layer (mmAl)		0.45	0.84	1.20	2.31	3.75	4.52	10.42	15.34
Half-value layer (mmCu)							0.18	0.69	1.78
Applicator SSD (cm)	Field size at SSD (cm)	Surface dose rate (Gy min ⁻¹)					Dose rate at 2 cm depth in water (Gy min ⁻¹)		
20	2 $\emptyset$	1.111	2.167	2.531	1.621	1.968	–	–	–
	3 $\emptyset$	1.143	2.264	2.668	1.738	2.082	2.037	2.912	1.953
	5 $\emptyset$	1.170	2.350	2.797	1.862	2.233	2.373	3.393	2.246
30	2 $\emptyset$	0.470	0.918	1.069	0.677	0.810	–	–	–
	3 $\emptyset$	0.482	0.955	1.123	0.724	0.859	0.904	1.312	0.866
	5 $\emptyset$	0.492	0.993	1.184	0.783	0.932	1.040	1.507	0.983
40	6 $\times$ 8	0.236	0.525	0.648	0.447	0.546	0.665	0.982	0.631
	10 $\times$ 10	0.239	0.536	0.669	0.471	0.585	0.730	1.092	0.700
	10 $\times$ 15	0.241	0.541	0.678	0.481	0.601	0.751	1.138	0.732

Al, aluminium; Cu, copper; SSD, source-to-surface distance.

Figure 6. Comparison between relative depth doses determined with different detectors in water and plastic. The solid lines are the polynomial curve fit to the measurements in the water tank with the IC-15 thimble ionization chamber. The measurements with film in PWDT are shown in triangles and the measurements with the Advanced Markus® plane-parallel ionization chamber in PWDT are shown with the star-shaped marker. The data interpolated from the Supplement 25 of the *British Journal of Radiology* (BJR-25) are shown in circles connected with a dotted line. Al, aluminium; Cu, copper; HVL, half-value layer; RCF, radiochromic film; SSD, source-to-surface distance. (a) RDDs at 50 kV/1.2 mmAl HVL; (b) 150 kV/0.69 mmCu HVL.

Beam profiles

Field sizes from all rectangular applicators measured on film were 1.5 mm larger than the nominal, whereas the diameters of field sizes for all rectangular applicators matched the nominal. The tolerance in field size was 2 mm.

For the rectangular field sizes and the circular field with 5 cm diameter, flatness in the cathode–anode direction ranged between values of 3.3 and 8% and in the orthogonal direction between 2.4% and 6.8%. The values of symmetry in the cathode–anode direction were between 102% and 109%. In the orthogonal direction, symmetry was between 102% and 104% (all data listed in Table 6). The values of flatness were within the 15% tolerance requirement by the Federal Office of Public Health in Switzerland.³⁶ Flatness and symmetry were slightly worse when assessed from profiles taken along the cathode–anode direction, and this could be indicative of a heel effect. However, on inspection of the profiles for all beams and applicators, values of relative ionization were in all cases lower at the side of the cathode and not at the side of the anode, the opposite to what was expected in the presence of a heel effect, and this is not necessarily uncommon.²⁰

QUALITY ASSURANCE PROGRAM

External dosimetry audit

The determination of beam outputs was independently checked through an external dosimetry audit carried out by MD Anderson Radiation Dosimetry Services (RDS) with mailed lithium fluoride (LiF) thermoluminescent dosimeters (TLDs). Because this service is only available for kV beams with HVLs ≥ 1.9 mmAl, the audit was performed for beams generated at tube potentials of 60, 80, 100, 150 and 200 kV and with the applicator of 6 × 8 cm most frequently used in our clinic.

The TLDs (enclosed in small capsules) were irradiated in air to receive the dose of 3 Gy under the reproducible set-up dictated by RDS. RDS corrected the raw TLD reading for fading, linearity, sensitivity and energy dependence. ISL corrections to convert readings to the nominal SSD and backscatter corrections to correct for the irradiation in air were also needed so that the results could be compared with the beam output under full scatter conditions. For all beams checked, the differences between the measured dose by the TLD and the expected dose were well within the 10% tolerance set by RDS.

Periodic quality control checks

The tests and their frequencies carried out as part of the QA program for T-200 are shown in Table 7. This was designed based on the recommendations in IPEM report 81.²³ The tolerances adhered to are those by the directive R-08-09 of the Department of Health of the Swiss Confederation.³⁶

Daily checks on beam outputs were carried out for 30-s beam on time under a reproducible geometry with a DIADOS solid state detector (diode T60004) together with an associated electrometer (DIADOS E T11035) (both by PTW-Freiburg) at a single field size (applicator 6 × 8 cm, SSD = 40 cm) (the set-up is shown in Figure 7). As part of monthly QA, beam outputs and energies are monitored with a cylindrical ionization chamber in the QA applicator (Figure 8). Reference values for beam outputs in nC min^{-1} were established at commissioning. The ratio of readings at two depths in this phantom served as a surrogate of a constancy check on beam quality.³⁷ Using this set-up, no variation of beam output with angle of the X-ray tube was observed.

Beam outputs, as monitored during monthly QA, were within $\pm 1\%$ for all beams over the course of 2.5 years, since the machine

Table 6. Summary of the flatness and symmetry analysis of ionization profiles measured with the two-dimensional detector array

Beam (kV)			30	40	50	60	80	100	150	200
Applicator	Direction of profile									
10 × 15 cm	In-out	Flatness (%)	3.86	3.38	3.85	4.31	4.93	5.33	6.64	6.77
		Symmetry (%)	103.80	102.79	102.83	102.6	102.77	102.79	102.71	102.27
	Anode-cathode	Flatness (%)	6.34	5.98	6.05	6.75	7.41	7.37	8.04	7.99
		Symmetry (%)	107.92	107.22	106.70	107.16	106.94	106.02	105.8	105.94
10 × 10 cm	In-out	Flatness (%)	2.67	3.27	3.61	4.07	4.38	4.36	5.74	5.97
		Symmetry (%)	102.77	101.94	101.72	102.01	102.09	102.12	102.15	101.74
	Anode-cathode	Flatness (%)	6.33	5.88	5.84	6.51	7.09	7.02	7.69	7.74
		Symmetry (%)	108.55	107.26	106.65	107.19	106.92	106.00	105.73	105.81
6 × 8 cm	In-out	Flatness (%)	2.89	3.46	3.71	4.13	4.41	4.41	4.63	4.58
		Symmetry (%)	104.14	103.79	103.57	103.35	102.99	102.83	102.23	102.16
	Anode-cathode	Flatness (%)	3.67	4.01	4.50	4.98	5.13	5.03	4.82	4.55
		Symmetry (%)	104.08	103.36	103.21	103.44	103.39	102.97	103.23	103.23
5cm Ø (SSD = 30 cm)	In-out	Flatness (%)	2.35	3.03	3.32	3.67	3.77	3.70	3.25	2.50
		Symmetry (%)	103.91	103.94	103.86	103.71	103.43	103.34	102.63	102.27
	Anode-cathode	Flatness (%)	4.39	3.84	4.18	4.65	4.78	4.66	4.18	3.25
		Symmetry (%)	103.86	103.11	102.86	103.00	102.73	102.42	102.12	102.00

was released for clinical use. For each exposure, the counts from the machine monitor chamber were displayed on the treatment console. These, once corrected for changes from reference environmental conditions, were also recorded, and this served as a check on the condition of the monitor chamber, used by the control software as an interlock to beam output.

Checks on the focal spot were scheduled as part of the annual QA for this machine and carried out only at the tube potential of 100 kV and at two applicator angles (0° and 180°).

SYSTEM CONNECTIVITY AND CLINICAL PRACTICE

The RadControl II software was installed under a server and client arrangement. The computer connected to the treatment unit is the server, and additional licences for client computers permit access to the beam and patient database on the server. Based on the clinician's prescription, treatment plans are created and treatment times are calculated by RadControl-II in the treatment planning room. Corrections to treatment times for irregular fields defined by cut-outs and/or for stand-offs are facilitated through a separate in-house software tool (discussed in the following paragraph). The server-client installation enables a workflow analogous to that of other treatments in our clinic, where patient plans are prepared in the planning room and undergo an independent check prior to being used for the treatment of the patients.

Treatments with stand-offs and/or irregular fields

In the case of stand-offs, standard outputs need to be corrected for dose reduction based on ISL. These ISL corrections are carried out using the effective SSDs instead of the nominal SSD of the applicator (the Effective SSD section and Table 2). For

a treatment using an applicator of 40-cm nominal SSD and with a stand-off of 5 cm, the differences in the calculated ISL correction would be close to 2.5%.

For the calculation of treatment times for irregular fields defined with surface cut-outs (typically made of lead and of at least 2 mm thickness), treatment times are calculated taking into account the reduction in dose as a result of the reduction in phantom scatter owing to the presence of the cut-out. The correction needed to approximately account for this effect is defined as the ratio of the backscatter factor (BSF) for the irregular field to that for the open field defined by the applicator. BSFs for the beam qualities and applicators available on T-200 were interpolated from the tables in the report of AAPM TG 61.⁶ The BSF of an irregular field is derived from a calculation based on field sector integration.³⁸ This correction is only an approximation because changes in the RDD are not considered. Differences in scatter from the applicator at shallow depths between the irregular and the open fields and the dose enhancement at the surface from electron contamination are not accounted for.^{39,40} Comparisons between correction factors calculated from ratios of BSFs and ratios of ionization readings at the surface of a phantom with and without the irregular cut-out were typically within ±5%, with the calculation systematically underestimating the ionization ratio.

Corrections for stand-off and/or irregular field sizes are computed using in-house software. RadControl-II offers the functionality to calculate treatment times for beams shaped with cut-outs, but only through the input of additional RDDs specifically for each cut-out, which in our clinical setting is not practical. A workaround was devised that enables the user to introduce a correction to standard

Table 7. Summary of the quality assurance (QA) programme established for the T-200 machine

Test and frequency	Tolerance	Comments
Daily QA		
Beam output constancy	$\pm 3\%$	With single diode detector
Interlocks and warnings	–	–
Patient-monitoring systems (audio and video)	–	–
Operating mode indicators	–	–
Monthly QA (or following repair)		
Beam output constancy	$\pm 3\%$	In special QA-applicator with Farmer-type cylindrical ionization chamber
Beam energy constancy (ratio at two depths)	± 0.005 from reference	
Time-end error	± 0.01 min	
Accuracy of machine timer	$\pm 2\%$	
Output reproducibility	$\pm 1\%$	
Output following interruption	$\pm 0.5\%$	
Interlocks, warnings and applicators	–	
Constancy check of detector for daily QA	$\pm 2\%$	Through simultaneous irradiation with a Farmer chamber
Mechanical movements and interlocks	–	
Patient monitoring systems (audio and video)	–	
Operating mode indicators	–	
Annual (or following repair)		
Focal spot: position and shape	± 2 mm from reference	With special jig in 5 cm diameter applicator
Beam quality	$\pm 10\%$ from reference	Under narrow-beam geometry (“half-value layer set-up”)
Reference dosimetry	$\pm 3\%$	Under reference irradiation conditions defined in the dosimetry code of practice
Dose-rate linearity	$\pm 2\%$	
Field size	± 2 mm	Profiles measured with a two-dimensional array and/or film
Field uniformity and symmetry	$\pm 5\%$	
Beam output with tube rotation	$\pm 1\%$	
Applicator integrity checks	Maximum 2-mm walk-out	Visual inspection on graph paper

treatment times based on the calculations from the in-house software tool. Briefly, cut-outs corresponding to known correction factors were pre-defined for each applicator in RadControl II, and these were assigned the RDDs of the open-field and corrected outputs. The user selects a cut-out together with the applicator for treatment “forcing” the software to use corrected treatment times. Corrections to standard outputs owing to the presence of stand-off and/or cut-outs are considered only if these introduce a change by $>3\%$ to the standard output.

CONCLUSION

This article presented the work on acceptance and commissioning of a Womed T-200 kV X-ray therapy unit with its integrated machine control, patient management and treatment verification software.

The mechanical performance (interlocks and movements) and X-ray tube leakage of the machine agreed with specification. The leakage seen through the screws at the base of applicators was attributed to a change in manufacturing practice in terms of choice of screws used, and as a result of this assessment, the manufacturer replaced the screws. Radiation leakage through applicator walls was negligible, and mechanically, the applicators were within specification.

The measured focal spot agreed in size of that specified for the X-ray tube. The machine timer agreed with an external timer within the tolerance limit of $\pm 2\%$, with typical deviations observed during monthly QA checks of no more than 0.5%. The homogeneity coefficient of most beams was >0.7 . Beam outputs were reproducible to within 0.5%, independent of

Figure 7. (a) Set-up for daily check on beam outputs with the applicator of 6×8 cm at source-to-surface distance = 40 cm using exposures of 30 s. The detector is a PTW DIADOS T60004 diode housed within a reproducible geometry. (b) The stability of the DIADOS detector is checked monthly through a simultaneous irradiation with a PTW TW30013 (0.6 cm^3) cylindrical ionization chamber.

orientation of the X-ray tube and exhibited a very linear behaviour with exposure time. Time-end errors were negligible. Reference dosimetry was audited with TLD, and beam outputs were confirmed within 10%.

RDDs for beam energies down to 50 kV/1.2 mmAl HVL determined in water with a thimble ionization chamber and fitted to a polynomial were in very good agreement with data measured with an Advanced Markus plane-parallel ionization chamber and with radiochromic EBT3 film in the PWD T solid phantom. At medium energies, >100 kV, the agreement with published data in *BJR-25* was within 5%. At lower energies, however, differences with the *BJR-25* data were $>10\%$. Most likely, the reason for this is the origin of the published data, namely the detectors and methodology (irradiated medium) that were used in their determination. The agreement between RDDs determined in this work using different measurement methodologies worsened for the 40 kV/0.84-mmAl HVL and 30 kV/0.45-mmAl HVL beams. Accurate determination of RDDs at such very low-kV energy requires further investigation. So far, it has been generally accepted that possible errors in these are of no major clinical consequence because prescriptions using such beams are limited to the skin surface. Beam profiles as measured with an ionization chamber array exhibited acceptable symmetry and homogeneity at all field sizes. Effective SSDs were determined for all applicators and

used in the calculation of treatment times in the presence of stand-offs.

The comprehensive QA programme designed for this treatment machine included daily, monthly and annual checks. In clinical practice, a methodology was developed for adjusting treatment times to account for the use of surface cut-outs.

The software suite that accompanies the Womed T-200 treatment unit facilitates a clinical workflow analogous to that in external beam radiotherapy, with treatment times computed on a planning computer and with these being checked independently with in-house software.

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Figure 8. The special quality assurance applicator together with a PTW TW30013 cylindrical ionization chamber used for routine checks on beam output, beam quality and the variation of output with the angle of X-ray tube.

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APPENDIX RELATIVE DEPTH DOSE DATA FROM BEAMS ON T-200

Table A1. Relative depth dose values for beam: 200 kV/1.78 mmCu half-value layer (HVL)

Field size (cm)	10 × 15	10 × 10	6 × 8	5 Ø	3 Ø	5 Ø	3 Ø
Nominal source-to-surface distance (cm)	40	40	40	30	30	20	20
Depth in water (mm)							
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	0.980	0.971	0.962	0.952	0.934	0.937	0.919
10	0.951	0.936	0.920	0.897	0.865	0.870	0.839
15	0.917	0.897	0.875	0.839	0.796	0.803	0.761
20	0.878	0.855	0.827	0.780	0.729	0.736	0.687
25	0.837	0.813	0.780	0.722	0.665	0.671	0.619
30	0.796	0.770	0.732	0.665	0.605	0.611	0.555
35	0.755	0.727	0.686	0.611	0.549	0.555	0.498
40	0.714	0.686	0.641	0.561	0.498	0.503	0.446
50	0.637	0.606	0.556	0.471	0.409	0.413	0.359
60	0.566	0.532	0.481	0.396	0.337	0.34	0.289
70	0.500	0.466	0.413	0.332	0.278	0.279	0.234
80	0.439	0.405	0.354	0.277	0.228	0.229	0.189
90	0.383	0.352	0.302	0.231	0.188	0.187	0.152
100	0.337	0.308	0.261	0.196	0.158	0.156	0.126

Table A2. Relative depth dose values for beam: 150 kV/0.69 mmCu half-value layer (HVL)

Field size (cm)	10 × 15	10 × 10	6 × 8	5 Ø	3 Ø	5 Ø	3 Ø
Nominal source-to-surface distance (cm)	40	40	40	30	30	20	20
Depth in water (mm)							
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	0.972	0.969	0.960	0.964	0.926	0.931	0.912
10	0.937	0.931	0.913	0.886	0.851	0.859	0.825
15	0.898	0.888	0.862	0.823	0.776	0.787	0.742
20	0.855	0.842	0.810	0.759	0.703	0.716	0.663
25	0.811	0.795	0.757	0.696	0.634	0.648	0.590
30	0.766	0.747	0.705	0.636	0.570	0.585	0.524
35	0.721	0.700	0.654	0.580	0.512	0.526	0.465
40	0.678	0.655	0.606	0.527	0.459	0.473	0.412
50	0.595	0.569	0.517	0.434	0.370	0.381	0.324
60	0.518	0.492	0.439	0.357	0.299	0.307	0.257
70	0.450	0.423	0.371	0.294	0.242	0.248	0.204
80	0.388	0.361	0.312	0.241	0.194	0.199	0.161
90	0.334	0.308	0.262	0.197	0.156	0.160	0.126
100	0.289	0.265	0.221	0.163	0.129	0.131	0.103

Table A3. Relative depth dose values for beam: 100 kV/4.52 mmAl half-value layer (HVL)

Field size (cm)	10 × 15	10 × 10	6 × 8	5 Ø	3 Ø	2 Ø	5 Ø	3 Ø	2 Ø
Nominal source-to-surface distance (cm)	40	40	40	30	30	30	20	20	20
Depth in water (mm)									
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	0.936	0.930	0.924	0.907	0.890	0.872	0.893	0.876	0.858
10	0.870	0.861	0.850	0.817	0.788	0.757	0.793	0.764	0.734
15	0.806	0.794	0.777	0.733	0.693	0.656	0.700	0.663	0.627
20	0.743	0.730	0.707	0.654	0.608	0.567	0.616	0.573	0.535
25	0.683	0.668	0.642	0.581	0.531	0.490	0.541	0.495	0.456
30	0.626	0.611	0.581	0.515	0.464	0.423	0.473	0.426	0.389
35	0.573	0.557	0.525	0.456	0.404	0.365	0.414	0.367	0.331
40	0.524	0.507	0.473	0.403	0.352	0.316	0.361	0.316	0.283
50	0.438	0.420	0.384	0.316	0.268	0.238	0.276	0.235	0.208
60	0.366	0.347	0.311	0.248	0.206	0.180	0.213	0.177	0.155
70	0.305	0.287	0.252	0.195	0.159	0.138	0.164	0.134	0.116
80	0.252	0.236	0.203	0.153	0.122	0.105	0.127	0.101	0.087
90	0.209	0.194	0.164	0.120	0.094	0.080	0.098	0.076	0.065
100	0.176	0.161	0.135	0.097	0.075	0.063	0.078	0.060	0.051

Table A4. Relative depth dose values for beam: 80 kV/3.75 mmAl half-value layer (HVL)

Field size (cm)	10 × 15	10 × 10	6 × 8	5 Ø	3 Ø	2 Ø	5 Ø	3 Ø	2 Ø
Nominal source-to-surface distance (cm)	40	40	40	30	30	30	20	20	20
Depth in water (mm)									
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	0.923	0.917	0.914	0.896	0.882	0.862	0.882	0.868	0.848
10	0.848	0.837	0.831	0.799	0.773	0.740	0.775	0.750	0.718
15	0.775	0.762	0.751	0.709	0.674	0.635	0.677	0.645	0.607
20	0.706	0.692	0.677	0.626	0.586	0.543	0.590	0.552	0.512
25	0.642	0.627	0.607	0.551	0.507	0.464	0.512	0.471	0.432
30	0.582	0.567	0.544	0.484	0.438	0.397	0.444	0.402	0.365
35	0.528	0.512	0.486	0.424	0.377	0.340	0.385	0.342	0.308
40	0.478	0.461	0.434	0.372	0.326	0.291	0.333	0.292	0.261
50	0.392	0.375	0.345	0.285	0.244	0.215	0.250	0.213	0.188
60	0.321	0.304	0.275	0.220	0.184	0.160	0.189	0.158	0.133
70	0.263	0.246	0.219	0.170	0.140	0.120	0.143	0.117	0.101
80	0.214	0.199	0.174	0.132	0.105	0.090	0.109	0.087	0.074
90	0.174	0.161	0.138	0.102	0.079	0.067	0.082	0.064	0.054
100	0.146	0.132	0.112	0.081	0.064	0.052	0.064	0.051	0.041

Table A5. Relative depth dose values for beam: 60 kV/2.31 mmAl half-value layer (HVL)

Field size (cm)	10 × 15	10 × 10	6 × 8	5 Ø	3 Ø	2 Ø	5 Ø	3 Ø	2 Ø
Nominal source-to-surface distance (cm)	40	40	40	30	30	30	20	20	20
Depth in water (mm)									
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	0.877	0.876	0.871	0.853	0.840	0.843	0.840	0.827	0.830
10	0.769	0.767	0.757	0.727	0.704	0.703	0.704	0.683	0.682
15	0.674	0.671	0.657	0.618	0.589	0.581	0.590	0.563	0.556
20	0.591	0.587	0.570	0.525	0.492	0.479	0.495	0.464	0.451
25	0.518	0.514	0.494	0.446	0.411	0.394	0.415	0.382	0.367
30	0.455	0.449	0.428	0.379	0.344	0.326	0.348	0.315	0.299
35	0.400	0.393	0.371	0.323	0.288	0.271	0.292	0.261	0.246
40	0.352	0.345	0.322	0.275	0.242	0.226	0.246	0.216	0.203
50	0.273	0.266	0.244	0.200	0.172	0.159	0.175	0.150	0.139

Table A6. Relative depth dose values for beam: 50 kV/1.2 mmAl half-value layer (HVL)

Field size (cm)	10 × 15	10 × 10	6 × 8	5 Ø	3 Ø	2 Ø	5 Ø	3 Ø	2 Ø
Nominal source-to-surface distance (cm)	40	40	40	30	30	30	20	20	20
Depth in water (mm)									
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	0.813	0.809	0.797	0.791	0.775	0.757	0.778	0.763	0.745
10	0.663	0.658	0.639	0.626	0.602	0.576	0.607	0.583	0.558
15	0.544	0.538	0.517	0.497	0.468	0.440	0.474	0.447	0.421
20	0.449	0.443	0.421	0.397	0.367	0.340	0.373	0.345	0.320
25	0.373	0.368	0.346	0.319	0.290	0.265	0.296	0.269	0.247
30	0.312	0.308	0.287	0.259	0.231	0.209	0.237	0.212	0.192
35	0.263	0.259	0.239	0.212	0.186	0.167	0.192	0.168	0.151
40	0.223	0.220	0.201	0.175	0.150	0.134	0.156	0.135	0.120
50	0.162	0.159	0.143	0.120	0.100	0.087	0.105	0.087	0.076

Table A7. Relative depth dose values for beam: 40 kV/0.84 mmAl half-value layer (HVL)

Field size (cm)	10 × 15	10 × 10	6 × 8	5 Ø	3 Ø	2 Ø	5 Ø	3 Ø	2 Ø
Nominal source-to-surface distance (cm)	40	40	40	30	30	30	20	20	20
Depth in water (mm)									
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	0.769	0.759	0.747	0.735	0.721	0.703	0.723	0.710	0.691
10	0.592	0.581	0.563	0.544	0.523	0.498	0.527	0.507	0.483
15	0.459	0.449	0.429	0.407	0.383	0.359	0.388	0.366	0.343
20	0.359	0.352	0.331	0.308	0.285	0.264	0.290	0.268	0.248
25	0.284	0.279	0.260	0.237	0.215	0.198	0.220	0.200	0.184
30	0.228	0.224	0.206	0.184	0.165	0.150	0.168	0.151	0.138
35	0.184	0.181	0.165	0.144	0.128	0.116	0.130	0.116	0.105
40	0.151	0.148	0.133	0.114	0.100	0.089	0.102	0.089	0.080
50	0.102	0.100	0.087	0.072	0.062	0.056	0.062	0.054	0.049

Table A8. Relative depth dose values for beam: 30 kV/0.45 mmAl half-value layer (HVL)

Field size (cm)	10 × 15	10 × 10	6 × 8	5 Ø	3 Ø	2 Ø	5 Ø	3 Ø	2 Ø
Nominal source-to-surface distance (cm)	40	40	40	30	30	30	20	20	20
Depth in water (mm)									
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	0.666	0.663	0.666	0.646	0.619	0.590	0.636	0.609	0.580
10	0.445	0.445	0.442	0.419	0.384	0.356	0.405	0.372	0.345
15	0.303	0.306	0.296	0.275	0.243	0.225	0.262	0.232	0.214
20	0.211	0.215	0.203	0.185	0.161	0.148	0.174	0.152	0.139
25	0.151	0.155	0.143	0.128	0.112	0.101	0.119	0.104	0.093
30	0.111	0.113	0.103	0.091	0.080	0.071	0.083	0.073	0.065
35	0.082	0.084	0.076	0.066	0.057	0.053	0.059	0.051	0.048
40	0.061	0.063	0.056	0.048	0.040	0.042	0.043	0.036	0.037