EPIDs and QA of advanced treatments

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Abstract. In this paper I will summarize the various possibilities of EPIDs for their use as tools for QA of advanced treatments. After elucidating the choice of EPIDs for this purpose, I will review the use of EPIDs for pre-treatment and in vivo (transit) dosimetry applications. Several solutions became recently commercially available, allowing relative and/or absolute dose verification at points (0D), in 2D, or in 3D. Each of these solutions will be briefly discussed, indicating the differences in possibilities with respect to QA of advanced treatments. I will conclude with some general remarks about the current status of EPID-based QA of advanced treatments and revealing some future developments in 3D pre-treatment and in vivo dosimetry using EPIDs.

1. Introduction
After the acceptance testing of a treatment unit, specific measurements are required for the commissioning and quality assurance (QA) of that unit, as well as for the verification of treatment techniques performed with that machine. These dose determinations are often performed using point dose (0D), or 1D measurements, e.g., for the determination of output factors, beam profiles and depth dose distributions. The introduction of advanced treatment techniques such as intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) required in addition 3D dosimetric approaches. For that purpose, various detector systems have been developed: full-3D, e.g., using gel or radiochromic detectors, semi-3D, using films or detector arrays in a phantom, or pseudo-3D using transmission chamber devices attached to the head of the treatment unit, or electronic portal imaging devices (EPIDs). A dose calculation using a linac log file can also be considered as a pseudo-3D technique. In my presentation at the IC3DDose2016 meeting in Galveston I have summarized the possibilities and limitations of these various 3D dosimetry techniques and evaluated those features relative to those of EPID-based techniques [1]. A more extensive comparison of semi-3D and pseudo-3D techniques can be found elsewhere [2, 3]. In this presentation I will discuss only the use of EPIDs as tools for QA of advanced treatments, with the emphasis on EPID-based solutions that became recently commercially available.

2. EPID-based dosimetry

2.1. The use of EPIDs in modern radiation therapy
In addition to their original use for patient setup verification during external photon beam therapy, EPIDs are increasingly used for other applications for the following reasons:
1. Most accelerators have an EPID or are sold with an EPID in combination with additional tools for image guidance such as cone-beam CT (CBCT). The role of EPIDs is then to evaluate the congruence between the CBCT image center and the radiation isocenter. Furthermore, EPIDs are used for several other QA tasks such as the verification of MLC leaf positions.

2. EPIDs have many useful dosimetric characteristics such as the (almost) linearity of the response with dose and dose rate, good long-term stability, high spatial resolution, and real-time readout. EPIDs exhibit both high data density and online efficiency as compared to the existing non-EPID based QA tools. However, using EPID dosimetry in clinical practice has also a number of challenges, including its over-response to low energy photons, a possible under-response due to image ghosting, and a contribution to the EPID signal of photons scattered in the EPID and sometimes in the EPID-arm. These characteristics, and methods to correct for deviations from the regular dose-response relationship, have been discussed in detail by McCurdy et al. [4].

3. Setup time, data analysis and processing time are small and can be automated. These are important prerequisites for large scale clinical implementation of EPID dosimetry. Generally in vivo EPID measurements and data analysis can be performed by radiation therapists (RTTs), while alert handling needs input of a medical physicist.

4. One of the most important reasons for performing EPID-based in vivo transit measurements, either by comparing EPID images in a relative way or by means of in vivo dosimetry, is that this measurement approach has a high effectiveness in detecting errors. In a study by Ford and colleagues it was noted that EPID dosimetry was a very efficient QA tool in detecting high severity incidents in combination with chart checks and reviews [5]. It was also much more effective than the pre-treatment QA procedures performed in the institutes participating in this study. This observation was confirmed in a follow up study concerning the effectiveness of EPID dosimetry in detecting incidents in radiotherapy [6]. In that study it was demonstrated that EPID in vivo transit dosimetry during the first fraction was able to detect 74% of the incidents, while pre-treatment EPID dosimetry could only trace 6%.

5. Many semi-3D and EPID-based tools are currently commercially offered for performing pre-treatment dose verification, but EPIDs are the only devices available for 3D in vivo dosimetry.

2.2. EPID-based QA approaches

The various EPID-based QA approaches have been discussed in a comprehensive way in a 2008 review by van Elmpt et al [7], which has recently been updated by McCurdy et al [4]. Briefly, if treatment beams have passed through a patient or phantom before being measured by the EPID, the method is referred to as transit or transmission dosimetry, otherwise, the method can be described as non-transit dosimetry. Note that sometimes the term “exit dosimetry” is used instead of “transit dosimetry”, which is not recommended because it has been defined in the past as the determination of the dose at the exit surface of an irradiated phantom or patient. Dose or image comparisons can be made at the EPID level or in the patient/phantom using a forward- or back-projection approach. Forward projection methods compare measured images or 2D dose distributions with predicted images or 2D dose distributions at the EPID level. Back-projection methods can provide point dose, 2D or 3D dose information in a patient or phantom, and the resulting dose values are then compared with planned dose data for that particular patient/phantom. Not many institutions perform EPID-based transit dosimetry with phantoms, and therefore I will discuss in this paper only transit in vivo EPID dosimetry.

In this presentation I will focus on the current commercial EPID dosimetry tools for patient-specific QA of advanced treatments. Some of these products became recently available and consequently not many publications on their clinical use are yet available in the literature. Information about the properties of the various EPID-based dosimetry systems discussed in this presentation, is therefore partly based on material provided by the website of the various companies and has therefore to be considered as preliminary info. A detailed report concerning the possibilities and limitations of
the various commercial EPID systems for patient-specific IMRT and VMAT QA is in preparation (AAPM TG-307).

2.3. Pre-treatment verification

Before starting clinically with a new treatment technique or class solution, validation of the planning and delivery of that technique should be performed by means of a dedicated measurement program. Such a program generally includes an end-to-end test in which the actual patient treatment procedure is mimicked as much as possible using a full-, semi-, or pseudo-3D system. After finishing such a series of systematic pre-treatment measurements, a patient specific pre-treatment QA measurement is performed before the start of each patient treatment with that technique, frequently in combination with an independent dose or MU check.

The utility of an EPID-based pre-treatment QA measurement depends on the type of software used. The minimum aim of such a procedure is to guarantee that data transfer between systems is correct before patient treatment begins. The Varian Portal Dosimetry system (www.varian.com/course/portal-dosimetry), developed by Van Esch and colleagues [8], is such a system. Basically, EPID images are used to verify if the fluence intensity distribution calculated by the TPS is transferred to and delivered by the linac correctly. It compares measured with predicted EPID images, for both IMRT and VMAT plans calculated and delivered by Varian equipment. Many publications of this product can be found in the literature, including improvements of the original software and the establishment of action levels [4, 7].

The Varian Portal Dosimetry system does, however, not verify the 3D dose calculation for that particular patient irradiation. One step closer to that situation is the Epica software (www.epidos.eu). It converts the EPID image into a dose map at dose maximum in a virtual water phantom, which is then compared with a reference dose distribution in that plane. The software is based on the GLAaS algorithm developed by Nicolini et al [9] and can be used for both IMRT and VMAT plans calculated and delivered by Varian equipment.

The perFRACTION Fraction 0 software from Sun Nuclear (www.sunnuclear.com) is also able to perform a 2D dose determination at the EPID level, which can be compared with the dose distribution in that plane calculated with the TPS for independent 2D planar analysis. The EPID image can also be used to determine MLC leaf positions, which can be used as input for a 3D dose calculation on planning CT data using the linac log-file.

The Dosimetry Check (www.lifelinesoftware.com) system is able to perform an independent 3D dose calculation in combination with the non-transit approach. It converts the measured photon fluence at the EPID level into relative number of monitor units per pixel. The 3D dose distribution is then calculated on planning CT data using a forward dose calculation pencil beam algorithm. By exporting the dose distribution from the TPS into the Dosimetry Check system, one is able to make a direct comparison between the calculated and planned 3D dose distribution. It allows DVH analysis and is therefore able to trace errors in the 3D dose calculation for a specific patient, in addition to checking the plan transfer and deliverability. The performance of the system, as well as a comparison with two semi-3D detector systems, has been studied on a Varian accelerator [10], but according to their website the Dosimetry Check software can also be used with EPID images obtained from Siemens and Elekta accelerators.

2.4. In vivo verification

Pre-treatment QA of advanced treatments using EPIDs involves a check of the dose delivery under well-defined conditions, while in vivo verification is performed under the actual daily clinical conditions [11]. Pre-treatment non-transit EPID verification approaches will miss errors due to changes in patient anatomy and patient setup, or due to malfunctioning of the treatment machine during the actual patient treatment. Transit in vivo EPID-based measurement systems allow day-to-day monitoring and can be used to highlight any major change in the patient anatomy during a treatment series that may have a clinical impact, as often occurs during head and neck or lung cancer treatments.
During transit in vivo verification using the forward approach, measured EPID images are compared either with a predicted image, or in a relative way to a reference image. In the first approach not only errors in the data transfer and delivery of the treatment can be determined, but also patient-related errors such as anatomy changes. Comparison with a reference image will only trace deviations during a series of treatments. It should be noted that deviations in transit EPID images observed by systems using the forward approach are not in a simple way related to variations in the dose distribution inside a patient.

PerFRACTION from Sun Nuclear (www.sunnuclear.com) compares EPID images from each field of each fraction \(n \geq 1\) behind a patient with a reference portal image using 2D gamma analysis. In a sensitivity study of this software it was demonstrated that PerFRACTION, using integrated EPID images, is sensitive enough to identify positional, angular, and dosimetric errors [12]. The EPID image can also be used to determine MLC leaf positions of that fraction, which can be used as input for a 3D dose calculation on planning CT data using the linac log-file. Such an approach should be considered as a pseudo-3D dose verification tool but not as an in vivo dosimetry method.

The Adaptivo software (www.standardimaging.com/qa-software/adaptivo/) is also able to compare in vivo transit EPID images with a reference EPID image using gamma analysis. According to the website their software can also be used in combination with the MV CBCT system of TomoTherapy.

SOFTDISO from Best Medical Italy has a similar option to compare subsequent daily EPID portal images using gamma analysis. The SOFTDISO software is in addition able to perform a comparison of the planned dose at the isocenter with a back-projection at the isocenter of the transit EPID dose. The software is in use in various Italian centers and has been described in several publications, e.g. [13]. In that paper it was shown that relevant discrepancies were observed using this software in head-and-neck cancer patients treated with VMAT including a setup error and major anatomical variations (weight loss/tumor shrinkage) during the second half of their treatment.

EPIgray (www.dosisoft.com) uses the transmitted signal on the EPID to reconstruct the dose at points of interest within the patient. The dose reconstruction method uses a back-projection of the transit EPID dose onto the patient planning CT. Measured vs calculated dose comparison can be performed in multiple points but not over the whole EPID area. Clinical experience has been described for both Varian [14] and Elekta [15] equipment. Both publications showed that EPIgray is able to pick up a number of anatomical changes and patient setup inaccuracies that could lead to intolerable dose delivery errors.

EPID-based 3D dose verification has been implemented into two commercial systems, each applying a different technique of dose reconstruction. In the Dosimetry Check software (www.lifelinesoftware.com) the photon fluence measured with the EPID is back-projected through the patient to the target of the linac, and then used to calculate the 3D dose distribution in the patient geometry using a forward dose calculation. This approach is similar to the way Dosimetry Check is used for pre-treatment 3D dose verification. The transit dosimetry option has extensively been tested using phantoms [16] but clinical experience has not yet been reported.

iViewDose (www.elekta.com/iViewDose) applies a different approach in which the 2D dose distribution measured with the EPID is back-projected in the 3D patient planning CT data. An example of the possibilities of a prototype of this software is given in Figure 1. The dose calculation algorithm used in this system is a pencil-beam type, as in Dosimetry Check, because it is fast and relatively easy to implement, but the accuracy is inferior to other dose calculation algorithms particularly with respect to tissue heterogeneity corrections. A comparison of iViewDose with a homemade 2D forward-projection in vivo EPID dosimetry software package for VMAT prostate treatments has recently been published [17].
Figure 1. The upper part shows the outcome of a 3D EPID-based in vivo dose verification of a VMAT treatment of a larynx cancer patient at NKI. Indicated are the results of the 3D gamma evaluation in a sagittal, axial, and coronal plane through the isocenter. A signed gamma display is used: the yellow and red color indicate regions where the EPID dose is higher than the planned dose, whereas the green and blue color indicate regions where the EPID dose is lower than the planned dose. The 50% isodose line is shown in black. The yellow dot means that at least one alert criterion is outside the action level. The bottom part shows a CBCT scan (green) made that day compared with the planning CT scan (purple) in the three orthogonal planes, showing a decrease of target volume. Note that the dose at the isocenter did not change.

3. Future developments

There are several issues that can be further developed to make EPID software for QA of advanced treatment better designed, more automated and more integrated into the clinical workflow. In addition, new options should be further explored such as the ones discussed in the following sections.

3.1. Combination of pre-treatment and in vivo EPID dosimetry

By combining pre-treatment and in vivo EPID-based dose verification data of the same patient treatment, it may be possible to separate patient-related errors from machine, planning, and dose reconstruction model errors. A prerequisite for such an approach is that the pre-treatment and in vivo dose calculation is performed with the same dose calculation algorithm. Such an approach has recently been developed in our institute [18]. As shown schematically in Figure 2, the primary portal dose distribution at EPID level obtained during a pre-treatment non-transit measurement, can be used in combination with patient CT data to reconstruct ‘virtual patient’ 3D dose distributions applying the same back-projection algorithm as used during the in vivo measurement. In this way pre-treatment and in vivo dose distributions can both be analyzed in terms of dose-volume histogram (DVH) parameters, providing a useful indication to radiation therapy staff of the type and impact of detected deviations. Dosimetry Check is in principle also able to combine pre-treatment and in vivo 3D dose reconstruction...
using the same algorithm, but no publication exists about the use of this option. More work is needed to test this approach in clinical practice.

Figure 2. *In vivo* and virtual patient EPID measurement configuration allowing *in vivo* and pre-treatment virtual patient 3D dose verification [18].

### 3.2. Combination of CBCT and *in vivo* EPID dosimetry

Most, if not all, EPID-based *in vivo* dose verification systems use planning CT data to reconstruct the dose in the patient geometry. An obvious question therefore is why not using the patient anatomy during treatment to determine a more accurate estimate of the dose delivered to a patient? Often a CBCT scan made on the same day is available and a number of errors observed with *in vivo* dosimetry can be understood already qualitatively by visual inspection of the accompanying CBCT scan. Variation in setup, anatomy changes due to changes in atelectasis and pleural effusion, as well as contour variations due to weight loss or other reasons (see Figure 1), can often be observed by CBCT.

There are, however, several concerns that have to be considered when merging the information from *in vivo* 3D dosimetry and CBCT in a quantitative way. First, there are practical issues that make it sometimes difficult to use CBCT scans in the clinic such as non-complete fields of view. Also, there is currently a lack of automation of the integration process requiring manual actions. Furthermore, in case of treatment adaptation, the radiation oncologist often has to define a new CTV in a CBCT scan, which is challenging due to the less good image quality compared to a CT scan, whereas in addition such a procedure is time-consuming. Finally, a more fundamental problem exists: how to incorporate disappearing voxels, for instance due to a shrinking tumor, in deriving the total dose delivered to a changing CTV. Consequently, dose comparisons and alert criteria are less obvious when using CBCT.

Nevertheless, *in vivo* transit EPID dosimetry should not be used in isolation but is most effective in combination with CBCT. For instance, a combination of CBCT and *in vivo* 3D dosimetry will help in selecting those patients that require an adaptive treatment. It will depend on the training of the therapists and the availability of clinical protocols if observed deviations in dose delivery and CBCT are considered to be clinically relevant. A combination of both sets of information will help in choosing the most suitable follow-up action. More work is needed to assess a further incorporation of CBCT when performing *in vivo* transit EPID dosimetry.

### 3.3. Real-time EPID dosimetry

*In vivo* transit EPID dosimetry should ideally be performed in real-time so that errors can be caught immediately and the treatment interrupted if the delivered dose is not within pre-defined limits of acceptance. This is particularly important for hypofractionated treatments, where detected errors cannot always be compensated for in subsequent fractions. Technically this is possible as demonstrated for a 2D forward dose reconstruction method [19] and a 3D backward dose reconstruction technique [20]. As an example, Figure 3 shows the result of a real-time verification using the latter system during an anthropomorphic phantom irradiation with VMAT rectum plans. The introduced serious delivery errors were detected after 5–10 s irradiation time.
The major challenge when using real-time EPID dosimetry clinically is to assess alert criteria able to detect those deviations in dose delivery that are so large that detecting them with off-line dosimetry, i.e. after completion of the total fraction, would imply unacceptable harm to the patient. The system should therefore be sensitive enough to detect gross errors in real-time, but on the other hand the system needs to be robust, in other words have a low false-positive rate. False positives in real-time dosimetry have serious consequences for the clinical workflow as it interrupts a treatment session leading to time loss and stress. More research is therefore needed to define criteria for halting the linac that should not miss serious errors but have at the same time a small number of false positives. Future work should also include the development of a workflow to integrate real-time dosimetry into routine clinical use.

![Figure 3](image.png)

**Figure 3.** Difference between reconstructed and planned near-maximum dose ($D_{2}$) outside the PTV for three scenarios (no error, all leaves open error, double MU error), as a function of delivery time. The horizontal line indicates a possible detection threshold [20].

4. Final remarks

The main purpose of EPID-based pre-treatment verification of advanced treatments is to identify dosimetrically unacceptable errors, i.e. deviations from the “true dose” considered from the physical/technical point of view. The aim of EPID-based in vivo dosimetry is often not to measure the “true” dose delivered to a patient, but to detect in a simple and reliable way a deviation between the planned and reconstructed dose at a point, in 2D or 3D, which should be within well-specified criteria. The question then arises when is a difference in dose distribution observed during in vivo treatment verification a clinically unacceptable error, i.e. when would the treatment outcome in terms of local control or toxicity be affected by this difference? To answer this question, it is necessary to perform for each EPID-based QA system a comprehensive sensitivity analysis, that should result in treatment site specific alert criteria, either gamma- or DVH-based or both, to ensure optimal detectability for various types of errors.

Alert criteria are generally a compromise between the requirement to detect all clinically relevant deviations and the workload to analyze these alerts. Generally, alerts are first reviewed by an experienced medical physicist, and might have many reasons as publicized comprehensively elsewhere [21]. When the error is understood by the physicist, and it was estimated that continuation of the treatment might have negative clinical consequences, the case should be discussed with a radiation oncologist. A decision for corrective action is then generally made by the physicist and radiation oncologist together.

The experience in some centers demonstrates that EPID-based in vivo verification of advanced treatments requires a change in attitude to patient specific dose verification. It is no longer purely a physics or technical matter but requires in addition clarifying dose differences observed in the clinic,
i.e. incorporating many issues that may happen during the daily treatment of patients. As a result, medical physicists are much more involved in assuring the quality of the actual patient treatment than when only performing a pre-treatment dose verification measurement [3, 21].

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