Comprehensive external audit for HDR brachytherapy systems – the national experience

Irena Koniarova, Ivana Horakova and Helena Zackova
National Radiation Protection Institute, Bartoskova 28, 140 00 Prague, Czech Republic
irena.koniarova@suro.cz

Abstract. On-site audits in brachytherapy are performed for all HDR units after commissioning in the Czech Republic. Air-kerma strength, source positioning accuracy, dose calculation accuracy by treatment planning system, and reconstruction algorithm in terms of geometry accuracy are verified. Results obtained in 2003 – 2018 for 24 audited HDR brachytherapy sources are described in the paper. Weak points in HDR brachytherapy process are emphasized. The audited centres often failed in good knowledge of applicators, especially of needles with different blind tip lengths.

1. Introduction
Brachytherapy is an important modality for cancer treatment with radiation. Dose distribution around radioactive sources is not as easily measurable as in case of external beams due to the large dose gradients and a shortage of convenient detectors, therefore QA for HDR brachytherapy sources is challenging.

This paper describes design of the audit in the Czech Republic for brachytherapy systems and shows the results obtained in 2003 – 2018 for 24 audited brachytherapy sources. The audits were performed after commissioning and acceptance testing for all new installations with high dose rate Iridium-192 sealed sources. The aim of the audit is to minimize errors that could lead to accidents in radiotherapy. The licensing of radiotherapy centres by regulatory authority in the Czech Republic is based on the result of the audit.

2. Materials and methods
The aim of independent audits is to verify that system is ready for operation after installation. It is the last step in the process of commissioning and licensing in the Czech Republic. Following parameters are evaluated within the audit:

1) Accuracy of source calibration.
2) Accuracy and precision of source positioning.
3) Accuracy and precision of reconstruction process.
4) Accuracy of dose calculation by treatment planning system.

The choice of tested parameters arose from the analyses of radiological accidents in radiotherapy reported worldwide which were mainly caused by wrong distances and times during planning, failures in data input into the treatment planning system, incorrect applicator specification, poor performance by the unit [1]. Originally, larger tolerances were used for evaluation, but with more advanced
equipment and software algorithms their reduction was possible. Reduced tolerances after revision based on analysis reported here and on published values [2, 3, 4, 5] are stated.

2.1. Accuracy of source calibration
The air-kerma strength from the source certificate is usually used in the treatment planning systems in the Czech Republic. Air-kerma strength was verified by an in-air method as recommended by [4] and occasionally by well-type chamber. Well-type chamber is not a standard device for dosimetry in brachytherapy in the Czech Republic, because calibration coefficients of ionisation chambers need to be validated by Czech Metrology Institute (SSDL) biennially according to the law but there is not Ir-192 source available for calibration nor validation in SSDL. The in-air method is widely used but calibration coefficient of the chamber for Ir-192 is affected by the uncertainty caused by the procedure of interpolation between calibration coefficients obtained in qualities of Co-60 and of kV x-rays. The ionisation chamber of a Farmer type was placed into the calibration jig at geometry suitable for measurement (usually in 10 cm distance from the needles that are placed opposite but symmetrically in relation to the chamber position). The air-kerma strength was calculated from the audit measurement [4, 5] and compared to air-kerma strength declared at the source certificate and air-kerma strength from acceptance testing. 24 audits were measured with in-air method of which 7 were measured with well-type chamber for comparison purposes. The well-type chamber was calibrated in PTW, Germany. The aim to measure with an in-air method and a well-type chamber alongside was to compare two different methodologies. The tolerance of 3% was used.

2.2. Accuracy and precision of source positioning
The physicist from audited centre were asked to use all types of catheters that were planned to be used at clinic. The most frequent were short and long needles, probe for vaginal cylinder, ovoid probe, and tandem probe. The catheters were then placed on the piece of the film (EBT3) and their tips were aligned with the film edge. The geometry was fixed with plasters. Auditor specified 3 source positions per applicator by the distances from the tip and the physicist was supposed to prepare the plan to send the source to the required positions. Dwell times were chosen to achieve satisfactory signal on the film. The agreement between asked and obtained positions was evaluated with the tolerance of 2 mm.

2.3. Accuracy and precision of reconstruction process
Imaging method can be a source of geometrical error, especially when 2D planning is being used. The phantom with 13 radio-opaque markers of geometry specified by vendor in PMMA cube was used for verification. The audited centre was supposed to obtain images used for planning (2D or 3D) by standard imaging technique. The physicist from audited centre than identified all the markers on images in the treatment planning system and aligned reference points with the markers. Coordinate system had the origin at the centre of the phantom and coordinates for all points calculated by treatment planning system were compared to known coordinates given by phantom manufacturer. Two levels of tolerances were used: lower for points closer than 2 cm from the phantom centre (tolerance of 3 mm) and higher for points at 5 cm distance from the phantom centre (tolerance of 5 mm).

2.4. Accuracy of TPS calculation
Monte Carlo data from TG-43 [6] have been used for analytical model as an independent tool to verify accuracy of dose calculation by TPS. The dose calculated by treatment planning system was verified in 6 points in different angles and distances from the source, including the point in the longitudinal axis of the source where the anisotropy correction was highest (see Figure 1). First, the local physicist prepared the plan with one source position with 1 Gy prescribed to the point A and reported the doses in other points. Later, the normalization was changed to achieve 1 Gy at each particular point and dwell times were reported for each point with 1 Gy prescription. Because not only doses but also times were reported, accuracy of the air-kerma strength $S_k$ in the treatment planning system was verified.
The doses and times calculated by treatment planning system should agree with independent dose calculation within 2% in points A-D and 3% in points E-F.

Figure 1. Position of points used for verification of dose calculation by treatment planning system (not in scale). Coordinates in cm of points are as follows for coordinate system origin placed at the source centre: A (0,-2), B(0,-5), C(-2, -2), D(2, -5), E(-3, 0), F(-3, 0.5).

3. Results

3.1. Accuracy of source calibration
Dosimetry results are stated in Table 1 in terms of ratios between measured and certificate values of air-kerma strength. The comparison has also been performed between audit value and acceptance test value, where the mean ratio was 1.000 with standard deviation of 0.013 (k = 1).

Table 1. Ratios of measured to source certificate air-kerma strength and to acceptance testing values.

| N = 24 audits | Certificate | Acceptance test |
|---------------|-------------|-----------------|
|               | In-air Farmer chamber | Well-type chamber\(^a\) | In-air Farmer chamber | Well-type chamber\(^a\) |
| Mean ratio    | 0.989       | 0.991           | 1.000       | 0.989       |
| Standard deviation\(^b\) | 0.013       | 0.016           | 1.013       | 1.015       |
| Min ratio     | 0.957       | 0.972           | 0.977       | 0.963       |
| Max ratio     | 1.006       | 1.011           | 1.025       | 1.006       |

\(^a\) Well-type chamber has only been used in 7 cases.
\(^b\) Standard deviation expressed for k = 1.
3.2. Accuracy and precision of source positioning

All types of used catheters were intended for the test at the department. In all cases, positions in needles were verified except one centre, where only vaginal cylinders were intended to be clinically used (therefore only vaginal probe was checked at this centre). Very often, needles were the most problematic. Difficulties were also found at centres, where different system from previous one was installed, especially when the first source position was considered from the opposite side of the applicator (i.e. change from Gammamed unit to Flexitron unit and vice versa). See Table 2 for results where statistical analysis from maximum deviations is shown.

| Deviation | Mean deviation (mm) | Standard deviation (mm) | Min deviation (mm) | Max deviation (mm) |
|-----------|---------------------|-------------------------|-------------------|-------------------|
| N = 24 audits | 1.5 | 0.5 | 1.0 | 11.0b |

* Standard deviation is expressed for k = 1.

b Maximum value was excluded from statistic calculations.

3.3. Accuracy and precision of reconstruction process

In two cases, the verification of reconstruction process could not be performed due to unavailability of treatment planning system. In Table 3, results obtained from reconstruction based on C-arm images are shown. The maximum deviation of 14.1 mm was found for C-arm with a very small field of view.

| Distance from the phantom origin (mm) | < 20 mm | > 20 mm |
|--------------------------------------|--------|--------|
| Mean deviation (mm) | 1.9 | 4.5 |
| Min deviation (mm) | 0.5 | 1.5 |
| Max deviation (mm) | 4.3 | 14.1a |

This value was excluded from statistical analysis so was not included in the calculation of the mean deviation.

3.4. Accuracy of TPS calculation

In Table 4, ratios of doses planned by treatment planning system to doses calculated from reference dosimetry parameters for source models used in brachytherapy [6] are shown. At one centre, TPS was not available - the centre only intended to use pre-planned applications with vaginal cylinders. In 4 other cases the test was not performed, because it was the case of repeated audit when there was not any change in TPS configuration since the last audit. The maximum and minimum for ratios of planned to reference dose relate to the old type of TPS which is no more available. Calculated doses were in tolerance for all contemporary treatment planning systems.
4. Discussion

In the case that the result was out of tolerance, investigation was always accomplished to reveal the cause of an error and to enhance the result. If relevant, improvement or recommendations was given to be applied to keep deviation as small as possible. We do not expect to exceed tolerance levels with well-established systems at radiotherapy centres.

4.1. Accuracy of source calibration

The agreement between measured and reference air-kerma strength was good despite different methodologies of measurement. In-air method was in agreement with well type chamber measurement. There were not serious problems with this parameter except one case when audit revealed wrong value of air-kerma strength in the source certificate. Although measured value from acceptance test is not used in the treatment planning systems, incorrect application of methodology was found in several cases especially in terms of incorrect calibration of Farmer chamber for the in-air method, so the audit helped to improve accuracy of measurements.

4.2. Accuracy and precision of source positioning

Often the test had to be repeated during the audit because after the first attempt the source was in the wrong position. The biggest problems were usually with needles because of different blind tip lengths. Problems were often found in centres where new system replaced the previous one with a different coordinate system. This part of audit is usually the most confusing and time consuming. In one case, alarming deviation of 11 mm was found. It was caused by coincidence of more contributing factors. The local physicist did not know the needle geometry and calculated with wrong needle blind tip length. The distance was calculated manually with mistake, because with previous system, the first source position was at zero coordinate, but zero coordinate was at the applicator connector with the new system. Local physicist was not familiar with a new way of source distance calculation and did not pay attention to all these aspects before. It refers to an interesting aspect when physicist who feel experienced with brachytherapy in general might underestimate the characteristics of new systems.

4.3. Accuracy and precision of reconstruction process

In several cases, tolerance was exceeded due to the wrong geometry configuration of the reconstruction jig in the treatment planning system. In one case, left-right orientation was incorrectly set as right-left in the TPS. When field of view of C-arm was too small, large deviations out of tolerance appeared for points in larger distances from the origin. However, it is expected that replacement of 2D brachytherapy planning with 3D imaging could reduce deviations in reconstruction process.

4.4. Accuracy of TPS calculation

Although Monte Carlo data for functions used in TG-43 formalism are easily achievable, it is complicated to perform independent verification of 2D maps because lots of treatment planning

| Table 4. Ratios of planned to reference [6] doses calculated independently by TG-43 algorithm. |
|---------------------------------------------------------------|
| **N = 19 audits** | Points A-D | Points E-F |
| Mean ratio | 1.015 | 0.000 |
| Standard deviation* | 0.014 | 0.015 |
| Min ratio | 0.973 | 0.961 |
| Max ratio | 1.051 | 1.035 |

*Standard deviation is expressed for k = 1.
systems for brachytherapy are unable to export dose maps. Comparison for audit purposes is therefore still point based. There were not found any serious problems with TPS configuration neither for points in longitudinal axis of source where anisotropy correction was largest. The reason of this high precision is that dose calculation algorithms in treatment planning systems are usually TG-43 based as is the independent tool for verification. The test therefore verifies only the values of functions in the TG-43 formula and their correct input in the treatment planning system.

5. Conclusion
Analysis of results from 24 brachytherapy audits have been performed and the weakest points in QA of HDR sources for brachytherapy observed in last 15 years were reported. In spite of the rapid technological progress and implementation of advanced methods, basic geometrical problems were observed more frequently than struggling with software setup and dosimetry. The analyses revealed that the commissioning of applicators is often not sufficient. It has been noticed that in some centres, physicists had no experience with new C-arms (orientation of images), data transfer between C-arm and treatment planning system, and data processing (reconstruction). The worst scenario was at centres transferring from systems of one vendor to another. Physicists who have the previous experience with brachytherapy can feel inappropriately self-confident and disregard differences between the old and the new system.

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Acknowledgements
This work has been supported by the Ministry of the Interior of the Czech Republic, project No. MV-25972-2/OBV-2012/2018.