EPID-based dosimetry and its relation to other 2D and 3D dose measurement techniques in radiation therapy

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Abstract. In this paper I will summarize the possibilities and limitations of different 2D and 3D dosimetry techniques used in radiation therapy, and evaluate these features relative to those of EPID-based techniques. After briefly discussing their characteristics, I will review the use of EPIDs for pre-treatment and in vivo dosimetry applications by separating them into transit and non-transit approaches, analysed by either forward- or backward-projection methods. I will then review the various types of 3D dosimetry systems by categorizing them into semi-3D, pseudo-3D, to which EPID-based back-projection approaches belong, and full-3D systems. All methods can in principle be used for pre-treatment 3D dose verification; the choice of a specific system depends on the aim of the measurement and the properties of the specific hard- and software. At this moment EPIDs are the only tools available for 3D in vivo dosimetry. I will conclude with revealing some trends and future developments in 3D pre-treatment and in vivo dosimetry.

1. Introduction
The success of a radiotherapeutic treatment is dependent on the accuracy of the planning and delivery of the 3D dose distribution to a target volume and the surrounding critical organs in a specific patient. 3D dosimetry therefore plays a vital role in radiation therapy [1]. Although it is difficult to generalize, an accuracy in the dose delivery, i.e., a difference between the actual and “true” dose, of the order of a few percent, is often required. For instance, in ICRU Report 83 [2] it is stated that the difference between measured and planned dose should be within 3.5% (1SD) and the distance to agreement within 3.5 mm for low and high dose gradient regions, respectively. As a consequence, the accuracy of all components involved in a radiotherapeutic procedure need a very high accuracy as elucidated and discussed in detail in an upcoming IAEA report [3].

Starting with the acceptance testing of a treatment unit and a treatment planning system (TPS), specific measurements are required for the commissioning and quality assurance of that unit and TPS, as well as for the verification of special treatment techniques. These dose determinations were, and still are, often performed using point dose or 1D measurements, e.g., for the determination of output factors, beam profiles and depth dose distributions [4]. The introduction of advanced treatment techniques such as intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT), both often using small fields, did not change the beam modelling process of the 3D dose calculation algorithms performed by a TPS for these advanced irradiation techniques. It is still based on data obtained by 0D and 1D measurements under reference conditions, even for small (≤ 3 cm x 3 cm) fields. The characterization of detectors to be used for measurements in small fields is, however, complicated. Data concerning their use are scarce and until recently [5] no recommendations were available. Because the TPS is the gold standard in the design of the specific 3D dose distribution for a patient, TPS commissioning verification is needed by means of independent methods. The validation of newly
developed software to design novel irradiation techniques, as well as the verification of the delivery of specific patient plans, is therefore a prerequisite for the safe introduction of advanced treatment techniques, requiring new 3D dosimetric approaches.

In this presentation various methods of 2D and 3D dose determination employed in radiation therapy will be discussed. The starting point will be the use of electronic portal imaging devices (EPIDs), their dosimetric characteristics, and their use for specific applications. Possibilities and limitations of 3D EPID dosimetry will then be elucidated, as well as how other 3D dosimetry techniques might complement the work performed with EPIDs. This presentation will partly be similar to that given by Korreman at the IC3DDose 2012 meeting [6] when reviewing the various 3D dosimetry approaches, but in my presentation the emphasis will be on the comparison of these methods with EPID dosimetry.

2. EPID-based dosimetry

2.1. Detector characteristics
In addition to their original and still major use for patient setup verification during external photon beam therapy, EPIDs are also used for many other quality assurance purposes including the verification of MLC leaf positions [7]. Previously, before 2000, various types of technology were used for EPIDs. Current amorphous silicon (a-Si) type EPIDs not only generate better quality images, but also possess 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. These characteristics, and their applications in radiation therapy, have been discussed in detail by McCurdy at the IC3DDose 2012 meeting [8].

In his overview McCurdy also discussed a considerable number of challenges to using EPID dosimetry in clinical practice of which I will summarize the most important ones. First of all, an a-Si EPID over-responds to low energy photons compared to a water equivalent detector due to the increased photoelectric effect in the copper/phosphor screen. As a consequence the EPID response will be modified when the photon spectrum is different compared to the calibration situation, for instance when different field sizes and phantom/patient thicknesses are used. Also the lower energy photons scattered from the phantom/patient to the EPID cause an additional signal, which complicates the analysis. Furthermore, image lag and image ghosting occur due to changes in the trapped charge in the photodiodes, and changes in individual pixel gain, respectively. These effects may result in an under-response up to 10% but are restricted to short irradiation times. Finally, photon scatter generated in the EPID, and sometimes in the EPID-arm, will contribute to the image signal and has to be taken into account. Consequently, correction-or model-based approaches have been employed to mitigate these challenges when using a-Si EPIDs for clinical dosimetry. It is obvious that when performing dosimetric measurements with an EPID, validation of the accuracy of the 3D EPID-based dose determination of that specific irradiation technique, is a prerequisite.

2.2. Methods
The various EPID dosimetry approaches have been discussed in a comprehensive way in a review article by van Elmpt et al. [9] and are schematically presented in Figure 1. If the 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 is described as non-transit dosimetry. Dose or image comparisons can be made at the EPID level or in the patient/phantom using a forward- or back-projection approach, respectively. Software for comparing a measured EPID image to an expected image in the forward non-transit dosimetry approach (Figure 1a) has been developed by many groups and is commercially available as discussed for instance by Greer [10]. In the forward transit dosimetry approach (Figure 1b) measured grayscale distributions are compared directly or after conversion to dose values, with predicted grayscale or dose distributions [11-13]. In the backward-projection non-transit approach (Figure 1c) the photon fluence measured with the EPID is back-projected to the focus of the linac and then used as input for a 3D dose calculation in the planning CT data of a patient using in-house
[14] or commercially developed [15] software. The resulting 3D dose distribution is then compared with the planned dose distribution for that particular patient, providing information about possible differences between the two calculated dose distributions.

EPID-based 3D transit dose reconstruction methods have been developed by many groups as discussed in the review article (published in 2008) by van Elmpt et al [9]. Two approaches of dose reconstruction can be distinguished. In the first method, the photon fluence measured with the EPID is back-projected through the phantom or patient to the target of the linac, and then used to calculate the 3D dose distribution in the phantom or patient geometry [16, 17]. In the second approach the dose distribution measured with the EPID is directly back-projected in the phantom or patient CT data set [18]. The dose calculation algorithms used in these models are a pencil-beam type [18], a collapsed-cone convolution method [17], or a Monte Carlo approach [16]. Dose calculation algorithms based on a pencil beam model are fast and relatively easy to implement, but the accuracy is inferior to other dose calculation algorithms particularly with respect to tissue heterogeneity corrections. In order to by-pass that problem, a modification of the pencil beam type of dose calculation has been developed providing the same sensitivity for detecting errors as in vivo dosimetry of sites without large tissue heterogeneities [19]. In addition to these in-house developed methods, commercial software has been released for 3D dose reconstruction using the transit dosimetry approach [15].

2.3. Pre-treatment dose verification

Before starting clinically with a new treatment technique, a thorough commissioning of the planning and delivery of that technique should be performed. Such a program generally includes an end-to-end test in which the actual patient treatment procedure is mimicked as much as possible using one of the 2D or 3D systems, often in combination with a suitable phantom, as will be discussed in the next sections. After finishing such a series of systematic pre-treatment measurements, a patient specific pre-treatment verification measurement is performed before the start of each patient treatment with that technique, frequently in combination with an independent dose or MU check. The purpose of such a patient specific pre-treatment measurement, commonly rather carelessly called “patient specific QA”, is to ensure that the dose delivered to the patient is identical to what is calculated by the TPS.

EPIDs are often used for pre-treatment verification applying the forward non-transit dosimetry approach (Figure 1a). Basically the EPID images are used to verify if the fluence intensity distribution calculated by the TPS is transferred to and delivered by the linac correctly. This method does, however, not verify the dose calculation for that particular patient/phantom irradiation. Some EPID-based systems using the back-projection non-transit approach (Figure 1c) are able to perform a 3D dose calculation. In this way errors in the dose calculation of the clinically used TPS can also be detected along with the plan deliverability. However, both non-transit verification approaches will miss errors due to changes in patient anatomy and patient set-up, or due to malfunctioning of the treatment machine during the
actual patient treatment. In the forward transit dosimetry approach (Figure 1b) not only errors in the data transfer and delivery of the treatment can be determined, but also patient-related errors such as anatomy changes [13]. Both forward approaches perform 2D image comparisons, and observed deviations are not in a simple way related to variations in the dose distribution in a patient.

The main purpose of pre-treatment verification of IMRT and VMAT patient plans is to identify dosimetrically unacceptable errors, i.e. deviations from the “true dose” considered from the physical/technical point of view. Pre-treatment verification by means of an EPID, as well as by many of the other dosimetry systems discussed in the next sections, may identify such errors.

2.4. In vivo dose verification

Pre-treatment dosimetry using EPIDs checks the dose delivery under well-defined conditions while in vivo dosimetry is performed under actual daily clinical conditions. EPID-based systems allow day-to-day monitoring and can be used to highlight any major change in the patient anatomy that may have a clinical impact (see Figure 2). The aim of 3D EPID-based in vivo dosimetry is often not to measure the “true” dose delivered to a patient with the highest possible accuracy, but to detect in a simple and reliable way a deviation between the planned and reconstructed 3D dose distribution, which should be within well-specified criteria. The question then arises if a difference in dose distribution, observed when analyzing in vivo treatment verification data, can be considered as a clinically unacceptable error, i.e. would the treatment outcome in terms of local control or toxicity be affected by this difference. Generally the alerts are first reviewed by an experienced medical physicist. When the error is understood by the physicist, and it was estimated that there might be negative clinical consequences, the case is discussed with a radiation oncologist. A decision for corrective action is then generally made by the physicist and radiation oncologist together.

3. Semi-3D, pseudo-3D and full-3D dosimetry systems

3.1. Semi-3D detectors

Multi-dimensional dosimetry systems have largely replaced the use of radiographic film, often in combination with an ion chamber, for many applications in radiation therapy such as IMRT and VMAT pre-treatment verification. Film can be used in the same way as these 2D ion chamber or diode arrays by inserting the film in phantoms, i.e., as a semi-3D detector. It has the advantage over these systems of having a much higher spatial resolution, which may be important in verifying IMRT or VMAT plans. These plans often have steep penumbras or a high degree of modulation, which require high resolution.
equipment for verification. Film provides a relative 2D measurement of the photon fluence while an ion chamber measurement gives an absolute point dose. Such a method is, however, time consuming, and requires extensive resources for calibration, processing and analysis, as well as the costs of single-use films. Also film cannot provide online information, as opposed to the other semi-3D equipment. Film dosimetry is therefore mainly used for special applications.

Several multi-dimensional detector systems have been developed, consisting of 2D arrays of diodes or ion chambers that can be positioned in a phantom, which can then be referred to as a semi-3D system. Figures 3b and 3c are examples of such an approach. Other types of semi-3D dosimetry systems include arrays which make measurements in two orthogonal planes (Figure 3a) or at various points on a helical curve at approximately 2.9 cm below the surface of cylindrical phantom (Figure 3d). All these systems construct a 3D dose distribution by interpolation of the measured data using their own software. The possibilities and limitations of each of these approaches have been reviewed by Korreman [6] and are related to the size of the individual detectors, spatial resolution, angular dependence to beam delivery direction, absolute or relative dose measurement and frequency of calibration. Since that review companies have worked on improvements of their systems. For instance, in addition to the PTW seven29 ion chamber array shown in Figure 3c, there now exists also a the Octavius 1500 system having 1405 vented ion chambers on a large field, and the Octavius 1000 SRS having 977 liquid-filled ion chambers on a 10 cm x 10 cm field. Furthermore a rotating phantom, Octavius 4D, has been developed in which these arrays can be positioned, allowing measurements perpendicular to the beam direction during VMAT delivery.

3.2. Pseudo-3D detectors

Recently a number of transmission chamber devices that have to be attached to the head of the treatment machine became commercially available. These devices measure the photon fluence exiting the linac head. The measured fluence can be used to calculate a 3D dose distribution in the patient anatomy in a similar way as done with an EPID-based in-air measurement shown in Figure 1c. Both approaches, as well as a dose calculation using a linac log file, can be considered as pseudo-3D techniques. They are designed to detect transfer errors from the TPS to the linac, and delivery errors by the linac when using them either pre-treatment or during treatment. If the dose calculation algorithm is different from that used in the clinical TPS, then these methods also check the 3D dose calculation for a specific patient treatment in an independent way. These systems do, however, not detect variations in patient anatomy or setup, i.e., cannot be used for in vivo dosimetry. It would, however, be interesting to assess their relation to EPID-based 3D in vivo transit dosimetry systems.

Both EPID-based back-projection approaches (Figures 1c and 1d), are able to reconstruct the 3D dose distribution in the patient anatomy from 2D EPID images, and can therefore be considered as

![Image](image_url)
pseudo-3D methods, a term which I prefer instead of “virtual 3D” systems used by Korreman [6]. One of the reasons is that the transit back-projection approach has the possibility to detect errors during real, and not virtual, patient treatments.

3.3. Full-3D detectors
To the best of my knowledge, the only dosimeters currently available that are able to measure a full-3D, sometimes called “true-3D”, dose distribution are polymer gel dosimeters and radiochromic 3D detectors. Understandably, sharing information about the further development and application of these detectors is one of the main purposes of this conference. The advantage of these dosimeters over most, if not all, of the semi-3D and pseudo-3D dosimetry systems is that they are tissue equivalent and can be molded into an anthropomorphic shape. They have the potential to be used as benchmarking tool for the commissioning of treatment plans of specific treatment techniques. Particularly when special IMRT or VMAT techniques or new treatments of a specific treatment site are clinically introduced, it would be helpful to have a full-3D dosimetry system in addition to the semi-3D and/or pseudo-3D systems presently used for that purpose. However, preparing these dosimeters is a time consuming process and the readout of dose after delivery is complicated. It is therefore obvious that at present full-3D dosimeters are at this moment not suitable for patient specific pre-treatment verification. The power of full-3D methods lies in their use for dosimetric end-to-end tests rather than for everyday use. In addition to end-to-end tests of clinically implemented irradiation techniques, full-3D dosimetry is also applied in pre-clinical studies, for instance for characterizing irradiations performed with small animal precision irradiators or synchrotron x-ray microbeams.

Regardless of its successful use for many applications, currently the technology of full-3D dosimetry is mainly restricted to research institutions. In other words, as mentioned by Schreiner in his IC3DDose 2014 presentation [20]: “However, despite its promise, true (BM: full) 3D dosimetry is still not widely practiced in the community. Its use has been confined primarily to select centres of expertise and to specialised quality assurance or commissioning roles where other dosimetry techniques are difficult to implement.” Hopefully during this congress newly developed dosimeter preparation and scanning techniques will be presented that can also be employed in a relatively simple way in a non-academic environment.

4. Final comments
Patient specific pre-treatment verification (“QA”) of IMRT/VMAT is often restricted to a check of the transfer of a plan from a TPS to the treatment unit and on its delivery, without performing a verification of the 3D dose distribution. Several studies have shown that there is a fundamental problem with such an approach, which is often unable to correctly differentiate an acceptable from an unacceptable plan [e.g., 18]. By comparing the various methods, EPID-based in vivo transit dosimetry might be a better approach to discover incorrect delivery of a specific treatment plan to a patient under clinical conditions.

Furthermore, in a number of institutions pre-treatment verification measurements are stopped after a certain number of checks, and replaced by an independent dose or MU calculation, in combination with a comprehensive QA program. For instance, the Netherlands Commission on Radiation Dosimetry recommends moving to calculation techniques after performing 100 or less experimental verifications of IMRT/VMAT for a specific treatment technique depending on the experience of the center, the complexity of the treatment, and if in vivo dosimetry is performed [21, 22]. In those situations the results of the dose/MU verification and in vivo dosimetry need to be evaluated before >20% of the total number of fractions is given.

EPIDs have a number of dosimetric characteristics that require a dedicated commissioning process to obtain highly accurate measurement results. It would be interesting if other types of transit dosimeters could be developed having, for instance, a less energy dependent response.

In vivo transit 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. EPIDs can in principle do that but more research is 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.

At this moment EPIDs are the only tools available for 3D in vivo dosimetry. Although there are a number of challenges related to their clinical use, 3D in vivo dose verification can be of great value in a department. The experience in some centers demonstrates that EPID-based 3D in vivo dosimetry 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 will be much more involved in assuring the quality of the actual patient treatment than when only performing a pre-treatment dose verification measurement.

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