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Physics

Mechanical evaluation of the Bravos afterloader system for HDR brachytherapy

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ABSTRACT

PURPOSE: The Bravos afterloader system was released by Varian Medical Systems in October of 2018 for high-dose-rate brachytherapy with ^{192}Ir sources, containing new features such as the CamScale (a new device for daily quality assurance and system recalibration), channel length verification, and different settings for rigid and flexible applicators. This study mechanically evaluated the Bravos system precision and accuracy for clinically relevant scenarios, using dummy sources.

METHODS AND MATERIALS: The system was evaluated after three sets of experiments: (*1*) The CamScale was used to verify inter- and intra-channel dwelling variability and system calibration; (*2*) A high-speed camera was used to verify the source simulation cable movement inside a transparent quality assurance device, where dwell positions, dwell times, transit times, speed profiles, and accelerations were measured; (*3*) The source movement inside clinical applicators was captured with an imaging panel while being exposed to an external kV source. Measured and planned dwell positions and times were compared.

RESULTS: Maximum deviations between planned and measured dwell positions and times for the source cable were 0.4 mm for the CamScale measurements and 0.07 seconds for the high-speed camera measurements. Mean dwell position deviations inside clinical applicators were below 1.2 mm for all applicators except the ring that required an offset correction of 1 mm to achieve a mean deviation of 0.4 mm.

CONCLUSIONS: Features of the Bravos afterloader system provide a robust and precise treatment delivery. All measurements were within manufacturer specifications.

Keywords: brachytherapy; Afterloader; Commissioning

Introduction

Bravos is the brachytherapy system released by Varian Medical Systems (Palo Alto, CA) in October of 2018, comprehending an afterloader with 30 channels, a CamScale (a new device that provides tools for daily quality assurance [QA] and recalibration for both source and dummy cables) and new control software. The Bravos system uses the same ^{192}Ir high-dose-rate (HDR) source as its predecessor, the GammaMedplus iX (1) and it has several new features, such as a reformulated transit time algorithm, differentiation between rigid and flexible applicator settings for any of the channels (there is a greater force threshold adopted during the length verification of rigid applicators, working as an obstruction test that could damage flexible applicators), and channel length verification. More features are listed in Table 1.

The purpose of this study is to evaluate the Bravos system for clinically relevant scenarios, verifying its precision and accuracy for parameters such as dwell positions, dwell

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times and transit time corrections, for a range of applicators, using multiple QA methods.

Methods and materials

The Bravos system that was evaluated with mechanical tests was the final and commercially available product. However, no dosimetric tests were performed because the Bravos afterloader uses the GammaMedplus iX source, which is already well documented in the literature (3−5). Hence, the afterloader had a source simulation cable instead of an active source, which is identical to a regular source cable (apart from not being active), and the focus of this study was the mechanical evaluation of the Bravos system itself. Nevertheless, the source simulation cable is referred to as source.

The system evaluation was performed in three groups of experiments:

1. Experiments using the CamScale device: The CamScale was used to verify intra- and inter-channel dwelling variability and system calibration by registering both dummy and source cable positions for three predefined positions (90, 120, and 150 cm).
2. Source behavior verification inside a QA device: For clinically relevant scenarios in brachytherapy, it is important to verify the precision and accuracy for different dwell positions than those verified with the CamScale and evaluate interdwell distances (IDD) and dwell times. To perform these evaluations, the source cable dwelling inside a transparent QA device was recorded with a high-speed camera for clinically relevant plans. The high-speed camera and the QA device are described in Source Behavior Verification Inside a QA Device Section.
3. Source behavior verification inside clinical applicators: An external X-ray source and an imaging panel (IP) were used to track the source movement inside clinical applicators.

Experiments using the CamScale device

The CamScale was first introduced as an internal system of the VariSource iX afterloader (6); however, with the only purpose of verifying wire position accuracy. The CamScale incorporated into the Bravos system is a separate device intended for daily QA and easy system recalibration when necessary.

The proper distance and alignment of the CamScale with respect to the afterloader is achieved using a built-in laser that places the afterloader and the CamScale at a distance of 50 ± 1.5 cm from each other, there is no need of height adjustment. Figure 1a shows the proper CamScale placement with an insert showing the laser projected onto the afterloader surface.

Table 1
Main different features between the GammaMedplus iX and the Bravos systems

Feature	GammaMedplus iX	Bravos
CamScale device	Absent	Present
Transit time calculation algorithm (more details in Appendix A)	Considers only the transit time between dwell positions	Reformulated to consider the source movement from the afterloader to the most distal positions
Maximum source speed	63 cm/s (1)	100 cm/s (2)
Obstruction verification	Performed twice during treatment	Performed once during pretreatment and once during treatment
Number of channels	24	30
Possibility of using coded transfer guide tubes	Absent	Channels 1−3 can be used with coded transfer guide tubes[a]
Differentiation between rigid and flexible applicators (a push test is performed for rigid applicators)	Push test is performed for channels 1−19 and not for channels 20−24	The option to perform a push test or not is defined during the treatment plan, regardless of the channel used
Channel length	Fixed at 130 cm	From 50 to 160 cm
Channel length verification	Absent	Present
Afterloader head height[b]	Adjustable between 90 and 130 cm	Fixed at 100 cm
Distal position correction	It is possible to add an offset to the distal position, however, not to correct it during pretreatment	Possible to correct the offset applied to the distal position (1 mm resolution) during pretreatment
Display of distal position when it is at the end of the channel (e.g. a channel with 130.0 cm)	There is a 1 mm offset from the source position to the end of the channel; however, position is displayed as if there was no offset, namely 130.0 cm	There is a 1 mm offset from the end of the channel, and the source position is displayed including the offset for clarity sake, namely 129.9 cm
Pretreatment checklist	There is no mandatory pretreatment checklist. It is responsibility of the oncology center to define an internal system to guarantee that the correct treatment is delivered	The treatment can only be delivered after approving a checklist with mandatory fields regarding patient identity and treatment settings. Nevertheless, more items can be added to the checklist

[a] Information provided in the user guide but not verified experimentally.
[b] From the floor to the center of the indexer head.

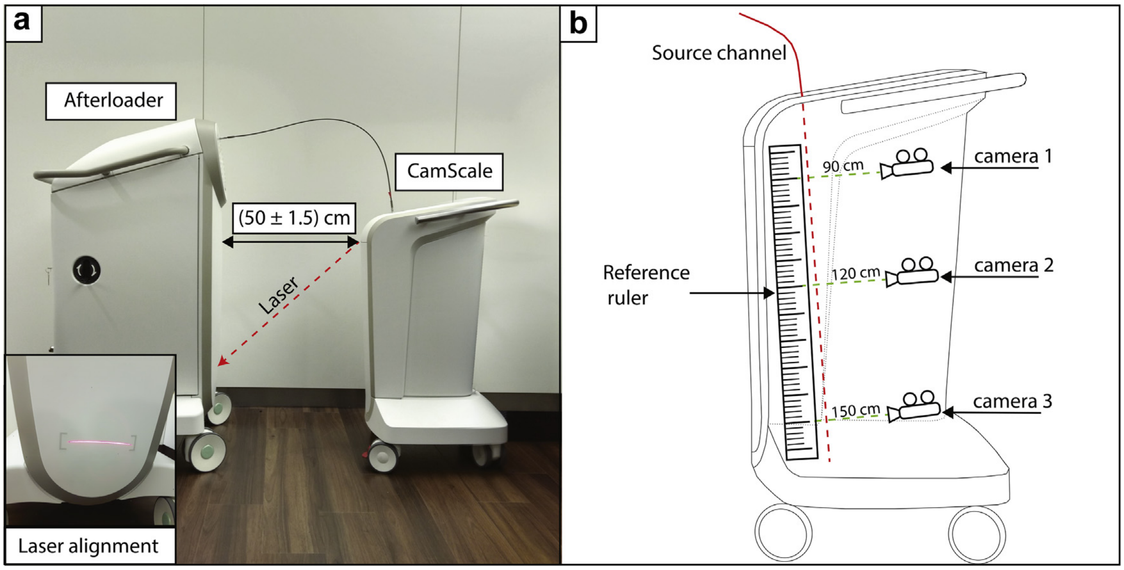

Fig. 1. (a) The ideal distance between the CamScale and the afterloader is 50 ± 1.5 cm (measured horizontally at the laser origin height), achieved by laser alignment. The inset shows the laser projected onto the afterloader used for alignment. For a proper alignment, the laser projection should be inside the region defined by two markers (visible in the insert figure). (b) Schematic drawing showing the position of the cameras and ruler used for position verification in the CamScale.

The CamScale contains a calibrated metal ruler with 0.5 mm resolution and three video cameras (1920 px × 1080 px resolution) that register both dummy and source cable positions at three predefined positions of 90, 120, and 150 cm (schematic drawing in Fig. 1b).

Position verification and system recalibration can be performed using any of the afterloader channels; nevertheless, the transfer guide tube presents the lowest curvature when connected to channel 1. For this reason, the user guide (7) recommends using channel one for most accurate and consistent results; however, such explanation is not mentioned in the current version of the user guide. Moreover, the CamScale comes with its own transfer guide tube with the sole purpose of verifying the afterloader calibration, but not to verify the length of different transfer guide tubes. Both cables (source and dummy) need to be properly calibrated to ensure that the channel length measured with the dummy cable is suitable for the source cable. Supplementary Video 1 shows the capture of the Bravos control software screen during the cables position verification of both cables (source and dummy). The system allows the user to perform a recalibration after position verification. Once the CamScale is connected to the afterloader and the system is running, it requires approximately 2 min to perform the position verification and system recalibration.

According to the Bravos user guide (7), a system recalibration is suggested if deviations greater than 1 mm are observed during a CamScale position verification, if the deviation is greater than 2 mm, the calibration is disabled and the user is instructed to contact Varian Customer Support. Three consecutive position verifications using channel one were performed before each experiment and, for most accurate results, a system recalibration was performed if deviations greater than 0.3 mm were reported or if the system was currently calibrated using another channel. The CamScale trolley was never moved between measurements performed in same experimental conditions; however, it was moved between different sets of measurements when necessary.

Reproducibility and interchannel variations

The Bravos afterloader has 30 channels arranged in a circular pattern with a diameter of 19 cm, causing a different transfer guide tube curvature for each channel when connected to the CamScale due to height differences (max. height difference of 18 cm between channels 1 and 15). The system was calibrated using channel 1 and 20 position verifications were performed using channels 1, 8, 15, 23, and 30 (total of 100 measurements) to evaluate inter- and intra-channel variations, followed by three measurements for every odd channel to cover a larger number of channels.

It was hypothesized that calibrating the afterloader with the CamScale using one channel and performing a position verification using other channels could affect the position verification results because of the different transfer guide tube curvatures. Channels 1 and 15 were used to evaluate this possible effect because the greatest difference in transfer guide tube curvature occurs between these channels. A total of 60 position verifications were performed using channel 15 while the system was recalibrated before starting the measurements and after every 10 measurements, resulting in a total of six recalibrations. The first three calibrations were performed using channel 1 and the remaining three calibrations using channel 15.

The Bravos afterloader contains a mechanical system that redirects the source and dummy cables toward the channel that will be used for irradiation (Fig. 2). To evaluate if the process of redirecting the cables to a different channel affects the system calibration over time, the system was calibrated using channel 1, and 40 CamScale position verifications were performed alternating between channels 1 and 15 (20 measurements per channel). These measurements were repeated in three consecutive days for a total of 120 measurements.

CamScale behavior when not in reference position

An accidental CamScale misplacement may occur because there is no interlock between the CamScale and the afterloader. The influence on the source and dummy cable position verification due to a misplacement was investigated for two cases in which the alignment was correct but the distance between the CamScale and the afterloader was off by ±9 cm (maximum distance possible without overextending the transfer guide tube), and for 2 cases in which the alignment was off by 45° and 90°. Five measurements for the channels 1 and 15 were performed for each case.

Source behavior verification inside a QA device

Dwell positions, dwell times, and transit times were measured with a high-speed camera and compared with the postirradiation report produced by the Bravos control software to verify its precision and accuracy. The postirradiation report shows planned, scaled (considering the source activity), and delivered dwell times for each dwell position, which may deviate from each other when scaled dwell times are close to minimum dwell times allowed because of the transit time.

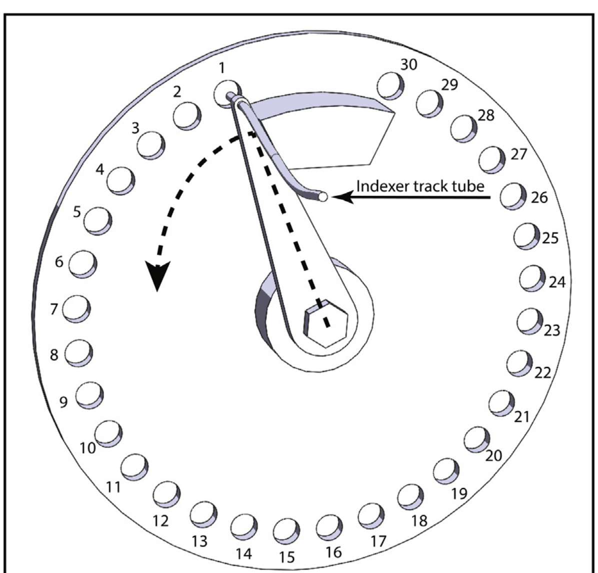

Fig. 2. Schematic drawing of the mechanism that directs the indexer track tube toward the channel used for irradiation. The indexer track tube is directed to channel one by default.

Experimental setup

The experimental setup adopted for the measurements was based on the work of Fonseca *et al*. (8), a transparent source step viewer QA device (model GM11008720; Varian Medical Systems) graded to 1 mm was used to track the source wire dwelling with a high-speed camera (model NEX-FS700 R; Sony, Minato, Tokyo, Japan), capable of recording up to 960 frames per second (~1.04 ms per frame), offering a high time resolution to verify accurately the smallest dwell time allowed by the afterloader (0.1 s) and measure speed profiles and acceleration.

The QA device was evenly illuminated with two diffused light sources positioned one at each side of the camera that was kept at the same height as the QA device to minimize parallax errors.

The accuracy and precision of the Bravos afterloader regarding dwell positions, dwell times, and transit time corrections were evaluated for IDD of 1, 3, 5, 10, 20, 25, 30, and 100 mm, for which the minimum allowed dwell time (t_{min}) is, respectively, 0.1, 0.15, 0.2, 0.25, 0.30, 0.35, 0.40, and 0.40 s. Dwell time precision and accuracy were evaluated for plans adopting dwell times = t_{min} for each IDD and dwell positions were evaluated for plans with dwell time of 1 s.

The high-speed camera field of view was varied between 30 and 125 mm according to the IDD of the plan being evaluated, making the pixel size range from 0.04 up to 0.12 mm because of the resolution of 720 × 480 pixels when recording at 960 fps, resulting in an uncertainty while tracking the source position ranging from 0.1 to 0.5 mm. All plans were executed using channel 1, adopting the same dwell time and IDD for all dwell positions within the same plan. Unless described otherwise, only the source cable movement was recorded because of the limited buffer size when recording at 960 fps (19 s). Videos were processed with a software developed by the authors in MATLAB (the MathWorks, Inc., Natick, MA) to track the source movement, and transit times were measured following the Bravos Reference Guide (2) (Appendix A shows the difference between calculation methods for transit time by the GammaMedplus iX and the Bravos systems). Average (V_{med}) and maximum (V_{max}) source speeds were measured for discrete source positions averaged every 0.01 s while the source was moving between dwell positions for all IDDs. The source cable acceleration was measured by applying a polynomial curve fitting of second order for the regions where the source was moving between consecutive dwell positions for IDD ranging from 20 to 100 mm (smaller IDDs did not have enough points for a good curve fitting) or moving from the afterloader to the distal position for all IDDs. Measured values of V_{med} and V_{max} were compared with its expected values calculated based on the measured acceleration. Table 2 shows a summary of the experiments performed with the high-speed camera.

Table 2
Summary of experiments performed with the high-speed camera

Objectives	IDD (mm)	Dwell time	Number of measurements	Settings
Verify dwell positions and dwell times	1, 3, 5, 10, 20, 25, 30, 100	t_{min} and 1 s	96	Reference settings[a]
Verify if the system accurately reports the delivered dwell time when transit time correction is disabled	1, 5, 10	t_{min}	12	No transit time correction
Verify correct offset[b]	5	t_{min}	15	Offset of 0, 1, 2, 4, and 10 mm
Verify correct distal correction[b]	5	t_{min}	12	Distal correction of 1, 2, 4, and 10 mm from tip
Verify difference between flexible and rigid applicator	5	t_{min}	5	Rigid applicator
Compare source and dummy cables behavior	Single dwell at the tip	t_{min}	10	Record dummy and source

IDD = interdwell distance.

[a] The reference settings adopted for the high-speed camera experiments were the standard settings offered by the system when a new plan is created: flexible applicator, transit time correction enabled, first dwell position at the tip of the channel, no distal correction.

[b] By applying an offset or a distal correction to a channel, all dwell positions will be shifted. The difference is that the offset is defined during the planning process, while the distal correction is applied during the pretreatment verification stage, after the channel length verification is performed.

Source behavior verification inside clinical applicators

A kV X-ray source (cone beam CT X-ray unit onboard TrueBeam linear accelerator) and an IP (Varex PaxScan 2530HE) were used to track the source movement inside six clinical applicators: needle (J26-019/GM11007580/2013), ring (VMS R12-061/GM11001240), tandem ring (VMS R11/GM11010990), tandem 15° (VMS S09/AL07522000), tandem 45° (VMS S09/AL07522002), and Right Colpostat (VMS S09/AL07523000) (9).

The IP was positioned on top of the LINAC treatment table and the applicators were aligned with the surface of the IP. Transfer guide tubes were positioned to avoid excessive curvature. In addition, a thin lead sheet was placed in front of the afterloader to prevent the X-rays coming from the kV imaging source to trigger the afterloader radiation detector and shutdown the system.

The IP acquisition rate was set to 14.8 fps (to synchronize with the X-ray source duty cycle) with spatial resolution of 0.14 mm. The tube voltage was defined at 120 kVp to optimize contrast.

Reference treatment plans were created using the treatment planning system BrachyVision v15 (Varian Medical Systems) based on CT images with 0.1 mm resolution of the applicators acquired with the X-RAD SmART system (Precision X-Ray, North Branford, CT). The source trajectory for each applicator was initially defined following the center of the channel and later adjusted to follow a more realistic path based on the experimental data. CT and IP images were registered considering the geometry of the applicators and user-defined landmarks to compare measured and planned dwell positions with an in-house software written in MATLAB version 8.5 (The MathWorks, Inc., Natick, MA). The treatment planning system uses the center of the source as reference for the dwell positions whilst the tip of the source is easier to detect using the described experimental setup. Therefore, dwell positions from the treatment plan were shifted by 2.47 mm along the source trajectory (based on the source geometry found in the literature (10, 11)) to correspond to the tip of the source when the positions were compared.

Dwell position precision and accuracy were evaluated for plans with rigid applicators settings and IDDs of 1, 2, 5, and 10 mm. Offsets of 0, 1, 2, and 5 mm were applied to the plans with IDD of 5 mm to evaluate if the average deviation between planned and measured dwell positions could be improved by applying an offset or distal correction to the dwell positions. The difference between rigid and flexible applicator settings was evaluated for plans with IDD of 5 mm and no offset. Each plan was repeated 5 times, with dwell times of 1 s and dwell positions covering a range of 45 mm starting at the tip of each applicator for IDDs of 2, 5, and 10 mm and a range of 20 mm for IDDs of 1 mm to better evaluate the source behavior close to the tip of the applicators. The same dwell positions range was adopted for all applicators for consistency while evaluating the Bravos system behavior. Different dwell times were evaluated with the high-speed camera using the QA device because of its higher temporal resolution. A total of 35 plans were executed per applicator. Supplementary Video 2 shows the source movement inside the tandem 45° applicator.

Results and discussion

Experiments using the CamScale device

For every case evaluated, the reported deviations by the CamScale from each of the target positions (90, 120, and 150 cm) had always a similar value (within a range of ~0.2 mm from each other). Hence, the results shown for dummy and source position deviations combine the deviations for the three target positions in what follows.

Reproducibility and interchannel variations

The system was calibrated using channel one before starting the measurements. Figure 3 shows the deviation

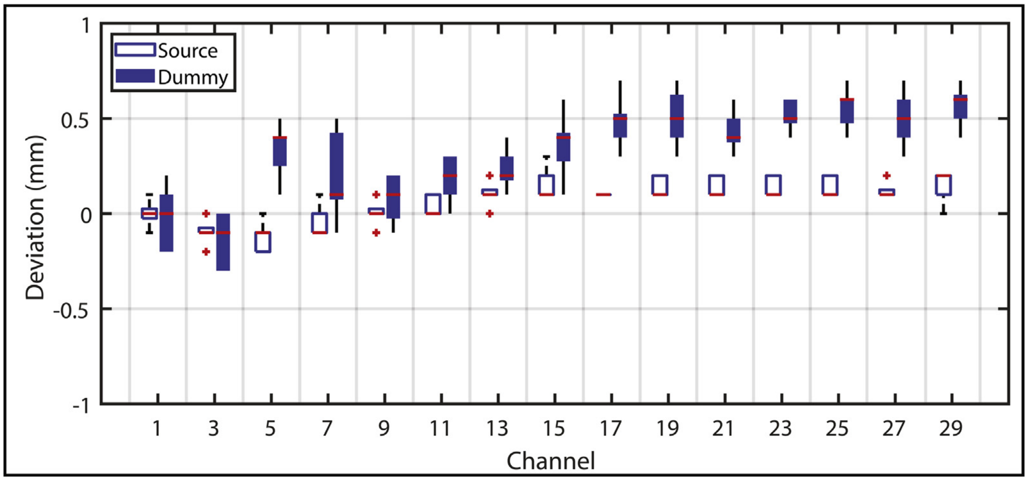

Fig. 3. Deviation from target positions measured with the CamScale for source and dummy cables with three measurements for every odd channel.

from target position for the source and dummy cables with three measurements for every odd channel. Channels with more measurements (not shown in Fig. 3) follow the same pattern observed for the other channels. The median deviation reported for all source cable measurements combined is 0.0 mm with a maximum absolute deviation of 0.4 mm for 4% of the positions. The median deviation for the dummy cable was 0.2 mm, with 17% of the deviation exceeding 0.4 mm and the maximum deviation measured was 0.7 mm for 2% of the positions.

Position verifications performed using channel 15 resulted in an average deviation for the dummy cable of 0.23 ± 0.11 mm and 0.00 ± 0.14 mm when the system was calibrated using channels 1 and 15, respectively, and 0.16 ± 0.08 mm and −0.08 ± 0.05 mm for the source cable. Results show a smaller deviation from target positions when the same channel is used for both calibration and position verification.

Alternating between channels 1 and 15 while performing position verifications with the CamScale did not affect the system calibration over time and no clear pattern of deviation from target positions was observed along multiple measurements for either channels. The maximum deviation from target position for channels 1 and 15 was 0.5 mm for 0.3% of the measurements with the source cable and 0.6 mm for 1.4% of the measurements with the dummy cable. A systematic cable position shift of 0.2 ± 0.1 mm was observed between channels 1 and 15 for both source and dummy cables (positions measured with channel 15 were more distal), which is in agreement with results shown in Fig. 3.

CamScale behavior when not in reference position

The maximum deviation from target position using channels 1 and 15 with the CamScale in nonreference positions was 0.4 mm for the source cable and 0.7 mm for the dummy cable. Such deviations are within the same range observed when cycling through the channels with the CamScale in reference position (Fig. 3). All reported deviations were within manufacturer tolerance of 1 mm.

Source behavior verification inside a QA device

Dwell positions and interdwell distances (IDDs)

All reported uncertainties related to source positions are only from standard deviations over multiple measurements, the precision while tracking the source position is 0.1 mm for IDDs ranging from 1 to 30 mm and 0.5 mm for IDD of 100 mm. Good agreement was observed between measured and planned IDDs. Measured IDDs for planned IDDs of 1, 3, 5, 10, 20, 25, 30, and 100 mm were, respectively, 1.0 ± 0.1, 3.0 ± 0.1, 5.0 ± 0.1, 10.0 ± 0.1, 20.0 ± 0.1, 25.0 ± 0.1, 29.9 ± 0.2, and 99.3 ± 0.1 mm. The greater deviation between measured and planned IDDs for planned IDDs of 30 and 100 mm is due to greater experimental uncertainty as the high-speed camera field of view and, consequently, pixel size are increased.

When recording both dummy and source cable movements for a single planned dwell position 1 mm away from the tip, the measured position for the dummy cable was 0.9 ± 0.1 mm from the tip, whereas the source cable briefly (~0.1 s) overshoots the target position, stopping at 0.8 ± 0.1 mm and then moves to the dwell position 1.2 ± 0.1 mm from the tip. This behavior of the source cable was present for all plans evaluated and can be seen on Supplementary Video 3, which shows the source movement for a plan with IDD = 10 mm and planned dwell time of 1 s. This small deviation (~0.2 mm) for the first dwell position of the source cable shifts the remaining dwell positions, causing an average negative deviation from target positions, as shown in Fig. 4, where deviations are grouped by IDD for all the plans with dwell times of 1 s. All measured deviations from planned dwell positions are within the manufacturer tolerance of 1 mm.

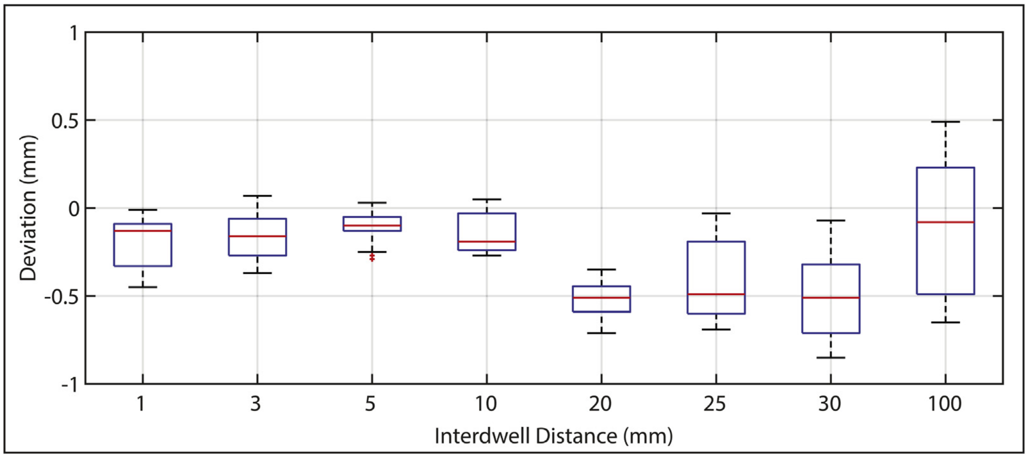

Fig. 4. Deviations between measured and planned absolute dwell positions related to the tip of the transparent QA device. Deviations (grouped by IDD) were obtained by comparison between high-speed camera measurements and the postirradiation report emitted by the afterloader. QA = quality assurance; IDD = interdwell distance.

The precision and accuracy of dwell positions for plans with offsets or distal corrections applied were evaluated with IDD of 5 mm, dwell time of 0.2 s, and flexible applicator settings. Results are shown in Table 3. All measurements showed a mean deviation from planned dwell positions below 0.35 mm, the maximum deviation was −0.49 mm and all dwell positions were within a range of 0.50 mm from planned positions. Deviations measured for the first dwell positions are equivalent to deviations for all dwell positions considering the uncertainties, indicating that dwell positions of the same plan were mostly shifted, but presented a small IDD variation. Deviations for plans with offsets or distal corrections applied are within the same range and according to manufacturer tolerances, resulting same practical effect.

Table 3
Deviation between measured and planned absolute dwell positions related to the tip of the transparent QA device for plans with IDD of 5 mm, dwell time of 0.2 s, flexible applicator settings with offset or distal corrections applied

	Deviation between measured and planned dwell positions Mean (range) (mm)	
Experimental settings	First dwell position	All dwell positions
Offset (mm)		
0	−0.22 (−0.35: 0.01)	−0.28 (−0.49: 0.01)
1	−0.15 (−0.31: 0.09)	−0.22 (−0.41: 0.09)
2	0.01 (−0.13: 0.09)	−0.07 (−0.35: 0.09)
4	−0.19 (−0.33: −0.01)	−0.27 (−0.47: −0.01)
10	−0.06 (−0.29: 0.07)	−0.09 (−0.33: 0.07)
Distal correction (mm)		
1	−0.26 (−0.31: −0.17)	−0.33 (−0.45: −0.17)
2	−0.12 (−0.19: −0.05)	−0.16 (−0.29: −0.05)
4	−0.20 (−0.25: −0.15)	−0.25 (−0.31: −0.15)
10	−0.08 (−0.13: −0.03)	−0.09 (−0.15: −0.03)

QA = quality assurance; IDD = interdwell distance.

Deviations for the first dwell position are highlighted in a separate column.

Measurements performed using the QA device for plans with rigid and flexible applicator settings did not affect IDD values, being 5.0 ± 0.1 mm in both cases. Nevertheless, the dwell positions were shifted because of deviations in the distal position. The mean deviation for the first dwell position was 0.1 ± 0.3 mm with rigid applicator settings and −0.2 ± 0.2 mm with flexible applicator settings. All deviations are within manufacturer tolerances. The shift in the dwell positions, however, is believed to be due to differences in length verification when a push test is performed for rigid applicators. Considering the uncertainties, these values are equivalent, nonetheless. Length verification deviations between rigid and flexible applicators are further discussed in the Section Source Behavior Verification Inside Clinical Applicators. A change in channel length due to temperature variations over multiple measurements was not detected experimentally at room temperature (23°C–26°C).

Transit time and dwell time evaluation

Measured transit time for the first dwell position was always equal or greater than the transit time for the remaining dwell positions (Table 4). Measured transit times were lower than minimum allowed dwell times for all cases evaluated, except for the first dwell position of plans with dwell times of 0.10 and 0.15 s, meaning that for these specific cases, the real dwell time will unavoidably exceed planned dwell times by at least 0.02 s.

Bravos system calculates the transit time considering a maximum region within 15 mm from the dwell position (see Appendix A), meaning that the transit time for IDDs greater than 30 mm or single dwell positions are considered the same, measured as 0.35 ± 0.05 s (Table 4). Doses measured by J. Jeong *et al.* (12) using the GammaMedplus iX afterloader for a single dwell position with and without transit dose resulted in an equivalent transit time of

Table 4
Minimum dwell time allowed by the Bravos system and measured transit time for the first and remaining dwell positions of plans with IDD ranging from 1 to 100 mm with first dwell position at the tip of the channel

IDD (mm)	Min. dwell time allowed (sec)	Transit time for the 1st dwell mean (range) (sec)	Transit time remaining dwells mean (range) (sec)
1	0.10	0.12 (0.11: 0.12)	0.03 (0.02: 0.04)
3	0.15	0.15 (0.14: 0.17)	0.08 (0.07: 0.10)
5	0.20	0.17 (0.17: 0.19)	0.11 (0.10: 0.13)
10	0.25	0.22 (0.21: 0.24)	0.19 (0.17: 0.20)
20	0.30	0.29 (0.28: 0.30)	0.27 (0.25: 0.30)
25	0.35	0.32 (0.31: 0.33)	0.32 (0.31: 0.33)
30	0.40	0.34 (0.33: 0.35)	0.34 (0.31: 0.36)
100	0.40	0.34 (0.33: 0.35)	0.34 (0.30: 0.40)

IDD = interdwell distance.

0.84 ± 0.09 s. Such correction was adopted by Bellezzo *et al*. (13) with good agreements. This difference in equivalent transit times is because J. Jeong *et al*. measurements considered the whole source path with the purpose of correcting the dose at one dwell position while the transit time considered by the Bravos system has the purpose of correcting the dose locally with minimum interference with the whole dose distribution.

Dwell times for the first dwell positions were also evaluated separately from the others because of the difference in transit time shown in Table 4. Good agreement between measured and reported dwell times was observed. Measured dwell times for the first dwell position were, on average, 0.01 s less than reported by the Bravos system (maximum deviation of 0.02 s) and 0.02 s greater than planned (maximum deviation of 0.07 s). For the remaining dwell positions, average deviations between planned, measured, and reported dwell times were lower than 0.01 s, with maximum deviation of 0.02 s between measured and reported dwell times, and 0.04 s between measured and planned.

The Bravos system not only detects when delivered dwell times are different than planned (dwell time accuracy of ±0.05 s (7)) but also compensates this difference by changing delivered dwell time for the closest dwell positions, aiming to achieve an average irradiation time according to plan. For the most critical case observed (IDD = 1 mm and 0.10 s dwell time), the delivered dwell time reported by the afterloader for the first dwell position was 0.09 s greater than planned; however, the next six dwell positions had a delivered dwell time lower than planned, making the average deviation from planned dwell times considering all dwell positions less than 0.001 s.

For plans in which transit time correction was disabled (only possible for test plans created using physics mode), the irradiation time unavoidably exceed the planned time, nevertheless, the mean difference between measured and reported dwell times was less than 0.001 s.

Speed profiles and acceleration

Speed profiles and acceleration were evaluated only for the source cable; the time required to perform dummy checks was not evaluated. The source cable moves in a similar fashion for the Bravos and GammaMedplus iX afterloaders; in a uniformly accelerated movement ($|a|$ measured as 152 ± 4 cm/s^2 for the Bravos and reported as 154 cm/s^2 (1) for the GammaMedplus iX) until reaching the mid-distance between dwell positions or achieving a maximum speed of 100 cm/s (2) for the Bravos system and 63 cm/s (1) for the GammaMedPlus iX. Bravos source acceleration is greater than reported for other afterloaders such as the Nucletron microSelectron v.3 (113 cm/s^2 (14)), Nucletron Oldelf (78 cm/s^2 (15)) and the GammaMed 12i (55 cm/s^2 (15)), although different values have been reported for identical afterloader models in different studies (not related to the Bravos afterloader), as summarized by Fonseca *et al*. (8, 16). Table 5 shows the maximum and average source speeds for different IDD for the Bravos afterloader. Results agree within combined uncertainties. Source speeds values for the Bravos afterloader are lower than measured by Fonseca *et al*. (8) for the Nucletron microSelectron v.3 afterloader and approximately twice as fast as measured by Wojcicka *et al*. (15) for the GammaMed 12i afterloader.

Source behavior verification inside clinical applicators

Cable snaking and first dwell position

The cable snaking effect caused when the source cable is curled inside the catheter when it is pushed against the end of the applicator is not present with the Bravos system due to the pretreatment length verification combined with the restriction of not having the first (most distal) dwell position closer than 1 mm to the tip of the applicator. The mean deviation from target position for the first dwell position considering all plans for rigid applicators without offset was 0.1 ± 0.3 mm, with maximum deviation of 0.6 mm

Table 5
Maximum and average source speed while moving between two consecutive dwell positions inside the QA device for IDD ranging from 1 to 100 mm

IDD (mm)	Average speed (cm/s) Measured	Average speed (cm/s) Calculated	Maximum speed (cm/s) Measured	Maximum speed (cm/s) Calculated
1	1.8 ± 0.2	1.9 ± 0.1	3.2 ± 0.4	3.9 ± 0.1
3	3.4 ± 0.2	3.4 ± 0.1	6.2 ± 0.3	6.7 ± 0.1
5	4.3 ± 0.2	4.4 ± 0.1	8.3 ± 0.5	8.7 ± 0.1
10	6.0 ± 0.3	6.2 ± 0.1	11.9 ± 0.4	12.3 ± 0.2
20	8.7 ± 0.3	8.7 ± 0.1	16.9 ± 0.4	17.4 ± 0.3
25	9.5 ± 0.5	9.8 ± 0.2	19.0 ± 0.4	19.0 ± 0.3
30	10.6 ± 0.4	10.7 ± 0.2	20.8 ± 0.8	21.3 ± 0.3
100	19.8 ± 0.4	19.5 ± 0.3	38.6 ± 0.6	39.0 ± 0.5

QA = quality assurance; IDD = interdwell distance.

Speeds were measured with a high-speed camera and calculated considering a uniformly accelerated movement with $|a|$ = (152 ± 4) cm/s^2.

Table 6
Average deviation between planned and measured dwell positions for the first (most distal) dwell position (results for IDD = 2, 5 and 10 mm combined) and for all dwell positions for a range of 45 mm starting at the tip of the applicator for IDDs of 2, 5 and 10 mm and a range of 20 mm for IDD of 1 mm

	Average deviation from target position mean (range) (mm)				
	First dwell position	All dwell positions			
Applicator	IDD = 2, 5, 10 mm	IDD = 1 mm[a]	IDD = 2 mm	IDD = 5 mm	IDD = 10 mm
Colpostat	0.2 (−0.1: 0.5)	−1.2 (−1.5: −0.4)	−0.3 (−1.0: 0.4)	−0.1 (−1.0: 0.7)	−0.3 (−0.9: 0.1)
Needle	0.1 (−0.2: 0.4)	0.1 (0.0: 0.3)	0.1 (−0.4: 0.7)	0.1 (−0.2: 0.6)	0.4 (0.1: 0.6)
Ring	−0.1 (−0.3: 0.1)	−2.5 (−3.2: −0.3)	−1.8 (−3.0: 0.1)	−1.6 (−2.6: 0.1)	−1.3 (−2.3: 0.1)
Tandem 15	0.2 (−0.1: 0.6)	−0.3 (−0.6: 0.5)	−0.6 (−1.0: 0.3)	−0.4 (−0.9: 0.5)	−0.1 (−0.6: 0.6)
Tandem 45	0.0 (−0.3: 0.3)	−0.8 (−1.1: −0.3)	−0.2 (−0.9: 0.3)	−0.1 (−0.8: 0.3)	−0.2 (−0.6: 0.2)
Tandem Ring	0.3 (−0.1: 0.5)	−0.4 (−0.7: −0.2)	0.2 (−0.5: 0.7)	0.3 (−0.4: 0.7)	0.2 (−0.3: 0.6)

IDD = interdwell distance.
[a] Evaluated range of 20 mm.

for 2% of the positions evaluated. Table 6 shows the average deviation from the first dwell position for each applicator evaluated.

Source path and IDD

For curved applicators, the source cable follows a longer path while moving from the afterloader to the first dwell position (following the outer wall of the channel) than while moving from the first dwell position to the remaining positions (following the inner wall of the channel). Only part of the retraction length causes a change in source position when the cable is retracted from distal dwell positions, while the remaining retraction length tightens the cable to a shorter path. The Bravos system extends the cable past the first dwell position to be able to tighten the cable when retracting it to the first dwell position. This correction may not be enough depending on the difference in path length of each applicator, resulting in shorter IDDs between first and second dwell positions. Such variations should be evaluated during applicator commissioning. Table 6 shows the average deviation from planned dwell position for the first 45 mm of each applicator evaluated for IDDs of 2, 5, and 10 mm, and the first 20 mm for IDD of 1 mm. For the 45 mm range, all applicators, except the ring, present an average deviation lower than 1.0 mm with local deviations of up to 1.0 mm for the Colpostat and Tandem 15 applicators. Deviations closer to the tip are highlighted for a 20 mm range and 1 mm IDD, resulting in average deviations greater than 1 mm for the Colpostat and Ring applicators, which are the two applicators with most accentuated curvatures.

Owing to its strong curvature, the ring applicator has average deviations from planned positions ranging from 1.3 to 2.5 mm, while the average deviations reported in

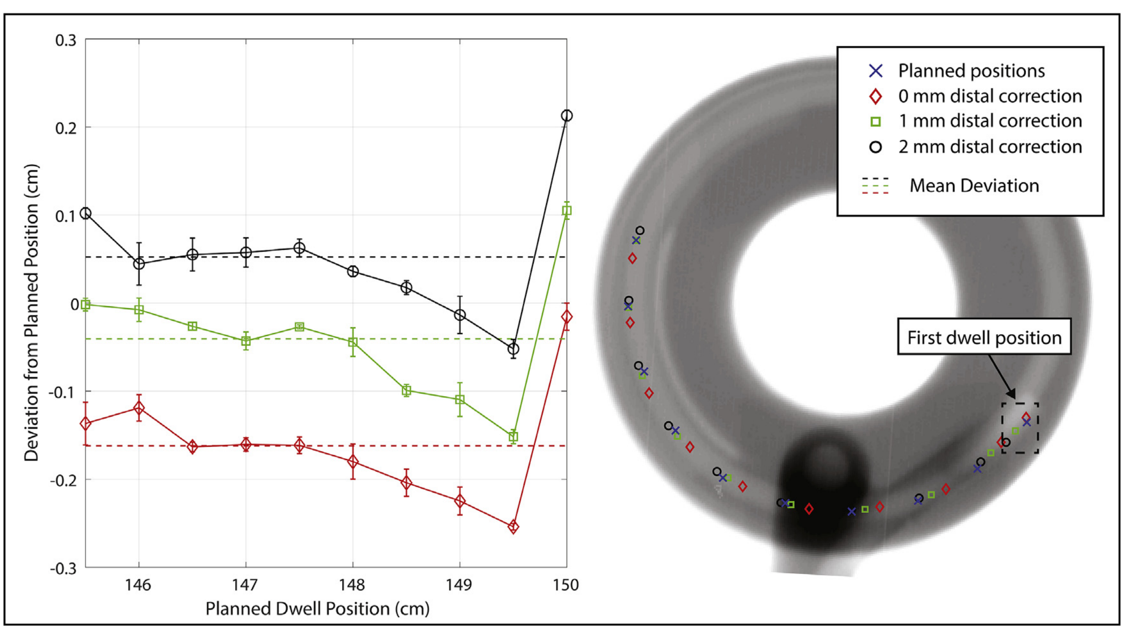

Fig. 5. Difference between planned and measured dwell positions for the ring applicator when distal corrections of 0, 1, and 2 mm are applied to shift the dwell positions and compensate for the smaller IDDs close to the end of the channel. Continuous lines show the deviation for each dwell position while dashed lines show the average deviation over a range of 45 mm. IDD = interdwell distance.

the literature are 2.5−4.5 mm (17, 18) when no offset correction is applied. The maximum local deviation found in this study was 3.2 mm. While deviations of up to 6.1 mm (also without offset correction) are reported by Awunor *et al*. (19), suggesting that the length verification feature of the Bravos system mitigates such deviations. Both local and average deviations can be reduced if dwell positions are purposely shifted from planned positions to compensate for the first few smaller IDDs, increasing the deviation for the distal position but reducing the deviation for the remaining ones. This effect can be achieved if a distal correction is applied during the pretreatment verification or by applying an offset to the original plan (see Fig. 5). For a plan with IDD of 5 mm, the initial deviation is −1.6 (−2.6: 0.1) mm (mean [range], from Table 6); however, this deviation changes to −0.4 (−1.6:1.2) mm if 1 mm of distal correction is applied and 0.5 (−0.6: 2.2) mm for 2 mm of distal correction.

Applying a distal correction on the ring applicator improves the average deviation from planned positions for the region evaluated. Nevertheless, the deviation between measured and planned dwell positions changes along the channel while the cable is not completely tightened, and different distal correction values may result in lower average deviation if different regions are evaluated. Considering the same IDD (5 mm) and dwell positions region (45 mm from the tip), distal corrections did not improve the average deviation from planned positions for the remaining applicators because all of them had an average deviation greater than −0.5 mm and the minimum distal correction possible is of 1 mm. A proper applicator commissioning is crucial to define the best protocol to be adopted for each applicator; however, this is out of the scope of this study.

Flexible vs. rigid applicator

The force threshold used to define the channel length for flexible applicators is lower than for rigid applicators to avoid damaging the tip of a flexible applicator. The lower force threshold can, however, interfere with the length verification of rigid applicator if they are wrongly defined as flexible. Such error would be detected during the commissioning of the applicators and the Bravos system warns the user if measured channel length is different than planned to mitigate human errors. Nevertheless, the choice between rigid and flexible applicator settings should be adopted with caution.

Conclusion

In conclusion, the Bravos system has several different features from its predecessor, the GammaMedplus iX, with the purpose of making the treatment workflow faster and less prone to human errors, which increase the system precision during treatment delivery, and consequently, patient safety. There are features designed specifically to avoid error that would result in a wrong dose distribution, for example, the length verification feature, that reduces the chances of using a wrong transfer tube, and the mechanically coded channels 1−3 that avoid switching channels for applicators such as the fletcher, and the mandatory pretreatment checklist (Table 1). It uses the same source as the GammaMedplus iX; however, with a greater top speed, which reduces transit dose and overall treatment time. Treatment time is also reduced by performing channel obstruction verification, once during the pretreatment stage and once during treatment instead of twice during treatment.

The CamScale device makes daily QA and system recalibration easier. Deviations from target position for the source cable were below 0.4 mm for all measurements performed when the CamScale was properly aligned with respect to the afterloader.

Measurements with a high-speed camera showed that the Bravos system can accurately report delivered dwell times and deviations from planned dwell times (if any) within its dwell time accuracy of 0.05 s. The maximum deviation between measured and planned dwell times was 0.07 s, which was automatically compensated by the system by correcting the dwell times for the next six dwell positions with IDD of 1 mm. Such correction resulted in an average delivered time as planned (deviation lower than 0.001 s) but with local variations.

Moreover, the possibility of defining applicators as rigid or flexible during a treatment plan allows the use of catheters in any of the channels. However, the choice between rigid and flexible applicator settings must follow the applicator specifications to avoid errors in length verification.

Features implemented in the Bravos system provide accurate dwell positions, such as the pretreatment length verification used to confirm that the correct transfer guide tube is used and to correct for small length fluctuations due to transfer guide tube curvatures, the source cable overshooting the first dwell position and then being retracted to reduce cable slack in curved applicators, and the possibility to apply pretreatment distal corrections. Nevertheless, such features are aimed to improve treatment delivery but not to replace a proper applicator commissioning.

Elfrink *et al*. (20) measured ± 1.0 mm source position accuracy for 16 HDR 192Ir afterloaders using straight applicators while the maximum and mean deviations measured in this work for a straight plastic needle were 0.7 and 0.1 mm, respectively. Rickey *et al*. (21) reported that bias in dwell time could be up to 0.08 s, which is greater than measured in this study. These references suggest that the Bravos system provides a lower uncertainty in treatment delivery than other HDR afterloaders. Other sources of uncertainty during a brachytherapy treatment are listed by Kirisits *et al*. (17).

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Supplementary data

Supplementary data to this article can be found online at https://dx.doi.org/10.1016/j.brachy.2019.06.005.

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