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Performance assessment of the BEBIG MultiSource® high dose rate brachytherapy treatment unit

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Abstract

A comprehensive system characterisation was performed of the Eckert & Ziegler BEBIG GmbH MultiSource® High Dose Rate (HDR) brachytherapy treatment unit with an ^{192}Ir source. The unit is relatively new to the UK market, with the first installation in the country having been made in the summer of 2009. A detailed commissioning programme was devised and is reported including checks of the fundamental parameters of source positioning, dwell timing, transit doses and absolute dosimetry of the source. Well chamber measurements, autoradiography and video camera analysis techniques were all employed. The absolute dosimetry was verified by the National Physical Laboratory, UK, and compared to a measurement based on a calibration from PTB, Germany, and the supplied source certificate, as well as an independent assessment by a visiting UK centre. The use of the 'Krieger' dosimetry phantom has also been evaluated. Users of the BEBIG HDR system should take care to avoid any significant bend in the transfer tube, as this will lead to positioning errors of the source, of up to 1.0 mm for slight bends, 2.0 mm for moderate bends and 5.0 mm for extreme curvature (depending on applicators and transfer tube used) for the situations reported in this study. The reason for these errors and the potential clinical impact are discussed. Users should also note the methodology employed by the system for correction of transit doses, and that no correction is made for the initial and final transit doses. The results of this investigation found that the uncorrected transit doses lead to small errors in the delivered dose at the first dwell position, of up to 2.5 cGy at 2 cm (5.6 cGy at 1 cm) from a 10 Ci source, but the transit dose correction for other dwells was accurate within 0.2 cGy. The unit has been mechanically reliable, and source positioning accuracy and dwell timing have been reproducible, with overall performance similar to other existing HDR equipment. The unit is capable of high quality brachytherapy treatment delivery, taking the above factors into account.

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1. Introduction

The treatment of cancer using high dose rate (HDR) brachytherapy requires accurate and careful planning and delivery, particularly as the majority of treatment sites are adjacent to critical organs and healthy tissues. The performance of the HDR unit and its ability to accurately implement a series of planned source dwells is critical to the quality of the treatment. The accuracy of delivered doses is particularly dependent on source positioning due to the short distances between target and source, steep dose gradients and large inverse-square law corrections for any geographic errors. Prior to clinical use, new HDR treatment units require a complete and thorough assessment to verify that the manufacturer's and clinical users' performance and accuracy requirements are met and that recommended baseline quality control and dosimetric criteria are satisfied. Previous performance evaluations (McDermott *et al* 1996, Wallace 1997) have shown that there can be appreciable source control and dosimetric differences between different models of HDR systems. There are several publications on the general quality control requirements for HDR units (Mayles *et al* 1999, Nath *et al* 1997, Venselaar and Perez-Calatayud 2004, Wilkinson 2006) and specific results for other manufacturer's HDR units (McDermott *et al* 1996, Wallace 1997), but there are no other publications for the BEBIG HDR treatment unit.

The Eckert & Ziegler BEBIG GmbH HDR system consists of the treatment unit, MultiSource® and a separate treatment planning system, HDRplus®, which uses TG43 formalism based dosimetry (Rivard *et al* 2004). The treatment unit operates in the same way as conventional HDR units, stepping a single radioactive source to discrete dwell positions for specified times, through either a single or series of transfer tubes and patient applicators. The source is welded to the end of a steel cable, which is driven out from the unit, using a position scale convention which has a zero distance at the end of the applicator, the furthest distal point, with an increasing position value as the source moves proximally back towards the HDR unit. Importantly, when delivering treatments, the BEBIG HDR unit moves the source through the planned dwells in a distal to proximal direction. The unit consists of 20 applicator channels and uses linear movement of the indexing plate to align with the required channel during treatment. Treatments may be performed with either an ^{192}Ir or ^{60}Co source, but not both. Results reported in this study relate to an ^{192}Ir source. A wide selection of conventional HDR applicators is available for the treatment unit, as well as 'Universal Applicators' which are flexible guide tubes that may be used independently or within metal applicators. The treatment unit has a two-stage source position calibration, consisting of a check of the cable drive mechanism and then a check of source positional accuracy, the latter enabling correction for any 'slack' in the source cable within the applicators. The second stage uses a novel integrated 'video camera and ruler' system where the user can directly adjust the calibrated source position based on the visualised location.

The first UK installation of the BEBIG HDR unit was at Portsmouth in the summer of 2009. Since there was a lack of published work on the performance of this particular treatment unit, a comprehensive commissioning programme was undertaken prior to clinical use. This was of wider scope than may normally be performed for pre-clinical checks of an 'established' HDR unit within the UK. In particular, detailed measurements were performed on the source dwell positioning accuracy, using both video analysis and autoradiography techniques, and on the transit dose and associated corrections made by the HDR unit.

It is accepted practice that HDR treatment planning systems do not make any correction for radiation dose resulting from transits of the source between dwells, presuming that these can safely be ignored due to the low actual transit time and dose and that the HDR unit will itself make correction to the planned dwell time to account for the transit dose. The magnitude of the transit dose and the actual corrected dwell time are not normally presented to the clinical user. The practice and validity of not considering transit doses in treatment calculations must be verified for each manufacturer's HDR unit, relating to its particular source velocity, resulting transit dose and the accuracy of transit dose corrections that are made by the system. Similarly, the ability of a particular HDR unit to accurately and reproducibly position the source at a series of dwell positions must be tested in a range of clinical situations, in order to provide reassurance of the ability to deliver high quality treatments. An action level of 2 mm source positioning error has been proposed as an upper limit in clinical conditions (Venselaar and Perez-Calatayud 2004). It is also important to consider the possibility of any affect on source positioning and dwell timing of variations in the clinical use of the HDR system. Our study considers in particular a novel assessment of the effect of transfer tube bending on source positioning accuracy, using a radiographic film and video camera capture. This technique may be applied to other HDR systems to assess the clinical impact of transfer tube bending.

Source strength measurements for HDR sources, specified in terms of the reference air kerma rate at a distance of 1 m (RAKR), are conventionally performed using well chambers or thimble ionisation chambers placed either in air or in solid phantoms. Well chamber and solid phantom measurements offer improved positional accuracy compared to in-air jigs, and they are also less sensitive to room scatter effects (Tedgren and Grindborg 2008). The use of the Krieger phantom in this work (Krieger and Baltas 1999) allows for a measurement of absorbed dose to water, using appropriate calibration factors, thus planned doses can be directly verified in-phantom.

2. Methods and materials

An Eckert & Ziegler BEBIG GmbH MultiSource® treatment unit with software version 7.4.0, firmware version 4, and ^{192}Ir source, model Ir2.A85-2, and an Eckert & Ziegler BEBIG GmbH HDR plus® treatment planning system, software version 2.5.3.0, was used throughout this study.

2.1. Acceptance testing and commissioning schedule

Commissioning of the BEBIG HDR unit was undertaken using the tests detailed in table 1, which were derived based on several publications (Bastin *et al* 1993, Evans *et al* 2007, Sahoo 2001, Mayles *et al* 1999, McDermott *et al* 1996, Venselaar and Perez-Calatayud 2004, Wallace 1997, Wilkinson 2006) and recommendations from other UK radiotherapy centres via personal communication. This report is concerned with the specific aspects of source positioning, dwell and transit timing, and source strength measurement for the BEBIG HDR unit. The full list of commissioning tests is provided here for completeness, to put the reported work in context, and for information for those commissioning HDR units, but the detailed results of these other measurements are not presented, only overall conclusions.

2.2. Measurement of source dwell positions and source transits

The actual source dwell positions were measured and compared to the planned dwell positions for a range of applicators and transfer tubes, in terms of absolute accuracy and reproducibility.

To assess source positioning and movements over large distances, a treatment consisting of three dwells at 0.0, 30.0 and 100.0 mm was evaluated using x-ray film autoradiography

Table 1. Commissioning activities undertaken for the BEBIG HDR unit.

Critical examination, radiation shielding survey, local rules
Manufacturer's acceptance testing schedule
Mechanical and electrical safety tests
Interlocks, safety features and basic operational checks, including timer accuracy checks
Source positioning
Source dwell time
Source transit time
Source specification data
Manufacturer's source certificate
Source strength measurement with a well chamber
Source strength measurement with a thimble ionisation chamber in-phantom
Data transfer from the treatment planning system (TPS)
TPS algorithm, functionality tests and source data
Applicator commissioning including labelling, rigidity, consistency with TPS library of applicators and transmission measurements
Definition of, and baseline results for, routine quality checks
Training materials and documentation

(Kodak EDR2 Ready Pack film), using dwells of 1 s for optimum film density. A scanning optical densitometer (Vidar VXR-16) was used to locate the centre of the source.

To assess source positioning and movements over smaller distances, a treatment consisting of three dwells at 10.0, 15.0 and 20.0 mm was evaluated using a high definition video camera (Panasonic HDC-SD10). The centre of the source was identified visually in each video frame, at a resolution of 25 frames per second, and the position recorded against a steel ruler also located within the video image. This data set was also used to evaluate the movement of the source between dwell positions.

Initial results indicated a potential dependence of source positioning accuracy on the curvature of the transfer tube between the HDR unit and the applicator. Measurements were made to investigate the effect on dwell positions of 'bends' in the transfer tubes. Actual source positions were measured using autoradiography and video camera recordings for a range of applicators and transfer tubes with a curvature induced in the transfer tube by displacing the distal end of the tube by a fixed distance (over a range from minor to maximum possible bend, of 5–90 cm), while maintaining a stationary proximal end at the HDR unit.

A simplistic assessment of the effect of source positioning errors on HDR treatment plans was undertaken to give an indication of the potential clinical impact. A single-channel line treatment and a typical three-channel gynaecological treatment were planned on the BEBIG HDR plus treatment planning system, with source dosimetry data from Granero 2008, and the source dwell locations modified to simulate positioning errors. The change in dose at several reference points was noted and the effect on isodose distributions visualised.

2.3. *Calculation of transit dose*

A detailed description of the source movement between dwell positions as a function of time was determined using the video camera (as above). The source position was recorded at 1/25 s intervals in the approach to the first dwell position, between dwells, and from the last dwell back to the HDR unit. This was evaluated for a treatment involving a series of three

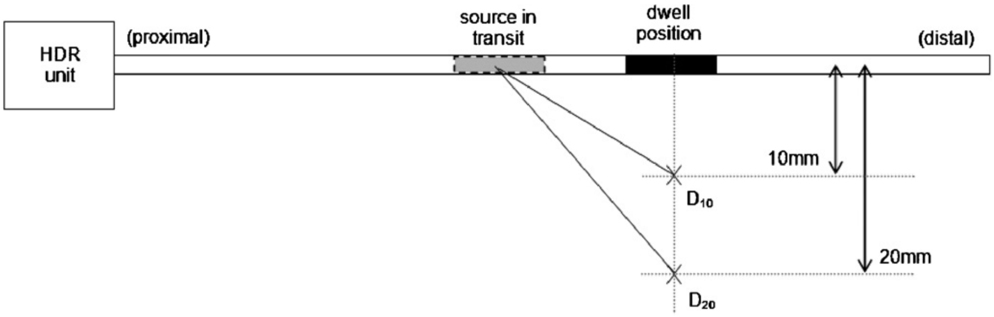

Figure 1. Transit dose calculation points, D_{10} and D_{20}, at 10 mm and 20 mm, respectively, perpendicular distance from the centre of the intended dwell position, due to the source in transit.

dwells at positions 10.0, 15.0 and 20.0 mm, being representative of the clinically typical 5 mm step-size.

This data set enabled the speed of source movement to be calculated by a simple division of displacement and elapsed time, and the dose due to the transit of the source to be estimated using published dose-rate distribution data (Granero and Perez-Calatayud 2008). An approximation of the true transit dose was calculated by the summation of the dose delivered by the source considered to be stationary for $1/25$ s at each of the imaged positions, rather than by continuous movement integration that includes acceleration and deceleration components. The transit dose was separately calculated for the movement of the source to the dwell position, and from the dwell position, and evaluated at two interest points, D_{10} and D_{20}, located at 10 mm and 20 mm respectively from the centre of the dwell position, shown in figure 1. The calculations were performed for source activities of 10 Ci and 4 Ci, being the approximate source strengths of a newly delivered source and one at the end of its normal clinical use (after 3 months).

2.4. *HDR system correction for transit dose*

The BEBIG MultiSource® makes corrections for transit doses by reducing the actual dwell time for each dwell position using the following algorithm (Spiller 2009):

$$\mathrm{pDT} = \mathrm{DT} - T_{r(\text{to dwell})} - T_{r(\text{from dwell})} \qquad T_r = cd + 100$$

where pDT is the performed dwell time, DT is the planned dwell time (ms), T_r is the time reduction applied to the dwell position for each transit (ms), d is the distance between dwell positions (mm) and c is a constant which equals 3 for dwell separations of less than or equal to 100 mm and equals 2 for dwell separations of greater than 100 mm.

Importantly, no dwell time correction is made for the transit of the source from the HDR unit to the first dwell position, nor from the last dwell position back to the HDR unit, although these transit times are recorded and displayed on the HDR system.

The HDR calculated time reduction, T_r, was evaluated using the above formula for the specific treatment situations assessed with the video camera for the estimation of actual transit dose. The 'equivalent dose reduction' resulting from the dwell time reduction was then calculated at a 10 mm and 20 mm perpendicular distance from the centre of the source dwell position (D_{10} and D_{20}) respectively using published dose-rate distribution data (Granero and Perez-Calatayud 2008).

2.5. Measurement of source strength

Source strength measurements were performed using a well-type ionisation chamber (PTW type 33004) and using a thimble ionisation chamber (NE2611) (both with a PTW Unidos E electrometer). The constancy of the well chamber and thimble chamber was checked before and after the source strength measurements by use of ^{137}Cs and ^{90}Sr check sources, respectively. For comparison to the source certificate data, all measurements were decay-corrected to the manufacturer's source calibration date.

The well chamber was supplied with PTW calibration factors of the ^{192}Ir sources used in the Nucletron MicroSelectron, MDS Nordion Gammamed, Varian Varisource and BEBIG Multisource® HDR systems. For each of these, calibration factors were provided for the calculation of the reference air kerma rate (RAKR) (in mGy h^{-1} at 1 m) or apparent activity (in Ci or GBq), as required. Well chamber measurements were made with the '1400 universal applicator' transfer tube using the calibrated chamber insert and locking ring. The point of maximum response for the chamber was first determined by stepping the source from the distal end in 5 mm step sizes for a distance of 12 cm using a dwell time of 10 s per position. Source strength measurements were then performed at the point of maximum response, and the relevant calibration factor was used in the following equation:

$$S = R \times \mathrm{CF}_{\mathrm{cal}} \times \mathrm{CF}_{\mathrm{ion}} \times \mathrm{CF}_{\mathrm{T:P}}$$

where S is the source strength (mGy h^{-1} at 1 m or Ci or GBq), R is the leakage-corrected electrometer reading (Amps), $\mathrm{CF}_{\mathrm{cal}}$ is the chamber calibration factor, $\mathrm{CF}_{\mathrm{ion}}$ is the correction for ion recombination and $\mathrm{CF}_{\mathrm{T:P}}$ is the air mass correction.

The thimble ionisation chamber had a RAKR calibration performed at the German Standard Laboratory, PTB, for both ^{192}Ir and ^{60}Co Bebig sources for measurements in the Krieger phantom. Measurements were made with the '1400 universal applicator' transfer tube inserted into the LAR01-01 steel applicator and positioned centrally within the Krieger phantom (Andrássy 2009). The supplied calibration factors are valid for this specific combination only. For source strength measurement, the chamber was inserted into each of the four peripheral holes of the phantom in turn, with the other cavities filled with Perspex plugs, see figure 2. Charge was measured for 3 min exposures, and the RAKR was calculated using the equation:

$$\mathrm{RAKR} = R \times \mathrm{CF}_{\mathrm{cal}} \times \mathrm{CF}_{\mathrm{T:P}} \times \mathrm{CF}_{\mathrm{app}} \times \mathrm{CF}_{\mathrm{sat}}$$

where $\mathrm{CF}_{\mathrm{app}}$ is the applicator correction and $\mathrm{CF}_{\mathrm{sat}}$ is the saturation correction factor. A measurement uncertainty of 2.5% ($k = 2$) is quoted for the PTB calibration (PTB 2009).

Independent dosimetry audits of the source strength were performed by the National Physical Laboratory (NPL) and by the Imperial College Healthcare NHS Trust. Both auditors used well chambers recently calibrated at the NPL with the Nucletron MicroSelectron Classic ^{192}Ir source. In addition to the source strength measurement, Imperial NHS Trust also performed an independent check of the treatment planning system's planned doses. A single channel plan comprising 11 dwell positions with 5 mm stepsize was used. The planned doses at 2 cm, 3 cm and 5 cm laterally from the location of the maximum dose point were checked using an independent (non-commercial) checking program and also measured in a Perspex phantom using a 0.1 cc rectal chamber (PTW type 23323).

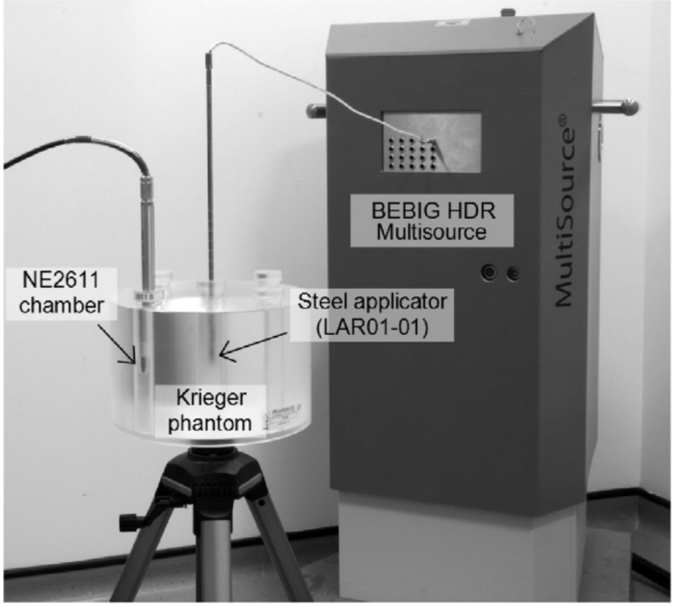

Figure 2. Source RAKR measurement using the NE2611 chamber in the Krieger phantom.

3. Results and discussion

3.1. Acceptance testing and initial commissioning

The comprehensive commissioning programme detailed in table 1 was completed. The results of all tests were satisfactory for clinical use of the system. All interlocks and safety features operated as designed and were deemed sufficient by the Radiation Protection Advisor. Detailed results of these tests are not provided in this report.

3.2. Video analysis of source movement, calculation of transit doses and comparison with HDR unit transit dose corrections

Figures 3 and 4 show the source location as a function of time, at 1/25 s resolution imaged with a video camera, for a series of three dwells at positions 10.0, 15.0 and 20.0 mm. Figure 3 provides 85 cm of movement data as the source approaches the first dwell position and as it leaves the last dwell position. Figure 4 shows the movement between the first and second dwells and between the second and third dwells. In each case, the calculated speed of the source movement between video frames is also shown.

The maximum speed of source movement recorded in this data is 400(±20) mm s^{-1}, figure 3. This is similar in magnitude to speeds reported by other investigators for alternative manufacturers' HDR units; up to 452 mm s^{-1} for the Gammamed-Plus (Supe *et al* 2007) and up to 467 mm s^{-1} for the Nucletron Micro-Selectron (Sahoo 2001, Wong *et al* 2001).

The movement of the source to the first dwell, shown in figure 3, is not direct, with a pause at a position 1.0 mm distal to the required dwell position for 0.32(±0.04) s. This characteristic is reproducible and was confirmed by BEBIG as the intentional movement path of the source to the first dwell position (Spiller 2009). Since the source is stepped from the distal to the

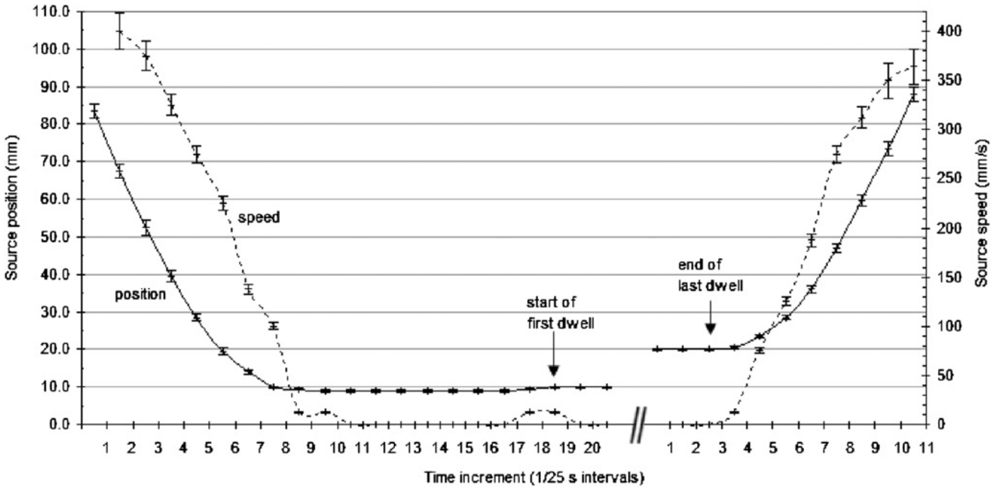

Figure 3. Position and speed of the source during transit from the HDR unit to the first dwell position (final 85 cm of movement shown), and from the last dwell position back to the HDR unit (first 85 cm of movement shown), from a series of three dwells at 10.0, 15.0 and 20.0 mm positions.

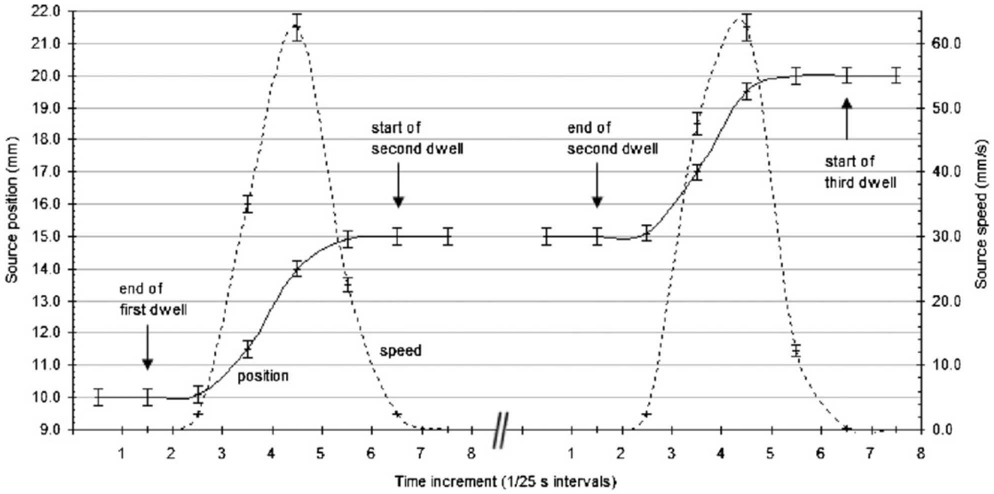

Figure 4. Position and speed of the source during transit from first to second dwell positions, and from second to third dwell positions, from a series of three dwells at 10.0, 15.0 and 20.0 mm positions.

proximal end, this feature is designed to reduce any slack of the cable inside the applicator. The return of the source to the HDR unit after the last dwell was direct, with rapid acceleration, achieving a speed of over 300 mm s^{-1} after 0.2 s, also shown in figure 3.

The maximum speed achieved between dwells of 5.0 mm separation is 62(±4) mm s^{-1}, figure 4, which is similar to the 72 mm s^{-1} reported by Wong 2001 for the Nucletron unit. Movement between dwells appeared smooth with equal phases of acceleration and deceleration, no 'overshoot' in dwell positioning, nor any fine corrections required to achieve final dwell location. Positioning accuracy was always within 0.5 mm.

Table 2. Comparison of calculated transit dose and HDR compensated transit dose, for each dwell position in a series of three dwells, at 10.0, 15.0 and 20.0 mm positions, evaluated at interest points D_{10} and D_{20}, located at 10 mm and 20 mm respectively from the centre of the source, perpendicular to the source axis, for source apparent activities of 10 Ci and 4 Ci.

First dwell position (10.0 mm)	Interest point: Source activity:	D_{10}, 10 Ci	D_{20}, 10 Ci	D_{10}, 4 Ci	D_{20}, 4 Ci
Transit dose from HDR unit to first dwell (cGy) (±0.05)		6.15	2.64	2.46	1.06
Transit dose from first to second dwell (cGy) (±0.05)		1.30	0.37	0.52	0.15
Total transit dose at first dwell (cGy) (±0.05)		7.45	3.00	2.98	1.20
HDR calculated time reduction for transit dose at first dwell (s)		0.15	0.15	0.15	0.15
Equivalent dose reduction (cGy) (±0.02)		1.83	0.47	0.73	0.19
'Actual–corrected' transit dose (cGy) (±0.1)		5.6	2.5	2.3	1.0
Second dwell position (15.0 mm)	Interest point: Source activity:	D_{10}, 10 Ci	D_{20}, 10 Ci	D_{10}, 4 Ci	D_{20}, 4 Ci
Transit dose from first to second dwell (cGy) (±0.05)		1.30	0.37	0.52	0.15
Transit dose from second to third dwell (cGy) (±0.05)		1.32	0.37	0.53	0.15
Total transit dose at second dwell (cGy) (±0.05)		2.62	0.73	1.05	0.29
HDR calculated time reduction for transit dose at second dwell (s)		0.23	0.23	0.23	0.23
Equivalent dose reduction (cGy) (±0.02)		2.81	0.72	1.12	0.29
'Actual–corrected' transit dose (cGy) (±0.1)		−0.2	0.0	−0.1	0.0
Third (last) dwell position (20.0 mm)	Interest point: Source activity:	D_{10}, 10 Ci	D_{20}, 10 Ci	D_{10}, 4 Ci	D_{20}, 4 Ci
Transit dose second to third dwell (cGy) (±0.05)		1.32	0.37	0.53	0.15
Transit dose from third dwell to HDR unit (cGy) (±0.05)		1.40	0.49	0.56	0.20
Total transit dose at third dwell (cGy) (±0.05)		2.72	0.85	1.09	0.34
HDR calculated time reduction for transit dose at third dwell (s)		0.15	0.15	0.15	0.15
Equivalent dose reduction (cGy) (±0.02)		1.83	0.47	0.73	0.19
'Actual–corrected' transit dose (cGy) (±0.1)		0.9	0.4	0.4	0.2

The transit doses calculated from the above 'position-time' data of the source movement are presented in table 2. The doses due to the transit of the source to and from each dwell point are separately calculated for points D_{10} and D_{20}, located at perpendicular distances of 10 and 20 mm respectively from the central axis of the intended dwell position, as defined in figure 1. Table 2 also provides the dwell time reduction calculated using the HDR transit dose algorithm, as defined in section 2.4 and the equivalent dose reduction at points D_{10} and D_{20}. This is presented for source activities of 10 Ci and 4 Ci.

Each dwell position has a transit dose contribution from the movement of the source to the dwell point and from the movement of the source away from that dwell point. The HDR unit does not make transit dosimetry corrections for doses resulting from the initial movement of the source to the first dwell point nor from the final movement of the source away from the

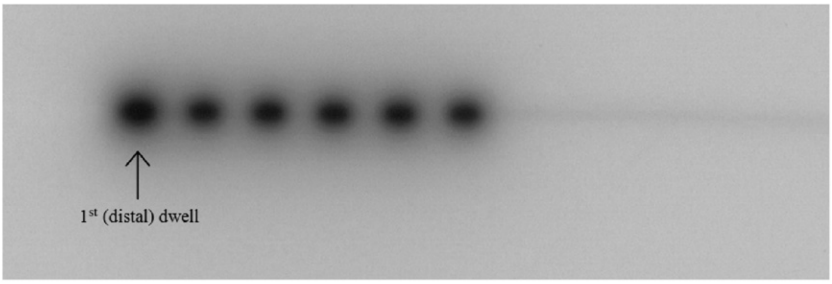

Figure 5. Autoradiograph of a series of six 1 s dwells, at uniform 10.0 mm spacing, showing transit dose enhancement of the dose at the first (distal) dwell point.

last dwell point. It is therefore expected that the calculated transit dose for the first and last dwell will be higher than the correction applied by the HDR unit, as only one of the two source movements is taken into account in each case. This is most significant for the first dwell, as the source 'pauses' at 1.0 mm from the intended dwell point during its transit. It is expected that the HDR unit will make more accurate corrections for intermediary dwell positions in a series, as both 'to' and 'from' transits are taken into account for these positions.

The results in table 2 are consistent with the anticipated agreement between actual transit doses and those calculated by the HDR system, as discussed above. The difference between actual and corrected transit doses is greatest for the first dwell point, lower for the final dwell position and least for the mid-treatment dwell position.

The empirical formula used by the HDR unit to correct for transit doses performs extremely well for the mid-treatment dwell point considered in table 2, with a maximum deviation of 0.2 (±0.1) cGy for the situations considered. The correction made for the last dwell point has a maximum deviation of 0.9 (±0.1) cGy from the true transit dose, for the worst-case calculation point close to the catheter with a 10 Ci source. The first dwell point has an actual transit dose calculated to be 7.45 (±0.05) cGy at 1 cm from the catheter and 3.00 (±0.05) cGy at 2 cm, for a 10 Ci source. The HDR dwell time reduction for this situation leaves an uncorrected transit dose of 5.6 (±0.1) cGy at 1 cm and 2.5 (±0.1) cGy at 2 cm. For a 4 Ci source, this is reduced to 2.3 (±0.1) cGy at 1 cm and 1.0 (±0.1) cGy at 2 cm.

The effect of the uncorrected transit dose at the first dwell position can be seen on the autoradiograph in figure 5, by visually comparing the optical density and size of the darkened area of the first dwell (on the left) to the others. The differential dosage is immediately apparent in this case due to the short 1 s dwell time required for correct exposure on the film, the uncorrected transit dose having a more noticeable effect.

3.3. Variation of the source dwell position as a function of the 'bend' in the transfer tube

The actual dwell position of the source may be affected by curvature of the transfer tube. Figure 6 shows a diagrammatic representation of experimental bends introduced to the transfer tube by displacing the distal end of the tube towards the HDR unit, keeping the proximal end position fixed.

The effect on dwell positions of curvature of the transfer tube is clearly illustrated in figure 7, which shows several autoradiographs taken with differing degrees of transfer tube bending.

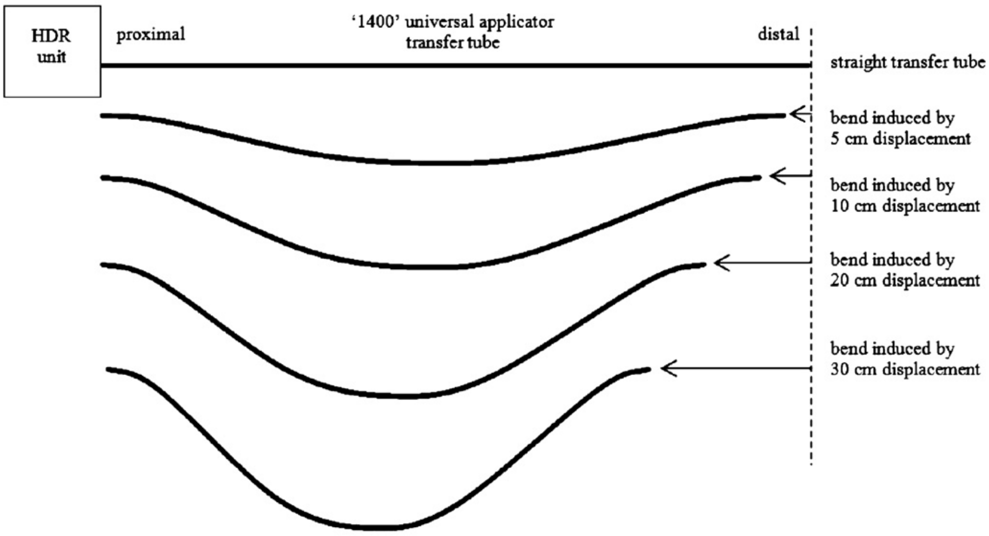

Figure 6. 'Diagrammatic representation' of the bend induced in the 1400 universal applicator transfer tube due to displacements of the distal end. The straight 140 cm transfer tube is shown in comparison to displacements of 5, 10, 20 and 30 cm.

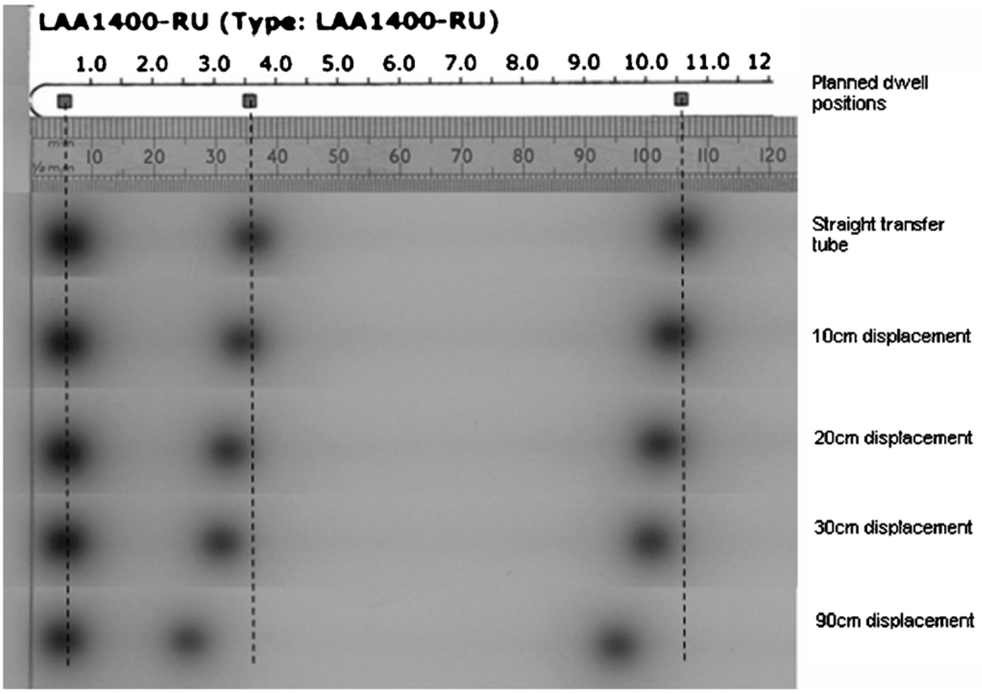

Figure 7. Autoradiographs of source dwell positions, compared to planned positions (dashed lines), as a function of bend in the transfer tube, for the 1400 universal applicator (140 cm length). The augoradiographs are for a straight transfer tube and for bends induced by displacements of the distal end by 10, 20, 30 and 90 cm towards the HDR unit.

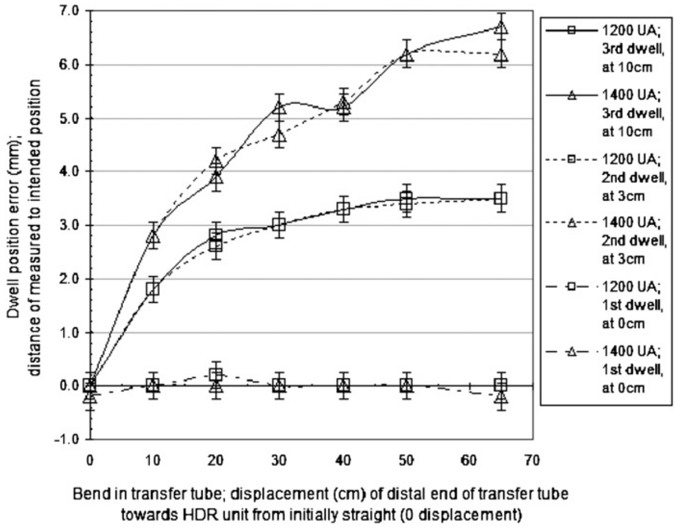

Figure 8. Source dwell position error as a function of bend in the transfer tube, for 1200 and 1400 universal applicators (UA).

Figure 8 provides the magnitude of the error in source positioning as a function of bend in the transfer tube, for two different applicator systems provided with the BEBIG HDR unit and for a series of three dwells at 0.0, 3.0 and 10.0 cm, imaged using autoradiographs. In each case, the first dwell position is accurately located compared to the planned position, irrespective of the amount of ‘bend’ in the transfer tube. With increasing displacement of the transfer tube, the error of all other dwell positions increases by the same magnitude: a systematic error is introduced which is dependent on the ‘bend’ in the transfer tube. The ‘1400 universal applicator’ (1400 mm length) shows dwell positioning errors of up to 3.0 (±0.2) mm for a 10 cm displacement of the transfer tube distal end and up to 6.5 (±0.5) mm for extreme case curvature of the tube. The ‘1200 universal applicator’ (1200 mm length) shows errors of up to 1.8 (±0.2) mm and 3.5 (±0.3) mm for these situations.

Figure 9 shows the actual source positions as a function of bend in the transfer tube, for a series of three dwells at 10.0, 15.0 and 20.0 mm, using the LAF1000 connector, imaged using a video camera. The first dwell position is consistently accurately located, whilst the second and third dwells are systematically displaced by an increasing magnitude with increasing curvature of the transfer tube; a 2.0 (±0.2) mm error is introduced with a 10 cm displacement of the distal end of the transfer tube. When extreme curvature is introduced to the transfer tube, by a displacement of 50 cm, there is no physical movement between the first and second dwell positions.

An explanation of the source dwell positioning errors which result from bends in the transfer tube can be made by considering the positioning of the source cable within the transfer tube and noting that the internal diameter of the transfer tube is larger than the diameter of the source cable. Figure 10 shows how the cable will navigate the inside edges of a curved tube while being driven out from the HDR unit to the first (distal) dwell point. When moving back towards the HDR unit for the second dwell, any ‘slack’ in the cable is taken up, as the cable adopts the inner edge of the curved tube. The resulting actual source movement is less than the cable movement at the HDR unit. For subsequent dwell positions, the movement of the

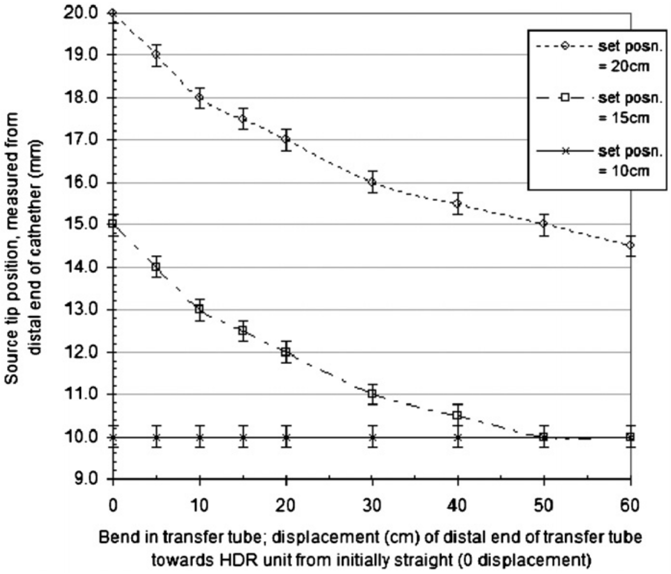

Figure 9. Actual source position as a function of bend in the transfer tube, for a 100 cm transfer tube length.

source is equivalent to the movement of the cable at the HDR unit, and the spacing between dwells is accurate (presuming the displacement between first and second dwells is greater than the extent of ‘slack’ in the source cable).

The results presented in figures 8 and 9 are consistent with the above explanation; the first dwell is accurately located, there is an error in the displacement between the first and second dwells, and subsequent dwells have the same systematic error as the second dwell, i.e. accurate displacement between second and third dwells.

A simple first-order geometric approximation can be used to test the validity of the ‘transfer tube bend’ explanation of source positioning errors. For the 1400 mm transfer tube, with one fixed end and a displacement of the other end from the straight position by 10 cm, a curve of radius 115 cm is introduced in the tube. For a tube internal diameter of 1.7 mm and a source cable diameter of 0.9 mm, the difference in path length for the cable running around the outside compared to the inside of the transfer tube curve is 2.1 mm. For a 20 cm displacement, a curve of radius 80 cm is introduced, leading to a path length difference of 3.0 mm, and for 30 cm displacement, with a curve of radius 50 cm, the path length difference is 4.8 mm. The differences in path length, which indicate the potential for ‘slack’ in the source cable, and therefore dwell positioning errors, are of the same order of magnitude for different tube curvature radii as the results presented in figures 8 and 9.

Whilst the purpose of this work is not to assess the detail of clinical or radiobiological impacts of source positioning errors, it is essential that such data are put into context in at least a couple of illustrative treatment situations. The effect on the dose at interest points and on dose distributions was considered for two typical clinical treatments: a simple single channel line treatment and a three channel gynaecological insertion. Each treatment was planned on the BEBIG HDRplus® treatment planning system.

For a single channel treatment consisting of nine uniform dwells, the dose delivered to a number of equally spaced interest points along lines 1 cm and 2 cm from, and parallel to,

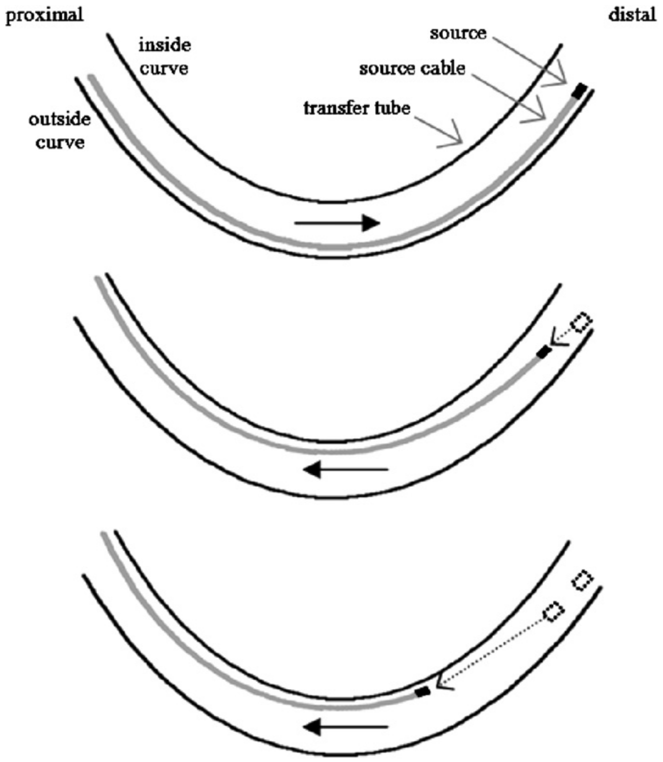

Figure 10. Diagrammatic representation, not to scale, of the source cable within the transfer tube, showing alignment along the outside curve of the tube during outward motion of the source to the first dwell, then positioning along the inside of the tube during inward motion of the source to the other dwell positions. Planned dwells at equal spacing can have different actual separations due to 'slack' in the source cable, as shown in the diagram.

the active length were considered. The most distal and proximal interest points were aligned to the centre of the first and last dwell positions. The intended dose for each interest point and the change in dose due to the characteristic 'transfer tube bend' errors of 1.0, 2.0 and 4.0 mm for all but the first dwell position (using the results presented above) were derived. As intuitively expected, the dose at distal interest points increases and proximal points reduces, by up to 3.2% for 1.0 mm, 6.4% for 2.0 mm and 13.2% for 4.0 mm error, at the 2 cm interest point. Closer to the catheter, resulting dose differences are larger, with deviations of up to 5.9% at a 1 cm perpendicular distance from the end of the active length for a 1.0 mm source positioning error, 12.2% for a 2.0 mm and 24.9% for a 4.0 mm error.

For a typical three channel gynaecological insertion, table 3 provides the percentage change in dose at several interest points due to simulated 'transfer tube bend' errors of 1.0, 2.0 and 4.0 mm (using the results presented above, with the same error introduced in all three channels), in comparison to the intended dose for each interest point, expressed as a normalised percentage. The location of the interest points ('Manchester point A', rectum and bladder) are indicated in figure 11, which also shows the effect on the isodose lines of the 4.0 mm error case. The magnitude of the change in dose at the interest points for the 3D gynaecological insertion is significantly less than for the 2D single channel treatment, considered above. A maximum deviation of 1.2% for the 1.0 mm error case, 2.4% at 2.0 mm and 5.3% at 4.0 mm is reported for the gynaecological treatment. The standard 'Manchester point A' prescription

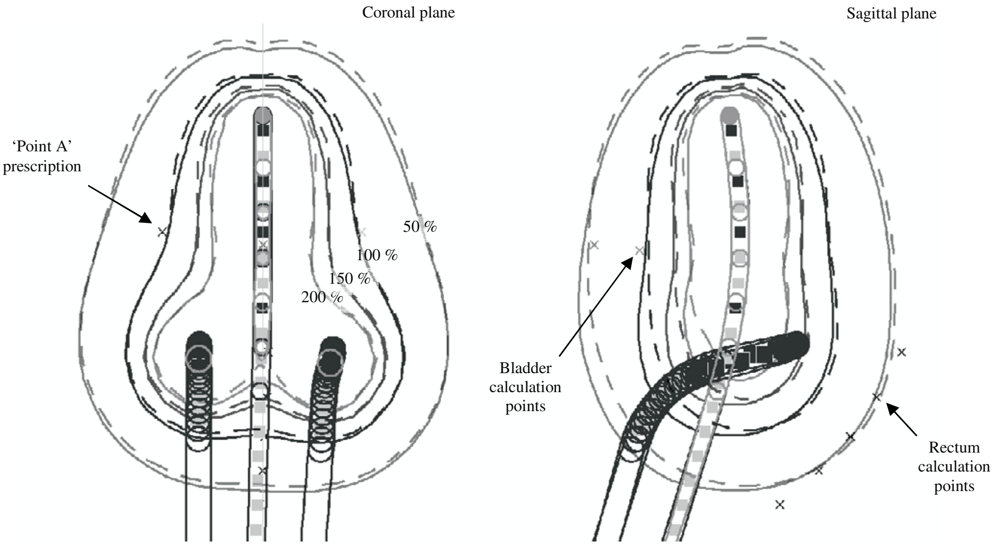

Figure 11. Comparison of isodose curves for a typical gynaecological three-channel treatment with correct dwell positions (solid isodose lines) and with simulated errors in dwell positioning of 4.0 mm that would occur as a result of bends in the transfer tubes (dashed isodose lines).

Table 3. Change in dose at standard gynaecological interest points, due to simulated error in dwell positioning of 1.0, 2.0 and 4.0 mm that would occur as a result of bends in the transfer tubes. Treatment consisting of a typical three-channel gynaecological insertion with a 4.0 cm intrauterine tube and two ovoids.

		Percentage change in dose due to dwell position error		
Interest point	Normalised dose for correct dwell positions (%)	1.0 mm error	2.0 mm error	4.0 mm error
'Manchester point A', left	98.3	0.4	0.5	0.4
'Manchester point A', right	100.0	0.6	0.8	0.9
Rectum point 1	45.7	1.0	2.2	4.9
Rectum point 2	52.1	1.1	2.4	5.3
Rectum point 3	53.6	0.9	1.9	4.0
Rectum point 4	50.8	0.3	0.5	0.7
Rectum point 5	43.2	−0.9	−1.7	−3.5
Bladder point 1	54.0	−1.2	−2.3	−4.9
Bladder point 2	97.6	−1.2	−2.4	−5.1

references receive a maximum variation in dose of 0.6% for 1.0 mm error, 0.8% for 2.0 mm and 0.9% for 4.0 mm. The cause of the reduced dosage errors compared to the single line source is likely due to a more complex 3D summation of contributions from the sources in the three channels and that the defined interest points are closer to the central portion of the series of dwells, resulting in an apparent reduced dependence of individual source positioning accuracy requirements.

Table 4. Results of the RAKR measurements for the BEBIG HDR unit ^{192}Ir source.

	RAKR (mGy h^{-1} at 1 m)	Percentage difference from certificate
Source certificate	54.68	–
NE2611 thimble chamber (local)	54.79	0.2
Well chamber (local)	54.70	0.0
Well chamber (NPL)	54.30	−0.7
Well chamber (Imperial)	53.91	−1.4

A diagrammatic representation of the degree of bending in a transfer tube, due to the induced displacements of the distal end, is essential to link the results of this work to clinical use of the equipment, providing an appreciation of the 'shape' of the bend of the transfer tube rather than just a mathematical description, see figure 6. Clinical users may find such a visual indication beneficial in interpreting an acceptable bend for the required source positioning accuracy.

3.4. Source strength

The local PTW well chamber point of maximum response was found to be 55 mm from the distal end. The well chambers used by NPL and Imperial NHS Trust measured the point of response to be within 5 mm of the local chamber value. The RAKR values measured by all the chambers were decay-corrected to the manufacturer's source calibration date for comparison, and the measured results are summarised in table 4.

For the local well-type and NE2611 chambers, the quoted RAKR in table 4 refers to the mean value from three repeat measurements and the percentage difference of this mean from the source certificate. Good agreement was seen, as expected, from the PTB- and PTW-calibrated chambers where a BEBIG MultiSource® ^{192}Ir source was used for calibration. Agreement was also good for the NPL-calibrated chambers where the Nucletron MicroSelectron Classic ^{192}Ir source is used for calibration. For the different HDR systems used to calibrate the local PTW well chamber, there is a maximum variation of 3.9% in the calibration factors, thus the independently measured values were in better agreement than expected. An uncertainty of 5% is quoted for the source certificate RAKR value, whilst the NPL measurement had a 2% uncertainty.

For the treatment planning system-based audit performed by Imperial NHS Trust, the independent check program values were within 1 cGy of the planned doses at 2 cm, 3 cm and 5 cm laterally from the point of maximum dose. The doses were also measured using a 0.1 cc ionisation chamber and this showed differences of 3.2% at 2 cm, 4.7% at 3 cm and 0.0% at 5 cm compared to the TPS planned doses. This was within experimental uncertainty and the expected tolerance for brachytherapy sources.

4. Summary and conclusions

The results of this work show that the performance of the BEBIG HDR system is sufficient for the device to be used clinically for brachytherapy treatments, and overall performance is similar to other available HDR treatment units. However, it is essential that the advice given by the manufacturer to use straight transfer tubes is followed in all cases, in order to avoid significant deviations in the delivered source dwell configurations from those planned.

Ideally, the HDR system would operate in a manner that would eliminate, or minimise, this potential source of error. Methods should be investigated to 'stiffen' the source transfer tubes to discourage/prevent clinical use with bends. Alternatively, the internal diameter of the transfer tubes could be reduced to minimise the potential for source cable movement lag. However, if the potential problem is noted and care is taken to avoid bends in the transfer tube, clinical treatments of high source positioning accuracy can be achieved. Indeed, the integrated 'ruler and video camera' novel quality control equipment provided with the BEBIG HDR unit enables the operator to confirm, and recalibrate if appropriate, the exact position of the source prior to each treatment. BEBIG confirmed that a 'special correction' factor is used to account for bends within applicators and for 'snaking' of the source cable, but this cannot account for variations in bend that may be introduced by the clinical user as illustrated in this work. In complex clinical situations cable bends may be unavoidable, such as in multiple-channel surface mould treatments; it is then advisable to verify the actual dwell positioning, using autoradiography. It may also be possible to calibrate the source position, using the video camera quality control tool, with the same degree of transfer tube bending as used for treatment, in order to minimise deviations.

In the opinion of the authors, the transit dose corrections made by the HDR system need to be improved for the first and ideally the last dwell positions. Although the clinical effect of the uncorrected transit doses is small, and considered to be negligible, this is a systematic error that could be eliminated and therefore should be addressed. Indeed, following reporting of this issue to BEBIG they have confirmed that a new firmware release will be developed for the HDR unit to improve the transit dose correction; release version 4.13 (Spiller 2009). The existing transit correction for all other dwell points was in good agreement with actual transit doses.

Good agreement was obtained in the source strength measurement using the PTB- and PTW-calibrated chambers and the NPL-calibrated instruments, and the results fell within the quoted uncertainties. Independent verification of the TPS planned doses by measurement and using a dose-checking program also gave results within the expected tolerance and experimental uncertainty.

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