Time-resolved QA and brachytherapy applicator commissioning: Towards the clinical implementation

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ABSTRACT

PURPOSE: Brachytherapy has a busy workflow relying on manual steps to ensure accurate delivery of the treatment. Systematic treatment errors have been reported due to faulty equipment, inadequate quality assurance (QA) and applicator commissioning methods. This study describes the use of a novel method, the Iridium Imaging System for QA (IrIS – QA), to automate and improve the applicator commissioning for HDR ¹⁹²Ir brachytherapy.

METHODS AND MATERIALS: A 3D printed holder attached to an Imaging Panel (IP) has been developed to: (1) acquire a high-definition projection of the applicator using the gamma rays of the ¹⁹²Ir source for imaging; (2) Track the source within the applicator verifying in a time-resolved manner the dwell positions and dwell times with a high resolution. Results obtained for two applicator models are described in this manuscript.

RESULTS: IrIS-QA is capable of measuring the dwell times with an accuracy better than 0.1 s and interdwell distances with submillimetre precision. The applicators tested in the study showed good agreement between planned and delivered dwell times and positions, with mean and maximum dwell position deviations below 0.5 mm and 1.3 mm, respectively. Dwell time measurements showed agreement superior to 0.05 s except for the first dwell position for which up to 0.15 s differences were observed.

CONCLUSIONS: IrIS-QA is a compact system that includes many features necessary to improve the accuracy and efficiency of applicator commissioning and daily QA. No commercial system exists with similar capabilities. IrIS-QA is intended to replace current clinical procedures using film dosimetry. © 2021 Published by Elsevier Inc. on behalf of American Brachytherapy Society.

Keywords: Applicator commissioning; Imaging panel; Time-resolved QA

Introduction

Brachytherapy has an excellent patient outcome for different cancer treatment sites and can be applied as monotherapy or in combination with external beam techniques, quite often for dose escalation approaches.(1–4) Despite being a successful technique, several incidents have been reported with systematic errors affecting hundreds of patients, caused by faulty applicators and inadequate applicator commissioning.(5–7) A recently published ESTRO task group report on in vivo dosimetry (IVD) for brachytherapy described the importance of IVD in brachytherapy and the lack of commercial alternatives allowing the adoption of IVD by radiotherapy centers.(8) There are also limitations related to quality assurance (QA) and applicator commissioning that are mostly based on time-integrated film measurements requiring several manual and time-consuming steps.(9–14)

Film measurement for applicator QA is cumbersome and has several limitations. For example, the applicator is not visible on the films and measurements are often performed in relation to marks drawn manually. In addition, the time-integrated response of the film does not allow the measurement of short interdwell distances used in the clinic, due to the blurry nature of the film response. There-

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fore, measurements are commonly performed with 10 and 20 mm interdwell distances to obtain sufficiently widely spaced film spots. These measurements are then extrapolated to more realistic clinical scenarios with a minimum interdwell distance of 1 mm. (9,13) An intermittent error (source getting stuck within the applicator) has been reported (9) indicating the need for multiple measurements for each applicator. In addition, systematic errors affecting hundreds of patients were caused by improper applicator commissioning. (6,7)

Our group previously developed and validated a novel time-resolved method for applicator commissioning using an imaging panel (IP), for the first time using an HDR 192Ir source to produce a high definition image of the applicator. (9) Other groups have also developed some alternative solutions to film using time-resolved methods (15,16). Nevertheless, recently developed methods are restricted to research groups and, to the best of our knowledge, are not being used in the routine clinical workflow.

This manuscript describes a novel system, the Iridium Imaging System for QA (IrIS-QA), based on our previously developed method, that is currently undergoing tests in a clinical environment. 3D printing technology makes the design and manufacturing of precise and robust devices achievable at reasonable costs allowing the upscaling from a feasibility study (9) into a working prototype tested in the clinic environment. The system was completely re-designed including significant hardware (e.g., IP with a higher acquisition rate and image resolution) and software (e.g., more efficient detection methods and automatic consistency checks) improvements followed by extensive user tests. This study focuses on the refinements of the system, the clinical application, workflow and evaluation of two different applicators.

Methods and materials

The current applicator commissioning in our clinic uses an x-ray projection of the applicator acquired using a cone-beam CT (CBCT) image from a linear accelerator (LINAC, TrueBeam, Varian Medical Systems, Palo Alto, CA) with and without dummy cables to verify the distance between the tip of the applicator and the first dwell position and also to check mechanical integrity. Radiochromic films are then cut, marked (for alignment and reference since the applicator is not visible in the film) and attached to an applicator during the irradiation. The user has to enter the treatment room, replace the film and realign the system to repeat a measurement. The analyses of the data and preparation of a report are done manually. The workload (hours) is significant and limits the number of measurements per applicator. Film measurement is the standard applicator commissioning method in most clinics. (12,13)

IrIS-QA reduces the workload for applicator commissioning to minutes instead of hours, and largely automates the process. The time required to prepare the experimental setup and acquire images of the applicator prior to automatic post-imaging measurement of dwell times and positions varies between 15 and 30 min, depending on the experience of the user and the number of acquired images (e.g., additional images can be acquired with a dummy cable placed inside the applicator).

The measurement time depends on the number of dwell positions and dwell times in the treatment plan (the IrIS-QA system works with dwell times as short as 0.5 s). The time necessary to process the data automatically was reduced by processing the frames as soon as they are acquired. Therefore, a report is available right after the irradiation. The user can also repeat irradiations from the control room with IrIS-QA without re-entering the treatment room or heavily impacting the workload. The workflow using films and IrIS-QA is shown in Fig. 1.

IrIS-QA

Our previous study (9) used PMMA slabs and double-sided tape to create a holder and fix the applicator, which was adequate for an experimental proof of concept (Technology Readiness Level (TRL) 3). The system was completely redesigned (including 3D printed holders, markers, IP and software), as shown in this paper, to reach TRL 7 (“system prototype demonstration in an operational environment”). (17,18)

The developed system (Fig. 2) consists of two main components: (1) An IP model PAXSCAN 2530HE (Varox Imaging, Salt Lake City, UT) capable of acquiring up to 33 frames-per-second (fps) with a maximum pixel resolution of 0.139 mm; (2) A custom 3D printed holder with a gamma imaging channel (the 192Ir source is sent into this channel to create a projection of the applicator with emitted gamma rays), an applicator-specific holder and radiopaque markers used for automatic image registration and to ensure the correct operation of the system. Video 1 shows the components of the system and the proposed workflow.

Workflow

Preparation (CT acquisition and treatment plan)

IrIS-QA was developed to compare dwell positions and dwell times from measurements against reference plans created with a Treatment Planning System (TPS). Therefore, it is required to create a treatment plan prior to the applicator commissioning. First, a CT image of the applicator placed into the holder (Fig. 3) is acquired. Second, a TPS (BrachyVision version 16, Varian Medical Systems, Palo Alto, CA) is used to define the channels and create a treatment plan. The user should also create reference points in the TPS indicating the position of three reference markers (Fig. 3b) that will be used for automatic alignment. Finally, the treatment plan (DICOM format) is exported by the TPS and added to the IrIS-QA database. Note that this step needs to be done only once for each applicator.
Multiple applicators can be placed into the same holder to improve efficiency (Fig. 3).

**IrIS-QA – Imaging and irradiation**

The measurement setup is shown in Fig. 4a and Video 1. The first step of the measurement consists of the acquisition (with the source into the imaging channel) of a background image of the holder without the applicators (Fig. 4b). In-house developed software written in Matlab (The MathWorks, Inc., Natick, MA) automatically detects the radiopaque markers measuring the distance between them as an operational test of the IrIS-QA system. Once the background image is acquired, the operator places the applicators into the holder performing another image acquisition. The background image is then subtracted from the image with the applicators to improve image quality.

The software allows additional image acquisitions of dummy sources and markers into the applicator. All images acquired are automatically corrected to account for magnification effects. (9)

After acquiring images of the applicators, the treatment plan (including information about dwell positions, dwell time and the coordinates of at least three markers) is imported into IrIS-QA. The software will use the coordinates of the three markers defined in the TPS to automatically align the treatment plan with the holder position. Note that the applicators were placed into the same holder during CT acquisition (section Preparation (CT acquisition and treatment plan)) therefore all the markers visible in the IP image (Fig. 4b) are also visible in the CT image.

**IrIS-QA – Irradiation**

The final step consists of the treatment delivery by sending the source into the applicators consecutively. IrIS-QA analyses the data in parallel to the data acquisition so a report comparing measurement and planned dwell times and positions is available immediately after the irradiation. The measurement can be repeated multiple times from the control room. IrIS-QA generates individual reports (see the Supplementary Materials section for examples) but can also combine multiple measurements including mean, minimum, maximum and standard deviation values in the report.

**Panel calibration and QA**

An IP panel usually requires ghosting correction, use of sensitivity maps and a series of other corrections commonly obtained by measurements under controlled conditions. However, the developed method, as proposed in this
Fig. 2. Illustration of the IrIS-QA system and its main components. An animation is available in the supplementary materials. The ring applicator was used for illustrative purposes and was not evaluated in this study since results for this type of applicator were reported in a previous study. (9)

Fig. 3. (a) CT acquisition of the applicator in the 3D printed holder; (b) CT slice showing two different applicator channels (green lines) in their holder and dwell positions (green rectangles), (c) CT slice showing the markers (blue crosses) fixed to the holder and used for automatic alignment and operational tests.
paper for a specific IP, does not require any calibration. A background image acquired without the applicator is subtracted from the image with the applicator in place. This method is necessary to verify the marker position but also accounts for pixel sensitivity generating a sharp image of the applicator. In addition, the applicator is very close to the IP creating an intense and sharp peak (Videos 2 and 3) under the source position that can be easily identified using a mathematical fit (9,19).

The mechanical properties of the holder are essential for the operation of the system. Besides the verification of the position of the markers, already automated in the software, the user should also visually inspect the marker positions and mechanical integrity before the measurements.

Applicators

Two tandem applicators (one made of plastic (GM11001240) and another of aluminium (AL07522002)) were tested to evaluate the effect of the material on the image quality. A custom holder was 3D printed to fit both applicators tightly and ensure reproducibility. Measurements were repeated three times for each applicator (without repositioning) for interdwell distances of 1, 5 and 10 mm using a 1 s dwell time. Measurements were repeated once for each applicator with a 5 mm interdwell distance using 0.5 s dwell time. A reference plan for each case was created using BrachyVision version 16. All acquisitions were performed with 20 fps.

Verification

The IP response shows a high-intensity region representing the source position that can be overlaid with the image of the applicator allowing the visual inspection of the results (e.g., to check if the source moves within the channel and stops at the detected dwell positions – Videos 2 and 3). In addition, reference points defined in the TPS are visible on IrIS-QA and can be used as an additional geometrical check. Moreover, IrIS-QA exports the acquired images to a pdf file preserving the dimensions and allowing a direct comparison against film measurements, which are the current clinical state of the art. (13)

The planned dwell positions are imported from the TPS using IrIS-QA and overlaid to an image of the applicator acquired using the $^{192}$Ir source that is then printed as a template (regular A4 paper). A radiochromic film was placed on top of the printed page (Fig. 5a) used as a reference to align the applicator that was fixed using tape (Fig. 5b). A measurement was performed for the metal applicator and used for visual inspection, as an example. A comparison between dwell positions measured using an IP and films has been reported in a previous study and will not be repeated here. (19)

Results

Mechanical inspection

Figure 6 shows the gamma ray image of the plastic (a-b) and metal (c-d) tandem applicators without (a,c) and with dummy markers (b,d). The user interface allows the user to inspect the applicator (e.g., to identify cracks, burrs, wearing or other structural problems), check the dimensions and use the dummy markers to measure the distance between the tip of the applicator and the first dwell position.

A qualitative inspection of the images shows a similar image quality for both applicators with sharp edges and visible inner channels. Dummy markers are also visible for both plastic and metal applicators. IrIS-QA has image processing tools to further improve visualization.
Dwell position measurement

Figure 7 shows the result from one measurement for the metal (a) and plastic applicator (b). IrIS-QA imports the points defining the channel (green line) and dwell positions (red squares) from the TPS overlaying the reference data with the measured projection of the applicator. The registration of the TPS data and the IP image is performed automatically using reference markers (Fig. 3c and Fig. 4b). The black (first dwell position, close to tip of applicator) and white circles show the measured dwell positions. Figures are exported to the evaluation report including a reference scale.

The report generated by IrIS-QA (see Supplementary Materials) includes detailed information about each dwell position. From each measurement we extracted the mean, minimum and maximum deviations per applicator as shown in Table 1 (interdwell distances) and Table 2 (absolute distance from the planned position).

Dwell time measurement

The measured and planned dwell times differ by less than 0.05 s excluding first and last dwell positions. A maximum difference of 0.15 s was observed for the first dwell position that showed dwell times consistently higher than expected (differences between 0.05 and 0.15 s). Differences are attributed to the transit time that has been discussed in detail in a previous publication. (20,22)

 Verification against standard procedure with film

The visual inspection of the irradiated film and printed paper template from IrIS-QA (Fig. 8a) observed against
Fig. 7. An example of an IrIS-QA output showing reference information (channel (green) and dwell positions (red squares)) imported from the TPS compared against measured dwell positions (black (first dwell position) and white circles). The horizontal and vertical lines with dimensions indicated in red are exported by IrIS-QA whilst lines indicated with red arrows and black labels (Fig. 7b) were added using the measuring tool from Adobe Acrobat Pro DC version 2021.01.20145 confirming dimensions were preserved while generating the report in the pdf format.

Table 1
Interdwell distance

<table>
<thead>
<tr>
<th>Applicator</th>
<th>Number of dwell positions per irradiation</th>
<th>Planned interdwell distance (mm)</th>
<th>Mean deviation (1STD) (mm)</th>
<th>Min. (mm)</th>
<th>Max. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tandem (plastic)</td>
<td>60</td>
<td>1</td>
<td>0.0 (0.1)</td>
<td>-0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Tandem (metal)</td>
<td>60</td>
<td>1</td>
<td>0.0 (0.1)</td>
<td>-0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Tandem (plastic)</td>
<td>21</td>
<td>5</td>
<td>-0.1 (0.3)</td>
<td>-0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Tandem (metal)</td>
<td>21</td>
<td>5</td>
<td>0.0 (0.2)</td>
<td>-0.6</td>
<td>-0.2</td>
</tr>
<tr>
<td>Tandem (plastic)</td>
<td>11</td>
<td>10</td>
<td>-0.1 (0.5)</td>
<td>-1.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Tandem (metal)</td>
<td>11</td>
<td>10</td>
<td>0.0 (0.2)</td>
<td>-0.6</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Results correspond to measured minus planned values.

Table 2
Absolute distance from the tip following the channel trajectory (all values in mm)

<table>
<thead>
<tr>
<th>Applicator</th>
<th>Number of dwell positions per irradiation</th>
<th>Planned interdwell distance (mm)</th>
<th>Mean deviation (1STD) (mm)</th>
<th>Min. (mm)</th>
<th>Max. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tandem (plastic)</td>
<td>60</td>
<td>1</td>
<td>0.5 (0.4)</td>
<td>-0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Tandem (metal)</td>
<td>60</td>
<td>1</td>
<td>0.4 (0.4)</td>
<td>-0.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Tandem (plastic)</td>
<td>21</td>
<td>5</td>
<td>0.1 (0.5)</td>
<td>-0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Tandem (metal)</td>
<td>21</td>
<td>5</td>
<td>0.4 (0.4)</td>
<td>-0.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Tandem (plastic)</td>
<td>11</td>
<td>10</td>
<td>0.2 (0.5)</td>
<td>-0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Tandem (metal)</td>
<td>11</td>
<td>10</td>
<td>0.2 (0.3)</td>
<td>-0.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

a regular room light shows a good agreement between planned and measured dwell positions confirming the applicator image and treatment plan coordinate registration performed using IrIS-QA is consistent.

It is difficult to visualize planned and measured dwell positions in the digitized film image (Fig. 8a) since contrast is not optimal. Film and paper were also digitized and enhanced (contrast and colour adjustment) separately (Fig. 8b-c) and combined (Fig. 8d) to improve visualization.

Uncertainty estimation

The analysis of uncertainties is limited due to the lack of systems with comparable resolution. There are three main uncertainty components for the source position that are related to the detection of the source position in relation to the panel, projection of the applicator image, and registration with the TPS.

Dwell positions measured with an IP were compared against film measurements showing \(0.0 \pm 0.3 \text{ mm}\) (mean deviation \(\pm 1 \text{ STD}\)). (19) Dwell positions calculated for consecutive IP frames with the source in the same position show a standard deviation <0.2 mm. The standard deviation of consecutive measurements is <0.5 mm which includes afterloader and IrIS-QA uncertainties (not possible to distinguish the components).

IrIS-QA also corrects the magnification effect since the sensitive layer of the IP is 30 mm below the applicator. The method requires the source to be always at the same position while performing the image acquisition which is verified using radiopaque markers that indicate deviations.
≥1 mm (the afterloader does not allow shifts of less than 1 mm so smaller deviations could not be tested). As the imaging channel is approximately 300 mm above the applicator (10-fold the distance between the applicator and a sensitive layer of the panel), a 1 mm deviation in the source position during imaging would have a negligible impact.

The catheters and dwell positions imported from the TPS are registered using radiopaque markers whose positions are defined manually in the TPS, which is an additional source of uncertainty. Experience indicates that 0.5 mm misalignment can be identified by the user and the use of multiple markers reduces the registration uncertainty. However, this uncertainty component has not been quantified yet. The uncertainty components are described in Table 3.

The spatial resolution of the system (0.2 mm) is smaller than the afterloader reproducibility (1 mm) and applicator specification (2 mm tolerance). If additional uncertainty components related to imaging and registration are accounted for, the system uncertainty is approximately 0.6 mm which is consistent with the standard deviation of the measurements shown in Table 2 and less than half of the maximum deviation (1.3 mm).

Dwell time measurement uncertainties are less than 0.1 s (using an acquisition rate of 20 fps) with larger differences (up to 0.15 s) observed for the first dwell position due to transit time correction and the fact that the source slightly overshoots its intended position and retracts. 20,21,22 Although the IP allows for higher acquisition rates, the time resolution used in this study (0.05 s) is six times smaller than the smallest dwell time allowed in our clinic (0.3 s). In addition, results showed good agreement between measured and references values with maximum differences of the same order as the estimated uncertainty. The observed deviations are also consistent with the precision of the system (0.1 s) and transit time corrections 20,21.

### Discussion

The core of the IrIS-QA method (high-definition gamma ray image of the applicator using an HDR 192Ir source and source tracking using an IP) remains the same 9,
but considerable improvements were introduced to bring the system to the clinical test stage. A high precision robust holder with radiopaque markers was designed and 3D printed improving reproducibility. The markers, placed at known positions, are used to verify magnification corrections and as an operational check to verify IrIS-QA prior to each measurement.

Applicator-specific 3D printed holders were developed improving applicator fixation and reproducibility and allowing a fast exchange of applicators. Multiple applicators can be commissioned repeatedly in the same session. The dwell position and channel information from the TPS (CT reference – Fig. 3b), are imported in a different coordinate system than the applicator image (IP reference – Fig. 4b) and registered automatically removing inter-user variability. Acquisition parameters and software were further developed including imaging processing tools, reducing the processing time and the amount of stored data.

The panel, XRD 1640 AG9 ES (Perkin Elmer, Waltham, MA), used in our previous study (9) has a maximum acquisition rate of 7 fps, pixel resolution of 0.4 mm, weighs ≈25 kg and required an additional peripheral component connected to a desktop. A more suitable detector, PAXSCAN 2530HE, has been incorporated in this study into IrIS-QA with a much higher pixel resolution (0.139 mm resulting in a sharper image of the applicators including internal structures – Fig. 5), acquisition rates up to 33 fps. The IP can be connected to a regular laptop using an ethernet connection instead of a dedicated acquisition hardware that requires a desktop computer. In addition to improved specifications and accuracy, the system is now much lighter, (could be carried in a suitcase, improving storage and transportation. The sensitivity of an IP to detect errors has been reported in previous publications (9,19) and is therefore not included in this manuscript.

Conclusion

Applicator commissioning in brachytherapy has received limited attention despite the fact it caused systematic errors that affected hundreds of patients in the past. IrIS-QA provides a more efficient and accurate method than the current state-of-art film commissioning. It is a unique system that uses 192Ir gamma rays to acquire high-resolution images of the applicator and measures dwell positions with submillimetre accuracy with high temporal resolution. In addition, measurements are directly compared against treatment plans imported from a commercial TPS. The cost of such a system, including an IP, is a limiting factor. However, the method does not require disposable films and reduces the staff hours necessary to perform the measurements lowering operational costs.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.brachy.2021.08.003.

References


