Australasian Physical & Engineering Sciences in Medicine (2019) 42:913–919
https://doi.org/10.1007/s13246-019-00788-9

SCIENTIFIC PAPER

Independent assessment of source transit time for the *BEBIG SagiNova*® cobalt-60 high dose rate brachytherapy afterloader

Abolfazl Kanani[1,2] · Sareh Karbasi[3] · Mohammad Amin Mosleh-Shirazi[1,3]

Received: 24 October 2018 / Accepted: 9 August 2019 / Published online: 26 August 2019

Abstract

Independent verification of transit time and the methodology employed in commercial high dose rate (HDR) afterloaders to compensate its effect is an important part of their commissioning and quality assurance. This study aimed to independently evaluate the Co-60 source transit time of the new *BEBIG SagiNova*® HDR afterloader unit by employing a dosimetric approach using a well-type ionization chamber. The source was placed at three dwell positions (DPs) to mimic a variety of clinical situations with different distances from the afterloader unit. The distances of the DPs to the afterloader were 129.37 cm, 124.50 cm and 118.57 cm. Plans were generated using the *SagiPlan*® treatment planning system to produce 3, 5, 10, 15, 20, 30, 40, 60 and 120 s dwell times (DTs). The residual transit times (following any possible system compensation) were assessed using the ESTRO-recommended approach of obtaining transit time compensation factors and another strategy established for teletherapy sources. The mean residual transit time depended on the distance between the afterloader and the DP, ranging from 0.43 to 1.10 s. The transit dose contribution was case-specific, ranging from 0.4% for a 60 s DT at the nearest DP to the afterloader up to 15.6% for a 3 s DT at the furthest DP from the unit. The results show that currently *SagiNova*® afterloader does not apply transit time compensation and suggest a 0.2–0.5 s compensation for each arrival and departure DP from/to the afterloader, depending on position in an 11 cm active length.

Keywords High dose rate brachytherapy · Source transit time · Well-type ionization chamber · *SagiNova* afterloader

Introduction

The dwell time (DT) and transit time components contribute to the overall delivered dose to patients in high dose rate (HDR) brachytherapy (BT) treatments. The transit dose results from a combination of source entry and exit from the housing to the applicator (sometimes called the ambient dose [1]) as well as sources movements between different dwell positions (DPs) [2]. It depends on various parameters such as the source speed profile and step size, source activity, prescribed dose, and number of catheters used in HDR BT treatments [3–5]. Generally, BT treatment planning systems do not apply a compensation for transit time. Instead, the afterloader unit control software itself adjusts the final DTs taking account of the transit time.

Independent verification of transit time or transit dose for each commercial HDR afterloader is recommended before clinical use [4, 6–8]. Some published reports have used a high definition video camera and/or Monte Carlo approaches [1, 3, 5, 6, 9], ionization chamber [10], diode [11, 12] as well as optical fibers [13] to perform this task. In practice, clinical users may even do this task simply using a stopwatch.

Palmer et al. reported the transit dose for the *Multi-Source*® HDR afterloader (Eckert & Ziegler *BEBIG* GmbH) [3, 6] with Ir-192 sources. To the best of our knowledge, there is no published paper on transit time measurement and transit dose for the recently released *BEBIG SagiNova*® HDR afterloader unit with Co-60 sources. The primary goal of this study is to independently evaluate the residual source transit time of this afterloader unit, following its compensation by the afterloader unit, using a simpler and more practical approach. Residual source transit time and dose is the

✉ Mohammad Amin Mosleh-Shirazi
mosleh_amin@hotmail.com; amosleh@sums.ac.ir

1 Ionizing and Non-Ionizing Radiation Protection Research Center, Paramedical School, Shiraz University of Medical Sciences, Shiraz, Iran

2 Student Research Committee, Shiraz University of Medical Sciences, Shiraz, Iran

3 Physics Unit, Department of Radio-Oncology, Shiraz University of Medical Sciences, Shiraz 71936-13311, Iran

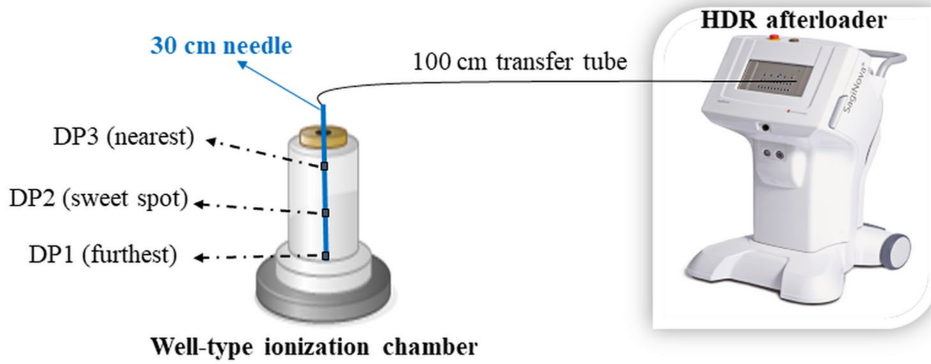

Fig. 1 Schematic representation of the experimental setup to assess the transit times for different dwell positions

remaining effects of source transit that are not compensated by the afterloader software. In cases where no software compensation has been applied by the manufacturer, this will be the total effect (as opposed to the remaining effect in cases of compensation by the manufacturer). Importantly, as will be shown by the results of this study, the SagiNova® afterloader in fact does not provide compensation for source transit time at present (Eckert & Ziegler BEBIG, private communication). As the secondary aim of this paper was to adapt a practical dosimetric method to evaluate transit dose during commissioning and quality assurance of HDR BT equipment, we have described a general method that is applicable to most afterloaders (i.e., with compensation) and refer to residual transit time. The investigation was carried out for source transit from the HDR unit to and from an intended DP (also called source transfer time). These findings can be useful for the users as well as the manufacturer.

Materials and methods

The assessed unit was a newly installed *SagiNova*® Co-60 HDR afterloader (software version 1.2.4; *Eckert & Ziegler BEBIG* GmbH). A dosimetric method was used. The measurements were performed using a previously commissioned *sourcecheck4π* (type 33005) well-type ionization chamber and *UNIDOS E*® electrometer (PTW Freiburg GmbH) [14]. A 30 cm plastic needle and a 100 cm transfer tube were used to accurately place the source at the intended DPs of the well chamber. The measurements were carried out with a fixed geometry for each DP [4]. According to manufacturer's instructions (*SagiNova*® user manual), in our experimental setup, we kept the transfer tube with a slight sag but such that the distance from the afterloader to the needle was about 90 cm, while lowering the position of well chamber to reduce curvature of the tube.

A naming scheme is used in this paper to distinguish between temporal and positional differences. We use "first" and "last" to refer to the time order of source dwells (i.e., the DP that the source arrives at from the afterloader unit, and the DP after which it leaves the applicator, respectively). It should be noted that a single DP was used in each of the treatment plans in our experiments, therefore, the first and last DP were the same. In terms of position, in this study three DPs were considered to mimic a variety of clinical situations with different distances from the afterloader to a DP in the needle (Fig. 1). DP1 was at 6.3 mm from the outer surface of applicator tip (the furthest DP from the afterloader in our experiment). DP2 was at the point of maximum response ('sweet spot') of the well chamber (48.3 mm distance from the tip). DP3 was at the upper region of the sensitive volume of the well chamber (114.3 mm from the tip; the nearest DP to the afterloader). The distances of DP1, DP2 and DP3 to the afterloader were 129.37 cm, 124.50 cm and 118.57 cm, respectively. This experimental setup can provide information about transit times for different distances to DPs.

Plans were generated using *SagiPlan*® version 2.0 to irradiate the well chamber by 3, 5, 10, 15, 20, 30, 40, 60, and 120 s DTs. All the measurements were repeated three times.

Transit time

The residual transit time, following its compensation by the afterloader software, was assessed for the intended DPs using two dosimetric methods: the ESTRO-recommended approach of obtaining transit time compensation factors [4] and another technique established for teletherapy sources [15, 16].

The ESTRO method

In this approach, the following formula was used to calculate a transit time compensation factor for each DT [4]:

$$f_{tr}(t) = 1 - \frac{M_{t_0}}{M_t(t)} \tag{1}$$

where t, M_{t_0} and $M_t(t)$ are the DT, the electrometer reading at $t = 0$ and the electrometer reading for dwell time t,

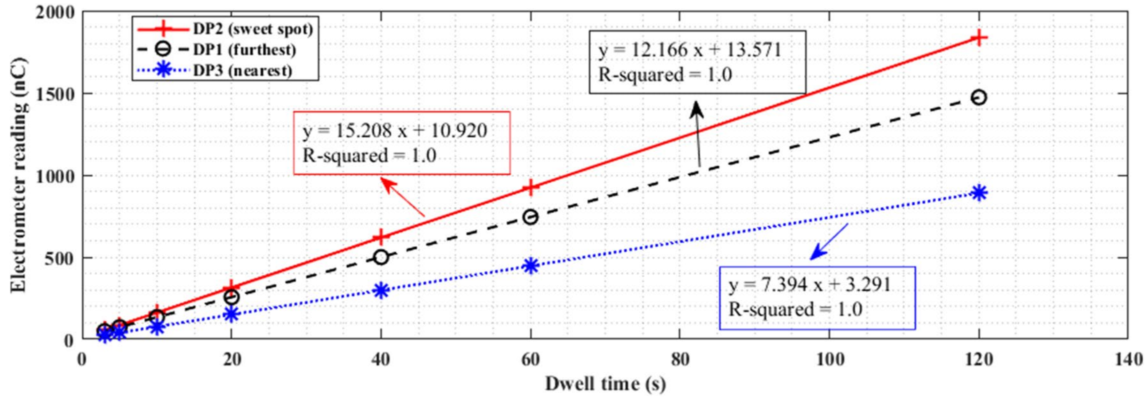

Fig. 2 The electrometer readings versus dwell times for different dwell positions

respectively. The value for M_{t_0} was obtained by setting different DTs, ranging from 3 to 120 s and then extrapolating to $t=0$. According to this formalism, f_{tr} will be equal to 1 if the afterloader control software compensates the effect of source transit perfectly. In case of imperfect compensation $(1-f_{tr})$ will show the contribution of the residual transit time in afterloader control software (i.e., the remaining effect of source transit after compensation by the afterloader software). Subsequently, multiplying f_{tr} by DT yields the residual transit time by the ESTRO method. $f_{tr} > 1$ will indicate an overcompensation of transit time by the control software and $f_{tr} < 1$ an undercompensation.

The teletherapy method [15, 16]

This formalism is well-established in quality control of Co-60 external-beam units:

$$\text{Transit time} = \frac{(2M_1 - M_2)(t_2 - t_1)}{(M_2 - M_1)} \tag{2}$$

where M_1, M_2 are the electrometer readings at DT values of $t_1$and t_2, and $t_2$is twice t_1. This approach will demonstrate a combination of the effects of transit time and any timer nonlinearity. In a similar fashion to the ESTRO method, to allow for a compensation factor to be applied by the manufacturer, we assign a DT compensation factor $f_{tr}(t)$ to each DT as follows:

$$f_{tr}(t) = 1 - \frac{t_{tr}}{t_{dwell}} \tag{3}$$

The contribution of transit dose

The additional dose due to the source transit was evaluated for various dwell times by measuring transit charge (charge collected by the ionization chamber) using a method described by Wong et al. [2]:

$$2Q_1 + Q_2(t) = Q_{T_1} \text{ and } 2Q_1 + Q_2(nt) = Q_{T_2} \tag{4}$$

where Q_1 was the transit charges due to transfer of the source from the safe to the intended DP and Q_2 was the stationary charge, i.e., the charge collected from the source purely when it is stationary at the DP. T_1, T_2 were two different set DTs of the source at the DP and $n = T_2/T_1$. Although a calibrated well-type chamber could be used to obtain dose from air kerma through the measured charge, only the proportionality of charge and dose is required in this set of relative measurements.

Results

Figure 2 shows the electrometer readings for different DTs and DPs. The value of M_0 for each dwell position is the vertical intercept for the extrapolated straight-line fit to its data. These values were used to compute the values of f_{tr} and transit time.

Tables 1, 2, 3 demonstrate the f_{tr} values and the residual transit times obtained by the two methods for various DTs at DP1, DP2 and DP3, respectively.

Table 4 shows the stationary charges obtained for each set of DTs as well as the percentage residual charge (percentage difference between the charges for stationary-plus-transit from the HDR afterloader to the dwell positions with the charge for the stationary component alone) using Eq. (4). The percentage residual charge gives the transit contribution of total dose from the afterloader following any compensation by the control software. The mean transit charges for all DTs were obtained 6.9 nC, 5.5 nC and 1.7 nC for DP1, DP2 and DP3, respectively.

As a reverse check of the results obtained using the ESTRO and teletherapy methods, we investigated the transit time using another simple approach. The total charge for

Table 1 The residual transit times for DP1

Dwell time (s)	Readout (nC)	f_{tr}		Residual transit time (s)	
		ESTRO	Teletherapy	ESTRO	Teletherapy
3	49.9	0.7280	–	0.816	–
5	74.2	0.8171	–	0.914	–
10	135.1	0.8995	0.8908	1.005	1.092
20	256.7	0.9471	0.9445	1.057	1.110
40	500.5	0.9729	0.9736	1.085	1.058
60	744.4	0.9818	–	1.093	–
120	1473	0.9908	0.9892	1.106	1.301
Average residual transit time (s) ± 1 standard deviation (s)				1.011 ± 0.108	1.140 ± 0.109

Table 2 The residual transit times for DP2

Dwell time (s)	Readout (nC)	f_{tr}		Residual transit time (s)	
		ESTRO	Teletherapy	ESTRO	Teletherapy
3	56.6	0.8070	–	0.579	–
5	87.0	0.8744	–	0.628	–
10	163.0	0.9330	0.9276	0.670	0.724
20	315.1	0.9653	0.9642	0.693	0.717
40	619.2	0.9823	0.9819	0.705	0.723
60	923.3	0.9881	–	0.710	–
120	1836.0	0.9940	0.9942	0.714	0.697
Average residual transit time ± 1 standard deviation (s)				0.671 ± 0.050	0.715 ± 0.013

Table 3 The residual transit times for DP3

Dwell time (s)	Readout (nC)	f_{tr}		Residual transit time (s)	
		ESTRO	Teletherapy	ESTRO	Teletherapy
3	25.5	0.8709	–	0.387	–
5	40.3	0.9183	–	0.408	–
10	77.3	0.9574	0.9554	0.426	0.446
20	150.8	0.9782	0.9742	0.436	0.517
40	299.3	0.9890	0.9922	0.440	0.310
60	446.9	0.9926	–	0.442	–
120	890.5	0.9963	0.9963	0.443	0.446
Average residual transit time ± 1 standard deviation (s)				0.426 ± 0.021	0.430 ± 0.087

Table 4 Stationary and residual charges for different source DTs and DPs

Dwell time (s)	Stationary charge (nC)			Residual charge (%)		
	DP1	DP2	DP3	DP1	DP2	DP3
3	36.4	45.6	22.2	15.579	10.763	6.921
5	60.7	76.0	37.0	9.844	6.754	4.269
10	121.6	152.1	73.5	5.259	3.489	2.520
20	243.8	304.1	148.5	2.577	1.776	0.768
40	487.8	608.2	295.2	1.285	0.896	0.689
60	728.6	912.7	443.6	1.073	0.598	0.371

a specific source strength and dwell time can be expressed through the following formula [12]:

$$Q_{total} = Q^{\cdot}_{dwell} \times t_{eff} \quad (5)$$

where $Q^{\cdot}_{dwell}$ and t_{eff} are the charge rate at the intended DP and the effective treatment time for a known source strength and dwell time. It should be mentioned $Q^{\cdot}_{dwell} = Q_{dwell}/t_{dwell}$ and $t_{eff} = t_{dwell} + t_{tr}$.

The transit times obtained from Eq. (5) and Table 4 for a reverse check were 1.131 ± 0.0438 s, 0.716 ± 0.006 s, and 0.454 ± 0.030 s for DP1, DP2 and DP3, respectively. The differences between these transit times and the ESTRO method were 11.8%, 6.7% and 6.6%, respectively. The corresponding differences from the teletherapy method were 0.8%, 0.1% and 5.6%, respectively. These differences are within 0.12 s and 0.02 s for the ESTRO and teletherapy methods, respectively.

Discussion

In this work, a well-type ionization chamber was used to assess the transit time for the recently released *BEBIG SagiNova*® HDR afterloader unit with Co-60 sources. We focused on source transit from the HDR unit to and from an intended DP. There are, of course, inter-DP movements that also contribute to the total transit dose in a patient treatment and manufacturers usually apply compensation methods to compensate the effects of inter-DP transit dose too [2]. Investigation of inter-DP transit time in this system is also of interest, but it has not been investigated as a part of this study. The residual transit time in the afterloader shows a dependency on the distance from the afterloader to the DP. The ESTRO method results show the residual transit times of 0.426 s, 0.671 s and 1.01 s for the distances of 118.57 cm, 124.5 cm and 129.37 cm from the afterloader to the DPs, respectively. The corresponding results from the teletherapy method are 0.430 s, 0.715 s and 1.140 s, respectively.

According to the Tables 1, 2, 3, for the 108 mm source transit between DP1 and DP3 inside the applicator, the ESTRO and teletherapy methods give the residual transit times of 0.584 s and 0.710 s, respectively. The reverse checks using Eq. (5) confirmed the results of these two methods to about a tenth of a second. The *SagiNova*® afterloader is capable of delivering treatments with an active length greater than the 108 mm used in this study. The length was limited by the size of the well chamber. However, this length is sufficient to cover most clinical scenarios in HDR BT. Reported typical active lengths for HDR BT is usually up about 63 mm for prostate cases [5, 9], 70 mm for cervical cancer with tandem and ovoids applicators [17], 80 mm for endometrial and cervix cancer patients with vaginal cylinders [18, 19], and 100 mm for endobronchial [20]. If required, transit times for longer active lengths can be measured using a different method or estimated by calculation based on a known source movement acceleration.

The *SagiNova*® afterloader in fact does not provide compensation for source transit time (either from the HDR unit to and from an intended DP, or inter-DP transit time) in the tested version (and also up to version 2.1.3) and the implementation of such compensation is planned for software version 2.1.4 by the end of 2019 (Eckert & Ziegler BEBIG, private communication). The magnitudes of the residual transit times we have measured indeed suggest that no compensation has been applied. Our observations showed that the *SagiNova*® software starts counting the treated time after 7.05 s, 6.96 s and 6.84 s for the source transferring from the HDR unit to DP1, DP2 and DP3, respectively. Also, it just displays and records an overall transit time (10.73 s, 10.58 s and 10.23 s for DP1, DP2 and DP3, respectively) that includes outbound and return transfers.

The actual DT of first DP starts immediately after the arrival of the source to that DP. The source then leaves that DP after its DT has elapsed. In this scheme, because the time is not counted from when the source leaves the afterloader unit, transit times always give rise to additional transit dose (i.e., an overdosage).

The values of f_{tr} in Tables 1, 2, 3 also confirm the importance of the effect of transit time for small DTs and large distances from the HDR afterloader to the DP. The importance of transit time for small DTs can also observed in Table 4. The percentage residual charge column in Table 4 shows the transit dose contribution for each DT and DP. It shows that the transit dose effect becomes more significant with smaller dwell times and larger distances.

For the BEBIG's latest unit *(SagiNova®)* with a Co-60 source, our results suggest the need for the manufacturer to apply compensation for residual transit times ranging from 0.4 to 1.1 s (depending on the intended DP, i.e., the distance from the treatment unit to the DP) for source transfers from the HDR unit to and from the first DP for the geometry considered in this study. The values of f_{tr} in Tables 1, 2, 3 can be a helpful guide for the manufacturer to compensate the transit time effect of the *BEBIG SagiNova*® afterloader. Palmer reported that the compensation implemented in the control software of the *MultiSource*® afterloader with an Ir-192 source (the previous generation of the *BEBIG* HDR afterloader) was 0.45 s for the first and last DP each, which resulted in an underdosage of 0.2 cGy at 10 mm perpendicular from the source (due to a slight overcompensation of the transit dose) [6]. Our results in Tables 1 and 3 demonstrate that for the furthest and nearest DPs to the afterloader (DP1 and DP3, respectively), the respective overall residual transit times are about 1 s and 0.4 s. An overall transit time includes the transit time from the unit to the first DP as well as from the last DP to the unit. The strategy implemented for the

MultiSource® afterloader was to apply an equal compensation time for the first and last DPs irrespective of the positions of those DPs [6]. If we assume equal transit times to and from the DP in the *SagiNova*® *afterloader* too, for a more detailed compensation scheme in its control software, our results suggest that a 0.5 s compensation can be implemented for the DPs near the tip of the applicator. The corresponding compensation for DPs around the middle of the applicator and those near its transfer-tube end can be 0.35 s and 0.2 s, respectively.

Palmer reported a 1.0 mm DP error due to transfer tube curvatures of up to 10 cm for the *BEBIG Multisource*® afterloader [6]. According to the *SagiNova*® user manual, its control software implements an approach to optimize DP positional accuracy for the case of a transfer tube with slight sag to produce an afterloader-to-needle distance of 90 cm for the 100 cm tube. This is the geometry we used for our measurements and the results are applicable to treatments with similar geometries.

As an example for better understanding of the effect of transit dose in the worst-case scenario for the *SagiNova*® afterloader, assuming a Co-60 source with a reference air kerma rate of 1.975 cGy/h and a typical DP with DTs of 3, 5 and 40 s, the doses at 1 cm on the transverse bisector of a typical catheter are 17.97 cGy, 29.95 cGy and 239.6 cGy, respectively. According to the residual charge column in Table 4 for DP1, the transit dose would be 2.80 cGy, 2.90 cGy and 3.07 cGy, respectively. But it is better to report the transit dose as 2.92 ± 0.14 cGy, because the transit dose should be the same for different DTs. The slight trend observed in the transit dose values is likely to be inherent inaccuracies in the model. This, however, does not change the overall results and conclusion of this study. Finally, it can be said that the effect of transit dose can be considered negligible for most clinical cases with common dwell times. However, this is a systematic error that should preferably be eliminated/reduced by compensation.

Although we did not measure the speed profile of the afterloader to obtain transit dose [6, 9], we can obtain an estimation for the average speed assuming a uniform acceleration for the source movement [9] and a further assumption of similar source acceleration in both *SagiNova*® and *Multisource*® ($|a| = 77\ \mathrm{cm/s^2}$ [3]). The average speed obtained will be 192 ± 73 mm/s and 166 ± 75 mm/s using the ESTRO and teletherapy method transit time results, respectively. Here, we used a simpler and more practical approach obviating the need for measurement of the instantaneous source speed. The method enables physicists to evaluate residual transit time for each HDR afterloader whether or not its control software considers any compensation for the transit time effect. This applied method is particularly helpful during commissioning and quality assurance stages.

Uncertainties in our measurements are mainly due to any errors in the charge measurement in the well-type ionization chamber. This, however, should not affect our results, because a relative approach is used in Eqs. 1–4. According to Tables 1, 2, 3, the trends with increasing DT for f_{tr} and $(1 - f_{tr})$ (i.e., contribution of the residual transit time) are similar for both teletherapy and ESTRO methods. As for residual transit times, however, the trends are dissimilar as well as the values obtained using the teletherapy method being slightly larger than those of the ESTRO. This may be due to the fact that teletherapy method has a different formula and gives a combination of transit time and timer linearity error. The closeness of the results obtained by the two measurement methods suggests a good timer linearity. Nevertheless, since the residual transit time should not depend on the DTs, we used the average of the residual transit time to estimate the compensation for the first and the last DPs. In any case, the differences between the residual transit times obtained from the two methods are small (about a tenth of a second).

Conclusion

This work demonstrates two accurate dosimetry-based methods to measure source transit time during the commissioning step of HDR afterloaders using a practical approach and available standard equipment. For the *SagiNova*® HDR afterloader, the two methods showed close agreement. The results show that the *SagiNova*® afterloader (software version 1.2.4) does not apply transit time compensation, which results in a slight overdosage. Our results can be used as independent data by the manufacturer to apply a suitable and reliable DT compensation for this afterloader. The results suggest a 0.2–0.5 s compensation for each arrival and departure DP from/to the afterloader, depending on position in an 11 cm active length.

Acknowledgements The authors would like to thank *Eckert & Ziegler BEBIG* GmbH for helpful information, in particular, Antonius Spiller, Thomas Osche and Lars Flemmig for their valuable comments on the manuscript.

Funding This study was funded by Shiraz University of Medical Sciences (Grant No. 97-07-75-18167).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Giménez-Alventosa V, Vijande J, Ballester F, Perez-Calatayud J (2016) Transit dose comparisons for 60Co and 192Ir HDR sources. J Radiol Prot 36(4):858
2. Wong TP, Fernando W, Johnston PN, Bubb IF (2001) Transit dose of an Ir-192 high dose rate brachytherapy stepping source. Phys Med Biol 46(2):323
3. Palmer A, Mzenda B (2009) Performance assessment of the BEBIG MultiSource® high dose rate brachytherapy treatment unit. Phys Med Biol 54(24):7417
4. Venselarr J, Perez-Calatayud J (2004) European guidelines for quality assurance in radiotherapy, ESTRO Booklet No 8. A practical guide to quality control of brachytherapy equipment. ESTRO, Belgium, pp 1–270
5. Fonseca G, Rubo R, Minamisawa R, Dos Santos G, Antunes P, Yoriyaz H (2013) Determination of transit dose profile for a 192Ir HDR source. Med Phys 40(5):51717
6. Palmer A (2013) Impact of software changes: transit dose and source position accuracy of the Eckert & Ziegler BEBIG GmbH MultiSource® high dose rate (HDR) brachytherapy treatment unit. J Radiother Pract 12(1):80–87
7. Fonseca GP, Viana RS, Podesta M, Rubo RA, Sales CP, Reniers B, Yoriyaz H, Verhaegen F (2015) HDR 192Ir source speed measurements using a high speed video camera. Med Phys 42(1):412–415
8. Dempsey C, Smith R, Nyathi T, Ceylan A, Howard L, Patel V, Das R, Haworth A (2013) ACPSEM brachytherapy working group recommendations for quality assurance in brachytherapy. Australas Phys Eng Sci Med 36(4):387–396
9. Fonseca G, Landry G, Reniers B, Hoffmann A, Rubo R, Antunes P, Yoriyaz H, Verhaegen F (2014) The contribution from transit dose for 192Ir HDR brachytherapy treatments. Phys Med Biol 59(7):1831.
10. Sahoo N (2001) Measurement of transit time of a remote after-loading high dose rate brachytherapy source. Med Phys 28(8):1786–1790
11. Jursinic PA (2014) Quality assurance measurements for high-dose-rate brachytherapy without film. J Appl Clin Med Phys 15(1):246–261
12. Jeong J, Barker CA, Zaider M, Gil'ad NC (2016) Impact of source position on high-dose-rate skin surface applicator dosimetry. Brachytherapy 15(5):650–660
13. Minamisawa R, Rubo R, Seraide R, Rocha J, Almeida A (2010) Direct measurement of instantaneous source speed for a HDR brachytherapy unit using an optical fiber based detector a. Med Phys 37(10):5407–5411
14. Mukwada G, Neveri G, Alkhatib Z, Waterhouse DK, Ebert M (2016) Commissioning of a well type chamber for HDR and LDR brachytherapy applications: a review of methodology and outcomes. Australas Phys Eng Sci Med 39(1):167–175
15. Wilkinson D (2006) High dose rate (HDR) brachytherapy quality assurance: a practical guide. Biomed Imaging Interv J 2(2):e34
16. Podgorsak EB (2005) Radiation oncology physics. International Atomic Energy Agency, Vienna, pp 123–271
17. Kim Y, Modrick JM, Pennington EC, Kim Y (2016) Commissioning of a 3D image-based treatment planning system for high-dose-rate brachytherapy of cervical cancer. J Appl Clin Med Phys 17(2):405–426
18. Supe SS, Bijina T, Varatharaj C, Shwetha B, Arunkumar T, Sathiyan S, Ganesh K, Ravikumar M (2009) Optimized dose distribution of Gammamed plus vaginal cylinders. J Med Dosim 34(1):20–25
19. Oyekunle EO, Obed RI, Akinlade BI, Ntekim A (2015) Comparison of doses to the rectum derived from treatment planning system with in-vivo dose values in vaginal vault brachytherapy using cylinder applicators. J Contemp Brachytherapy 7(6):485
20. Nag S (2004) High dose rate brachytherapy: its clinical applications and treatment guidelines. J Technol Cancer Res Treatment 3(3):269–287