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Review Article

Novel methodologies for dosimetry audits: Adapting to advanced radiotherapy techniques

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ABSTRACT

With new radiotherapy techniques, treatment delivery is becoming more complex and accordingly, these treatment techniques require dosimetry audits to test advanced aspects of the delivery to ensure best practice and safe patient treatment.

This review of novel methodologies for dosimetry audits for advanced radiotherapy techniques includes recent developments and future techniques to be applied in dosimetry audits. Phantom-based methods (i.e. phantom-detector combinations) including independent audit equipment and local measurement equipment as well as phantom-less methods (i.e. portal dosimetry, transmission detectors and log files) are presented and discussed. Methodologies for both conventional linear accelerator (linacs) and new types of delivery units, i.e. Tomotherapy, stereotactic devices and MR-linacs, are reviewed.

Novel dosimetry audit techniques such as portal dosimetry or log file evaluation have the potential to allow parallel auditing (i.e. performing an audit at multiple institutions at the same time), automation of data analysis and evaluation of multiple steps of the radiotherapy treatment chain. These methods could also significantly reduce the time needed for audit and increase the information gained. However, to maximise the potential, further development and harmonisation of dosimetry audit techniques are required before these novel methodologies can be applied.

1. Introduction

Dosimetry audits are widely known to be an important tool in verification of treatment planning system (TPS) modelling and treatment delivery, as well as to facilitate and support the safe implementation of new techniques and technology [1–7]. National and large scale dosimetry audits are able to set, maintain and improve standards as well as the accuracy of dosimetry in many centres over time [2,7–9].

Various frameworks provide dosimetry audits, including the International Atomic Energy Agency (IAEA) [10], the European Organisation for the Research and Treatment of Cancer (EORTC) [11,12], the Imaging and Radiology Oncologic Core (IROC, previously the Radiological Physics Centre (RPC), Houston, TX, USA) [5,13], the Trans-Tasman Radiation Oncology Group [14], the UK Radiotherapy Trials Quality Assurance Group (RTTQA) [2,15] and the Radiation Therapy Study Group (RTSG) of the Japan Clinical Oncology Group (JCOG) [16]. The Global Clinical Trials Quality Assurance of Radiation Therapy Harmonisation Group (GHG) aims at harmonising and improving the quality assurance (QA) for radiation therapy within multi-institutional clinical trials [17,18]. In addition to these frameworks and according to the IAEA Dosimetry Audit Network (DAN), 45 organizations in 39 countries operated dosimetry audit services for radiotherapy in 2017 [19]. However, dosimetry audits are often carried out on a voluntary basis and not all audit activities are published.

Several dosimetry audit procedures are used worldwide, including postal audits of reference beam calibration and on-site visits aiming to investigate advanced radiotherapy techniques [11,20–23] with these being carried out as peer-to-peer or by central review. As diversity and complexity in radiotherapy increase, there is a need for new methods in dosimetry audits and strategic auditing is required. Thus, audit design needs to focus on multi-functional approaches to ensure efficient performance analysis, detection and identification of delivery errors that may exist. Furthermore, the most complex radiation delivery

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techniques require audits to test extra aspects of the delivery to ensure best practice and safe patient treatment [7]. With these new techniques, dosimetry audits are becoming more resource expensive and strategies that streamline and increase efficiency are needed to focus audits on issues which have the most impact on the clinical outcome for the patient [2].

This review gives an overview of novel developments and future methods in dosimetry audits including phantom-based and phantomless approaches.

2. Search strategy

A comprehensive search strategy through the indexed database 'Pubmed' was performed using search terms that included 'radiation therapy' and 'audit', 'multicentre', 'dosimetry', 'quality assurance', 'intercomparison' and 'credentialing'. Relevant papers and cited references in these papers published in English between 2010 and 2018 were included.

3. Phantom based methods for dosimetry audits

End-to-end audits typically use physical phantoms which pass through the entire radiotherapy chain. Generally the local staff scan the phantom and then generate a treatment plan based on predefined planning objectives. The treatment plan is delivered to the phantom filled with 1D (i.e. thermoluminescent dosimeters (TLD), optically stimulated luminescence (OSL) detectors, alanine pellets) or 2D detectors (eg. radiochromic films). The phantom and the detectors are then sent to, or taken by the audit coordinator for evaluation. However, methodologies have also been developed where a CT dataset with a set of planning structures is provided (virtual phantom) for direct planning [24–26], avoiding the CT scan step. The plan is then copied to the image dataset of a phantom, which is used for dose measurements.

Dosimetry audits can be performed using either local measurement equipment or with independent equipment. Both approaches have been used for dosimetry audits and are discussed in the following sections.

3.1. Independent systems

Independent auditing systems offer the advantage of being independent of the equipment used in each centre and they increase homogeneity between the measurements performed in different centres. Additionally, all irradiation results can also be processed, analysed and evaluated in a consistent manner [21,27]. Audits with independent audit equipment can either be performed by on-site visits or via post.

While postal audits are easier to schedule for the participating centre, the consistency of procedure might be diminished due to the interpretation of instructions [28]. Outliers measured during a postal audit may be caused by user errors, for example setup errors using conventional dosimetry audit detectors (film, TLD or OSL detectors). Other potential difficulties might be file transfer to central review software or potential damage to the equipment during shipping. While there is no published evaluation of damage that happened, these issues should be mitigated by on-site audits. On-site audits, on the other hand, offer increased consistency and precision, but they are significantly more costly, labour and time intensive than remote or postal auditing since they require not only phantom and transportation costs but also audit staff [2].

3.1.1. Conventional linacs

For on-site audits, commercial phantoms and array combinations have been investigated recently; mainly for volumetric modulated arc therapy (VMAT) auditing with virtual phantom planning exercises in several multi-institutional studies [24–26,29–31], see Tables 1 and 2. Detector arrays offer advantages over conventional methods such as film dosimetry, point detectors or ion chambers because they give an online 2D or 3D dose result [24,26] and measurements can easily be repeated in case of failure, thus being convenient to track any discrepancies while the audit team is still on-site.

Hussein et al. [24] compared 2D array measurements with individual ionisation chambers, film and alanine pellet measurements. Results of this UK VMAT audit [24] showed good agreement between 2D array measurements and the conventional ionisation chamber and alanine measurements with a mean difference of $-1.1 \pm 1.1\%$ and $-0.8 \pm 1.1\%$, respectively. Several authors have suggested that using a commercial detector array for a dosimetry audit of rotational radiotherapy is suitable instead of conventional dosimetry audit systems [24–26,31–32]. However, it should be recognised that any array of detectors has a fixed geometry, finite detector spacing and size as well as finite temporal resolution that can limit the achievable accuracy and precision during dosimetry audits [33–36]. Fredh et al. [36] investigated the sensitivity of error detection for four different QA systems in a comparative study and found considerable variation in the type of errors that the various systems detected. For example, when using 2% and 2 mm criteria and a pass rate of 95%, one array device detected 15 of 20 errors, while other arrays detected 8 of 20 errors, and the portal dosimetry system found 20 of 20 errors. They reported that different measurement systems tended toward identifying errors with varying degrees of sensitivity, suggesting that using multiple systems might be marginally beneficial. Moreover, poor correlation between gamma evaluation and comparison of DVH has been discussed by several authors [33–37]. In addition, non-anthropomorphic phantoms can jeopardise the detection of discrepancies between planning and delivery related to inaccuracies in dose calculation in heterogeneous/non regular geometries [38].

Therefore, limitations of detector arrays must be carefully taken into account when implementing them in dosimetry audits. Nevertheless, they have proved to be suitable for auditing complex delivery techniques such as IMRT and VMAT and play an important role for novel treatment techniques that require temporally resolved dosimetric measurements.

In a recent multicentre dosimetry audit, motion management in terms of phantom/patient movement has also been taken into account [39]. Palmer et al. [39] reported an end-to-end dosimetry audit using films inserted into a respiratory motion lung-phantom for both static and moving phantom measurements in 12 radiotherapy centres (Table 2).

3.1.2. Tomotherapy

For Tomotherapy systems, output check verifications have been performed in independent remote audits for TG 51 noncompliant photon beams using special TLD phantoms to audit beam calibration [13]. The Japanese Clinical Oncology Group (JCOG) have conducted an on-site audit for dosimetry credentialing of IMRT techniques including Tomotherapy [40]. They performed chamber and film dosimetry using an in-house developed phantom. Clark et al. [26] included Tomotherapy systems in their multi-institutional dosimetry audit for rotational IMRT performing a virtual phantom planning exercise (3DTPS test). The results of these audits are included in Table 2.

3.1.3. Stereotactic units

For stereotactic techniques the key areas of interest in the dosimetry audit lie in the accuracy of the small field and potential FFF modelling, as well as the targeting accuracy. Stereotactic Body Radiotherapy (SBRT) and Stereotactic Radiosurgery (SRS) dosimetry audits have been performed by means of measurements in anthropomorphic phantoms [41–44]. Audit results are included in Table 2.

Dosimetry audits for stereotactic techniques that verify TPS modelling of small MLC-shaped fields are challenging and require high quality methods. Recently, the IAEA has developed a solid slab phantom with heterogeneities containing special measurement inserts for TLD and radiochromic films [10]. The phantom and the audit

Table 1
Results of studies comparing independent audit equipment results with local QA measurements (IC = ionisation chamber).

Reference	Dosimeter	Independent audit phantom	Treatment technique	Gamma/TLD criteria	Pass-rates Local QA equipment	Pass-rates Independent equipment
Kry et al. [27]	Gafchromic film, TLD	IROC Houston's IMRT head and neck phantom	IMRT	90% pass rate 3%/3 mm	99,4%	86%
Weber et al. [12]	TLD, radiochromic film, planar array portal dosimetry	anthropomorphic head phantom, virtual planning phantom	IMRT	> 90% pass rate 3%/3 mm	75%	17%
				5%/5 mm	100%	92%
				7%/4 mm	100%	100%
Jornet et al. [25]	Planar array, film, portal dosimetry	MapPHAN phantom	IMRT	Global gamma > 95% for 3%/3 mm	98% prostate case	97% prostate case
				Global gamma	98,3% HN case	96,3% HN case
Jurado-Bruggemann et al. [31]	planar array, IC	ARCCHECK	VMAT	> 95% for 3%/3 mm Global gamma	100%	100%

methodology have been tested in multi-centre studies and found to be adequate and feasible for meeting the audit objectives. Other dosimetry audit approaches have focused on verifying the beam output for small fields [45], see Table 2.

The EORTC has launched the EORTC 22113-08113 Lungtech trial to assess safety and efficacy of SBRT for centrally located NSCLC [41]. They have developed a comprehensive RTQA program for trials involving modern lung radiotherapy including 4D imaging that will soon be implemented for auditing.

3.1.4. MR-linac

MR linacs have become clinically available recently and dosimetry equipment is being investigated for compliance in a magnetic field. For MR-linacs, published data on dosimetry audits is not yet available, so this section discusses non-implemented dosimetry techniques only.

Two kinds of audits should be considered for future audits: one is an independent verification of the dosimetry which would ideally take place post commissioning and pre-clinical. Performing such an audit before clinical implementation is particularly important because not many systems are clinical yet and experience is limited. The equipment used here needs to be MR-compatible.

The other kind of dosimetry audit would be for credentialing to join a trial (eg. an adaptive one) and where some, but not all centres may use MR- linacs. In this case the equipment used in the independent audit needs to be compatible with all types of treatment delivery systems.

3.2. Local QA systems

3.2.1. Conventional linacs

By using local phantoms that are used by the centre for routine pre-

Table 2
Audit results for advanced radiotherapy techniques (IMRT, VMAT, Tomotherapy, stereotactic body radiotherapy (SBRT) and stereotactic radiosurgery (SRS)). IC = ionisation chamber; DD = dose difference.

Reference	Audited systems	Treatment technique	Dosimeter	Phantom	Dosimetric/Gamma Criteria	Results/success rate
Clark et al. [26]	43	VMAT, Tomotherapy	Planar array	Commercial phantom	> 95% for 3%/3 mm global gamma	Test plan: 79,1% Clinical plan: 97,6%
Schiefer et al. [48]	20	Tomotherapy	TLD, IC	Cylindrical Perspex phantom	< 5% DD	100%
					< 3% DD	93,3%
Lafond et al. [23]	13	IMRT, VMAT	IC, film	Commercial phantom		IC dose within 3%
					> 95% for 5%/3 mm	Sag/cor plane 100%/100%
					3%3 mm Local gamma	80%/93%
Palmer et al. [39]	12	Conformal, IMRT, VMAT	film	Respiratory motion lung-phantom	3%2 mm Global gamma	Static phantom: 98,7% Moving-phantom: 88,2%
Miri et al. [79]	6	IMRT, VMAT	Portal dosimetry	none		3 Varian/3 Elekta
					3%/3 mm	99.5%/99.7%
					3%,/2 mm	98.9%/97.8%
					2%/2 mm	95.9%/95.3%
Nakamura et al. [40]	44	IMRT, VMAT, Tomotherapy	IC, film	In-house developed phantom	IC: < 3% DD	100%
					Film: < 2 mm positional difference	100% (1,0 ± 0,4 mm)
Espinosa et al. [45]	14	IMRT, SRS	TLD	Cylindrical PMMA phantom	< 5% DD	1 × 1 cm^2: 69%
						3 × 3 cm^2: 64%
Izewska et al. [10]	9	IMRT Small MLC fields	TLD, film	solid slab phantom with heterogeneities	TLD: < 3% DD	97%
					TLD: < 5% DD	100%
					Film: < 3 mm	64%
Distefano et al. [42]	27	SBRT Lung (VMAT, Cyberknife, Conformal)	Alanine pellets, film	anthropomorphic thorax phantom	Alanine: < 3%DD	92,6%
					Film: < 3% DD	55,6%
					3%/2 mm local gamma	80,1%
Dimitriadis et al. [43]	n/a	Cranial radiosurgery	IC, alanine pellets, film, PSD	anthropomorphic head phantom	DD PSD & alanine	< 0,4%
					Film: 2%/2 mm global	> 93,2%

treatment QA, the handling of unfamiliar equipment by medical physicists, who are less experienced with its set-up, can be avoided and potential set-up errors are thus reduced. Also, time consuming on-site visits and expensive mailing of audit phantoms are not required.

While the approach of using local pre-treatment verification methods is convenient and easy to apply, data shows that local QA measurements do not necessarily correlate with external audit phantom measurements [12,25,27,31,37,46]. These discrepancies can be due to different sensitivities and limitations of each QA equipment, as well as to differences in their evaluation software. Table 1 summarises studies comparing independent and local QA equipment for dosimetry audits. Several weaknesses of using local QA methods for auditing make this approach problematic and cause differences in results when compared to independent audit QA measurements: QA measurement accuracy of each institution with respect to their phantom and measurement procedure is unknown; the QA systems have unequal sensitivities to detect errors due to different implementations; gamma analysis is very sensitive to using different measurement devices and software settings such as normalisation and dose-threshold [12,25,27,37].

These differences can be partially mitigated by providing standardised guidelines to the participating centres. At the same time, the heterogeneity of data analysis methods could be overcome by submitting the institutions' own measurement data to be evaluated centrally and independently, however, data submission and data transfer issues increase the complexity of that approach [11,12]. Further, potential errors during the implementation of IMRT may remain undetected if the same method is used for both pre-treatment verification and TPS modelling [25]. These findings raise several concerns about local QA methods that need to be improved and highlight the importance of independent audit methods.

Overall, individual local QA equipment is not recommended for auditing [25,27]. However, the concerns about using local QA equipment have to be weighed against the costs, efficiency and severity of errors that should be detected. Ideally, an auditing system should be completely independent and standardised, and this needs to be considered when developing an auditing procedure.

3.2.2. Tomotherapy

For general dosimetric QA, Tomotherapy systems provide a set of standard treatment plans and a standard cylindrical solid water phantom [47]. Schiefer et al. [48] have designed and implemented a phantom-based TLD dose intercomparison for Tomotherapy, applying the standard calibration plans for the TomoHelical and TomoDirect irradiation techniques. These plans were tested at 20 Tomotherapy systems in Germany and Switzerland using a phantom provided by the Tomotherapy manufacturer and a small Perspex cylinder phantom (Table 2). In this case, the local measurement equipment is the same for all participants, therefore the authors concluded that this local phantom-based set up is appropriate and accurate for Tomotherapy dosimetry audits.

3.2.3. Stereotactic units

Various pre-treatment verification methods are applied for stereotactic radiotherapy, such as film dosimetry [49], 2D or 3D dosimetry [50–52]. Dosimetry audits using local QA equipment have not yet been performed for stereotactic units. It can be assumed that similar limitations as reported for conventional linacs [12,25,27,31,37] can be expected if different systems are used for auditing.

3.2.4. MR-linac

Several vendors provide an MR-compatible version of their measurement equipment that offers similar functionalities to conventional dosimetric tools, such as 2D arrays [53–55] and 3D dosimeters [56]. These measurement devices will soon provide similar 2D, 3D and 4D dose information as for the conventional pre-treatment QA systems. The potential application of these tools for dosimetry audits needs to be investigated.

3.3. Phantom-based methods for future dosimetry audits

3.3.1. Conventional and MR- linacs

In this section, methods which have not yet been used for dosimetry audits are discussed. Until now most phantom-based dosimetry audits have compared 1D or 2D dose measurements with dose calculations using dose differences or gamma evaluation. The major limitation of gamma evaluation (true for both phantom-based and phantom-less methods) is that there is no quantification of the clinical impact of the gamma deviations, i.e., their effect on target volumes and OARs [37]. Furthermore, passing rates have been shown to not correlate well with dose errors in anatomic regions-of-interest, and therefore the predictive power of gamma analysis for QA of patient outcome is limited [33–36]. Despite these limitations gamma analysis is a widely-accepted approach for quantitative comparison of 2D dose distributions and is commonly used in both treatment plan verification and dosimetry audits. However, other methods must be considered in the future for evaluating 3D dose distributions. 3D dose reconstructions based on 2D measurements can offer a more comprehensive and intuitive dosimetric evaluation. Phantom-based 3D dosimetry is based on the ability of 2D dose measurement systems to calculate or reconstruct (rather than measure) 3D dose distributions, i.e. measurement guided dose reconstruction (MGDR) [57]. Several phantom-array combinations with 3D dose reconstruction tools are commercially available and described in the literature [36,58–61]. Phantom-based 3D dosimetry does not require additional measurement time with respect to phantom-based 2D dosimetry; however, additional calculation tools are necessary for accurate volumetric dose reconstruction. These calculation tools introduce other sources of uncertainty and they should be carefully validated before clinical use. To this aim, it is important to evaluate the dose reconstruction algorithm, for instance by comparison with measurements in a phantom. Various groups have investigated the ability of 3D dose reconstruction to detect VMAT and IMRT delivery errors [34,36,61–64] and overall, all the systems performed in a comparable manner: typically, multi leaf collimator (MLC) errors ranging from 1 to 5 mm, dosimetric errors > 1% and single control point errors were correctly detected by the systems and hence could be of use in dosimetry audit.

Gel dosimetry is considered the only "true" 3D dosimetry solution [57] and has been tested in the IROC-H head phantom [65,66], but it is not yet easily available and it is reported that other gel-holding systems are not robust enough for wider audit use [3].

End-to-end audits would benefit from 3D dose reconstruction and the associated DVH analysis, as this approach enables direct assessment of the clinical impact of dosimetric errors. Since no additional measurements are required, 3D dosimetric evaluation would increase the capability of dosimetry audits.

For motion management, measurement guided 4D dose reconstruction on the patient is a novel phantom-based approach for dosimetric verification. With this method, the RTplan data is synchronised to absolute delivery time [67]. Therefore dose to a moving target can be estimated and organ motion within the resulting 4D dose grid could be simulated. Implementing this method in dosimetry audits could provide an estimate of volumetric, time-resolved dose errors in planned dose distributions and thus more clinically relevant information. Virtual motion simulation methods have also been developed for the purpose of dynamic MLC-tracking verification using a commercial bi-planar dosimeter, where time-resolved measurements allow identifying transient dose errors during VMAT delivery [68–70]. For dosimetry audits, this approach could be applied to discriminate between errors in the dose delivered to moving targets, which could be due to either target motion or erroneous motion or behaviour of linac parts. However, further development is still needed to support audit of a wider range of treatment units and TPSs.

Future audit methods will also need to focus on other aspects such as treatment planning based on MR images with a special emphasis on density/Hounsfield values related dosimetric inaccuracies. Further,

online and adaptive planning strategies will need to be audited, as online intrafraction replanning is being implemented into routine clinical service [71], so time-resolved measurements will be needed. MR guided radiotherapy techniques are an excellent example of where dosimetry audit needs to keep pace with the clinical need and novel equipment.

3.3.2. Tomotherapy

Similarly to the previously mentioned audits for advanced treatment techniques, 3D dose reconstruction has not yet been applied in Tomotherapy auditing. CT data sets for planning and phantom-based 3D dosimetry have been investigated and validated [72]. The volumetric dose reconstruction based on helical diode array measurements is generally similar to the approach in rotational IMRT [67], but the calculation algorithm is different due to the conceptual differences between helical Tomotherapy and VMAT.

3.3.3. Stereotactic units

For stereotactic VMAT delivery, 3D dose reconstruction based on 2D array measurements was investigated and found suitable for the application in stereotactic radiotherapy [51]. Moreover, the feasibility of cylindrical and planar arrays has been demonstrated for treatment plan verification for the CyberKnife system [52]. However, the study also demonstrated that the spacial resolution of array devices limits the accuracy of 3D dose calculation [52].

Until now, dosimetry audits for stereotactic techniques have not yet incorporated 3D dose reconstruction. However, as stated above, DVH analysis enables to assess the clinical relevance of potential dosimetric inaccuracies during the audit without requiring additional measurements.

4. Phantom-less methods for dosimetry audits

Phantom-less dosimetry systems typically use fluence measurements (i.e. portal dosimetry, transmission detector) or delivery log files without the presence of a phantom. Hence, dose is not delivered and measured in a physical phantom. Instead, the dose is delivered in-air and the results are calculated.

4.1. Portal systems

4.1.1. Conventional and MR- linacs

In recent years, real-time EPID dosimetry has emerged by speeding up the dose verification process [73–77]. While time resolved EPID dosimetry can be used as a phantom-less approach to monitor linac performance only, a more clinical application, which could be of high interest for auditing, is online 3D EPID in vivo dosimetry. For in vivo EPID dosimetry, a back-projection algorithm may be applied to compute the dose in the planning CT or in room CBCT scan, thereby enabling DVH analysis, which aids evaluating the delivered dose distribution during treatment [74]. Hence, real-time 3D EPID dosimetry refers to 3D dose reconstruction while the dose is being delivered. Real-time in vivo EPID dosimetry could play an important role in future end-to-end audits, especially in adaptive RT trials that require QA of the adapted dose delivery, as online and time-resolved dosimetric analysis in the patient geometry could be provided during the actual treatment session.

Another in vivo dosimetry method is to compare real-time measured EPID image frames with predicted EPID frames [76–78] allowing for 2D dosimetric comparison but no 3D dose reconstruction. Hence, this approach is comparable to 2D gamma analysis that does not provide DVH evaluation. Despite this limitation, this method could be applied as an efficient secondary measurement in dosimetry audits since no additional equipment is needed.

Recently, a virtual EPID standard phantom audit (VESPA) has been tested for remote auditing using multi-vendor equipment for both IMRT and VMAT in Australia [79], see Table 2. In summary, the audit team provided comprehensive instructions and CT datasets for treatment planning for the participating centres. The participating centres delivered their treatment plan to their own EPID without any phantom present and acquired non-transit EPID images. Additionally, a set of calibration fields were required for system calibration, to convert EPID grey scale values to absorbed dose and to determine EPID central axis location and EPID sag with gantry angle. The EPID images together with the calibration images were uploaded electronically and analysed centrally by the audit team. For analysis, the dose was back-projected onto a virtual cylindrical phantom and 3D gamma analysis was performed for comparison with the TPS calculated dose distribution. Disadvantages of the current implementation of VESPA are that absolute dosimetry is not yet provided and that it relies on the correct delivery of calibration fields [79]. Further, the implementation of portal imaging varies widely between vendors.

For flattening filter free (FFF) beams, new models for EPID dosimetry have been developed and successfully validated for pre-treatment QA [80,81] hence portal dosimetry is also a feasible tool for FFF modes and may soon be available for dosimetry auditing.

EPID dosimetry is being adapted for the MR-linac [82] to provide independent dosimetric verifications but future work on fluence-based 3D dose reconstruction is still needed.

4.1.2. Tomotherapy

For Tomotherapy, exit fluence data from the integrated on-board detector in combination with log file data (ion chamber measured output, gantry and couch position; see Section 4.3) is used to calculate and verify delivery performance for each treatment fraction. Thus, 3D dose distribution can be calculated in patient geometry to evaluate the accuracy of treatment delivery [83].

This method could be applied to any Tomotherapy device for 3D dose reconstruction, hence it would be an optimal tool for auditing. However, further development is needed to adapt this method for dosimetry audits.

4.1.3. Stereotactic units

EPID based dosimetry was recently investigated for small field sizes (down to 2x2cm^2) using a conventional linac [84]. Other groups have implemented portal dosimetry for VMAT SBRT treatments [85,86]. 3D dose reconstruction based on portal dosimetry proved to be accurate and can thus be applied for in vivo dose verification [86]. Similar to conventional linacs, the VERO system is equipped with an EPID [87], but there is no published data on its application for portal dosimetry.

Portal dosimetry has not yet been applied for dosimetry audits of stereotactic devices, hence first experiences need to be gained and a suitable workflow needs to be developed before it can be used for auditing.

4.2. Transmission systems

Several transmission detector systems are currently available and have been described in the literature [88–96], however none of them has been applied for auditing yet. They can be used for pre-treatment verification and can also provide online dose verification for each fraction during treatment delivery.

Both EPID dosimetry and transmission detectors can be used online simultaneously with phantom measurements. Therefore they could be employed as a secondary measurement system to complement conventional methods to gain volumetric and time-resolved dosimetric information during the actual treatment delivery. Despite their practical aspects for dosimetry audits, phantom-less methods suffer from some disadvantages that need to be considered: (I) there is no actual measurement of absorbed dose in a full-scatter phantom, (II) an additional uncertainty component is introduced due to the uncertainty associated with the computational algorithms used either for fluence

prediction or for dose calculation (forward or back projected) inside the phantom or patient.

For future dosimetry audits, phantom-less methods could be implemented to either replace phantom measurements, as demonstrated by the VESPA study [79] or to complement phantom measurements in terms of multi-level dosimetry. Fredh et al. [36] reported that different measurement systems tended toward identifying errors with varying degrees of sensitivity, suggesting that there might be marginal benefit in using multiple systems.

Phantom-less methods facilitate remote and parallel auditing as no transfer of QA equipment is needed and data can be exchanged digitally and analysed centrally by the audit team. Moreover, measurement data could be analysed automatically if the different vendor systems had standard data, i.e. were harmonised.

Additionally, complementary phantom-less measurements could also be used for voluntary audits, in-house constancy checks and to gain volumetric and time-resolved dosimetric information that could be of use for error tracking.

4.3. Log files

4.3.1. Conventional and MR- linacs

Log files are a useful tool to test the transfer of data to the machine and MLC control system and the continued monitoring of data over the course of treatment, especially for complex and dynamic treatment techniques such as VMAT [97,98]. Log files give insight into the interplay and coordination of dynamic parameters and are able to detect machine malfunctions. Moreover, recording and displaying log files can provide visualisation of the synchronisation and correlation of multiple aspects of treatment delivery during dosimetry audits.

Multi-institutional studies demonstrated how log file evaluation can be used for inter-departmental comparison [99–102]. Results from log file analysis can help to identify sources of errors during treatment delivery and were shown to correlate with time-resolved gamma analysis [101]. McGarry et al. [103] investigated the use of log file analysis for VMAT audits in an end-to-end testing approach, which is the only published study to date that incorporates log files with dose measurement in a dosimetry audit. Their results demonstrated differences in MLC positioning accuracy for different linac models (Varian TrueBeam < 1 mm vs. 2300IX $< 2{,}5$ mm). Thus, log files characterise differences between linear accelerator models and offer additional information which may help to identify sources of errors during audits.

Boylan et al. [98] developed a VMAT delivery emulator that predicts the characteristics of a given treatment plan based on the plan parameters included in the dicom RT plan file. This tool enabled a virtual VMAT delivery based on actual linac performance characteristics that could be used as a first line of analysis before a full dosimetry audit takes place.

Converting log files to treatment plan format for dose recalculation has been investigated by several authors [104–111]. Different approaches to recalculate delivered dose distribution have been developed, either using the same TPS [105,106,109,110] or an independent one [108,112,113].

If the machine behaviour over time is well known and audit results are not satisfactory, plan specific log file analysis can help to eliminate the machine delivery from the troubleshooting process and divert attention to other aspects of the delivery chain [103]. Several studies have reported on the use of log files for finding the source of an error [101,103,114]. During end-to-end testing, a meaningful investigation of the log file results and comparison to baselines may help to quickly identify potential machine malfunctions. Some of the data included in the log files is monitored by the linac in real time and can trigger machine interlocks if parameters are out of tolerance. However, machine performance monitoring over time can help finding baselines for and further increase delivery accuracy. Thus, log files could be integrated in several steps of dosimetry audits to address multiple stages of the radiotherapy treatment chain: (I) comparison of actual linac performance with delivery simulation; (II) tracing potential delivery errors; (III) inter-linac comparison; (IV) dose recalculation. There is also potential for log files to be collected during the treatment delivery of patients in clinical trials and thus verify that each treatment fraction was delivered in a reproducible way.

One major limitation of log files is that they are generated by the delivery system and rely on feedback data from the linac, therefore they are not independent and their accuracy is unknown. Neal et al. [115] and Agnew et al. [114] found discrepancies between image-based and log-based MLC positions, which cautions the use of log file based methods in audits. Any systematic error introduced in the MLC calibration might lead to actual leaf positions different from the expected ones that would not be detected by log file analysis [111]. Moreover, there are differences between the different manufacturers systems regarding the data included in the log files that make a direct comparison of different vendors difficult (see Supplementary Table 1). The harmonisation of recorded parameters would be an essential prerequisite for inter-linac comparisons in dosimetry audits and would also be necessary for automation of data analysis.

Overall, end-to-end tests for complex radiation delivery techniques, such as adaptive radiotherapy (ART) or 4D radiotherapy (i.e. MLC-tracking), will need to test extra aspects of the treatment chain. Log file analysis in combination with 3D and 4D dosimetry tools will help in achieving that need efficiently. Hence, log files should complement (rather than replace) audit tools and be used as an additional source of information which could shed light on machine specific delivery issues. However, strategies for recording, processing and evaluating log file data need to be developed before log file analysis can be fully implemented in multi-vendor dosimetry audits.

MR-guided radiotherapy devices such as the ViewRay system provide log files that record MLC leaf positions, beam-on times, gantry angles, and couch positions. ViewRay delivery log files have been investigated for 2D fluence verification [116], delivery time prediction [117] and verification of treatment delivery parameters [118]. Currently there are no studies published on log file analysis for MR-linacs, but it is assumed that log files similar to those from conventional linacs will be available for Elekta's MR-linac Unity.

Both EPID dosimetry and log file evaluation could be employed in remote dosimetry audits to complement measurement-based methods if developed and adapted appropriately. Similarly to current audit developments for conventional linacs [79,103], these phantom-less approaches could be integrated in multiple steps of dosimetry audits (dose recalculation, evaluation of delivery performance, intercomparison), improving auditing efficiency and facilitating remote auditing.

4.3.2. Tomotherapy

For Tomotherapy, information such as ion chamber measured output, gantry and couch position are recorded during treatment delivery by the Tomotherapy data acquisition system (DAS) and saved into a log file at a sampling rate of 300 Hz [83]. MLC data is not recorded in log files, instead, the imaging device contains an exit detector which records fluence [83,119]. Although log file evaluation is considered a precise and efficient method to confirm that the planned parameters are achieved and to verify machine performance, it also has some weaknesses since the sensors collecting data are not calibrated with the same accuracy as independent detectors that are used for phantom-based QA methods [83]. Nevertheless, log files could provide valuable additional information during dosimetry audits, visualising dynamic characteristics of the treatment machine and allowing for efficient multi-institution comparison as no additional measurement or equipment is required.

4.3.3. Stereotactic units

While log files have not yet been used for dosimetry audits for stereotactic techniques, several authors have recorded log files to assess

the accuracy of the integrated tracking system of stereotactic treatment units that compensate for tumour motion [120–123]. Seppenwoolde et al. [120] used patient motion data extracted from CyberKnife log files to evaluate the accuracy of the motion compensation algorithm. Hoogeman et al. [121] and Pepin et al. [122] have investigated the prediction model of the CyberKnife system which overcomes the latency between tumour recognition and beam adjustments based on lung cancer treatment log files.

For the VERO system, log files have been analysed to monitor in vivo tracking accuracy [124], to determine the geometric accuracy of synchronised gantry ring rotations during dynamic wave arc delivery [125] and to develop a 4D dose calculation system for real-time tumour tracking [126].

Dosimetry audits for stereotactic techniques are challenging and require high quality methods. Stereotactic techniques that incorporate tumour tracking are even more complex and corresponding dosimetry audits would benefit from the time-resolved characteristics of log files. Log file-based dose recalculation has the potential to estimate the impact of dosimetric and positional errors on clinical outcomes without additional phantom measurements. However, suitable techniques for incorporating these methods in dosimetry audits still need to be developed.

5. Conclusions

Advanced treatment techniques require novel auditing methods. As treatment techniques become increasingly complex, more aspects will need to be verified. This will require more items to be analysed and therefore, streamlining and automation will become key aspects in future audits. The presented methods offer several advantages in auditing complex delivery techniques, such as time-resolved measurements or 3D dose reconstruction. Moreover, they facilitate gathering treatment delivery data in clinical trials or in large databases. Future dosimetry audit methods should address multiple stages of the radiotherapy treatment chain, facilitate parallel auditing (i.e. performing an audit at multiple institutions at the same time) and automation of data analysis. Novel dosimetry techniques and incorporation of additional information such as data from log files has the potential to increase both the effectiveness and efficiency of audits. The reviewed methods provide the potential to significantly reduce the time needed for audit and increase the information gained.

However, increased experience is needed to quantify these improvements and further development and harmonisation are still necessary to facilitate implementation of these novel methods in dosimetry audits. Moreover, before any novel technology can be applied for auditing, suitable and comprehensive procedures must be developed and tested to ensure that the methodology used is valid for the different existing treatment units and treatment techniques.

Conflict of interest

The authors have no conflict of interest to declare.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.phro.2018.03.002.

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