3D EPID-based *in vivo* dosimetry for IMRT and VMAT

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Abstract. In this paper the various approaches of EPID-based *in vivo* IMRT and VMAT dose verification, and their clinical implementation, are described. It will be shown that EPID-based *in vivo* dosimetry plays an important role in the total chain of verification procedures in a radiotherapy department. EPID-based dosimetry, in combination with in-room imaging, is a fast and accurate tool for 3D *in vivo* verification of VMAT delivery. EPID-based *in vivo* dosimetry provides clinically more useful information and is less time consuming than patient-specific pre-treatment dose verification. In addition to accurate 3D dose verification, *in vivo* EPID-based dosimetry will also detect major errors in the dose received by individual patients, and provides a safety net for advanced treatments such as IMRT and VMAT.

1. Introduction

The implementation of IMRT and VMAT has increased the need for a high accuracy in the dose delivery to patients. For that purpose comprehensive quality assurance (QA) programs have been introduced to verify the correct functioning of all components in the radiotherapy treatment planning and delivery process. In addition to these QA programs of the separate components required for a patient treatment, often additional pre-treatment verification checks for individual patients are performed using a variety of phantoms in combination with ionisation chamber or diode arrays. With these different QA programmes in place, one may question the necessity for additional *in vivo* dose measurements during the actual treatment of an individual patient. The clinical use of *in vivo* dosimetry (IVD) in external beam radiotherapy has been addressed in a large number of studies, which were mainly related to the use of point detectors. Some review papers, for instance the recent IAEA Human Health Report Nr. 8 [1], identified a number of treatment errors by means of *in vivo* entrance and/or exit dosimetry during conventional radiotherapy. Also by means of EPID-based *in vivo* dosimetry a number of serious errors during 3D conformal radiotherapy [2] and IMRT delivery [3] were observed that could not have been detected by other QA checks using pre-treatment measurements. Although able to detect major errors, the main application of IVD is to assess all clinically relevant differences between planned and delivered dose. Another important aspect of IVD is that it also provides a record of the actual dose received by individual patients and fulfils legal requirements in some countries.

In this paper we will elucidate the current experience with EPID-based *in vivo* dosimetry for IMRT and VMAT dose verification, and the additional information that can be obtained compared to other patient-specific dose verification measurements.
2. EPID-based in vivo IMRT dose verification

2.1 IVD during IMRT
The use of EPID dosimetry has proliferated since several groups have demonstrated its unique possibilities for QA of IMRT, including IVD applications. Two approaches have been reported for using EPID-based in vivo dosimetry. In the first approach, a portal dose image with a patient in the beam at the position of the EPID is predicted using the planning CT data of that patient, which is then compared with a portal dose image measured with the EPID [e.g., 4]. A limitation of this forward approach is that it is not always clear how dose differences in the plane of the EPID are related to dose differences in the patient. Several groups have therefore explored back-projection methods for the derivation of the patient dose distribution from a measured portal dose image. These models require the primary dose component at the position of the EPID, which is obtained by correcting the EPID response for the scattered component inside the EPID, and the radiation scattered from the patient/phantom. This primary radiation component is then back-projected to a point inside the patient/phantom and the scattered dose at that position is added (see figure 1).

![Figure 1: Schematic presentation of the various steps involved in the reconstruction of the dose distribution inside a patient/phantom from an EPID measurement using a back-projection model.](image)

Nijsten et al [2] correlated the dose measured with an EPID on the central beam axis with dose values at 5 cm depth using a back-projection model having a (semi-) empirical relationship between these two quantities. Piermattei et al [5] reported a simple method for the in vivo determination of the midplane dose along the central beam axis using a transmitted signal measured by the central pixels of an a-Si type of EPID. Recently the first results of a national Italian project using this method have been published for photon beams generated by linacs of different manufacturers equipped with a-Si EPIDs [6]. The various back-projection models based on transit dosimetry have been discussed in a review article on EPID-based dosimetry by van Elmpt et al [7].

2.2 Clinical implementation of EPID-based in vivo dose verification of IMRT at NKI-AVL
In the Netherlands Cancer Institute-Antoni van Leeuwenhoek Hospital (NKI-AVL), back-projection algorithms have been implemented for the 2D and 3D dose verification of IMRT using a-Si EPIDs [8, 9]. For in vivo dosimetry, the reconstructed dose is generally compared for each IMRT field with the patient plan in a plane parallel to the EPID perpendicular to the beam intersecting the isocentre, i.e. by means of a multiple 2D approach. For some sites (e.g., breast) the isocentre is not always very relevant for in vivo dose verification and a new reference point and other planes are chosen for the 2D $\gamma$-evaluation. As an example, the results of a verification of a 6-field IMRT plan for oesophagus cancer treatment are shown in figure 2 to illustrate how EPID-based in vivo dosimetry is clinically implemented. The comparison of the EPID-reconstructed and planned dose distribution is done by a 2D $\gamma$-evaluation method (3%/3mm dose-difference and distance-to-agreement) using the mean $\gamma$-
value, the maximum 1% \( \gamma \) value (i.e. the 99th percentile of the gamma distribution) and the percentage of points with \( \gamma \leq 1 \) within the 20% isodose line of the planned maximum dose. In addition, the difference between the measured and predicted isocentre dose for each beam is provided, while the difference of the total dose is used as an alert criterion. The results of this analysis are given as an “EPID dosimetry report” for each patient. The yellow dot in the patient dosimetry report shown in figure 2 indicates that for fields 1, 2 and 6 at least one of the alert criteria is outside the tolerance level but still within the action level; i.e. a warning is given but the patient treatment may continue. The dose comparison is done versus the TPS dose calculation based on the anatomy in the planning CT scan. All curative patients at NKI-AVL are irradiated either with an IMRT or VMAT technique, and almost all are verified by means of EPID-based in vivo dosimetry during three fractions in the first week of their treatment.

| Field | OES0.1,100 | OES0.5,105 | OES0.4,50 | OES0.9,10 | OES0.2,150 | OES0.1,215 |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|
| G, C, T, E | 0.96,0.46,1.2,0.0,0.0 | 0.95,0.5,1.2,0.0,0.0 | 0.95,0.5,1.2,0.0,0.0 | 0.95,0.5,1.2,0.0,0.0 | 0.95,0.5,1.2,0.0,0.0 | 0.95,0.5,1.2,0.0,0.0 |

**Figure 2**: EPID dosimetry report showing the results of a 2D EPID-based in vivo dose verification of a 6-field IMRT treatment of an oesophagus cancer patient.

## 2.3 2D vs 3D IMRT dose verification

Verification of IMRT generally applies a 2D comparison of measured and planned dose distributions in a plane in a phantom, or patient, perpendicular to each IMRT beam, often using a \( \gamma \)-evaluation. 2D dose deviations in a single IMRT beam or segment may be diluted in the total 3D dose distribution and errors in the dose calculation or changes in the anatomy of a patient may no longer be detected. Furthermore identical criteria generally yield smaller \( \gamma \)-values in 3D dose verification than in 2D. These effects can clearly be seen by comparing figures 2 and 3. Figure 3 shows the results of a 3D \( \gamma \)-evaluation of the total dose distribution, which has a green dot, i.e., all alert criteria are within tolerance level. Stricter \( \gamma \)-criteria for 3D dose verification, such as 2%/2 mm or 2%/1.5 mm, or adapting the tolerance/action levels, might therefore be necessary to trace the same number of deviations as observed when using 2D dose verification. For these reasons at NKI-AVL the multiple 2D approach is still used instead of a full 3D analysis. More research is needed to assess optimal values for alert criteria for 3D verification of IMRT and VMAT treatments of various treatment sites. This information is not only required for the analysis of 3D in vivo dose verification,
but is also necessary for the evaluation of pre-treatment verification results. These studies are urgently needed because it has been shown by several groups that there exists a lack of correlation between passing rates based on $\gamma$-values during 2D verification of single IMRT fields, and clinically relevant dose differences, particularly with highly modulated fields [10-12].

![Figure 3: Results of a 3D EPID-based in vivo dose verification of the same 6-field IMRT treatment of oesophagus cancer as shown in figure 2.](image)

3D EPID-based dose distributions provide the possibility to determine dose-volume histograms (DVHs) in vivo. Important clinical parameters can then be estimated from these DVHs, such as the median dose ($D_{50}$), the near-maximum dose ($D_2$) and the near-minimum dose ($D_{98}$) in the target volume as recommended in the new ICRU Report 83 [13]. In this way it is possible to estimate the effect of an under- or over-dosage in a small volume on the overall dose distribution in the target volume or organ at risk. However, knowledge of the anatomical location of this volume, as well as its size and dose level at which failure occurs, are important properties to evaluate IMRT QA results.

3. 3D EPID-based in vivo VMAT dose verification

3.1 Clinical implementation of EPID-based in vivo dose verification of VMAT at NKI-AVL

For VMAT verification it was necessary to modify our software to incorporate gantry-angle resolved image acquisition as well as an automatic correction for the EPID panel flex. Furthermore, the 3D back-projection model applied for IMRT verification [9] was adapted to include the transmission of the primary dose calculated from planning CT data instead of using measured transmission data. The total 3D dose distribution is reconstructed and compared with the planned dose distribution using a fast 3D gamma evaluation algorithm [14], with 3% of the prescribed dose and 3 mm as dose difference and distance-to-agreement criteria, respectively. Details of the adaptation of our back-projection EPID dosimetry method for accurate 3D dose verification of VMAT can be found elsewhere [15].

3.2 Examples of clinically relevant deviations

The results of the 3D verification of each arc of a clinical VMAT plan are also presented as an EPID dosimetry report, similar to that for 2D IMRT verification. Figure 4 shows a dosimetry report of the 3D in vivo verification of a dual arc VMAT treatment of a head-and-neck cancer patient, and figure 5 of a hypofractionated lung cancer patient VMAT treatment, respectively. The pictures illustrate the results of the 3D gamma evaluation in a sagittal, axial and coronal plane through the isocentre, while the data for the various gamma evaluation parameters within the 50% isodose surface, as well as the total dose at the isocentre, are also given. If the total dose is deviating more than 3.0% a warning is given (tolerance level exceeded), while for a deviation larger than 5% an error report is sent to a physicist (action level exceeded). Gamma evaluation statistics are reported with site-specific
tolerance/action levels, which are for instance for the lung case: 0.50/1.00 for the mean gamma value, 2.0/4.0 for the maximum gamma value, and 85%/70% for the percentage of gamma values below one, respectively. The gamma evaluation data presented in figure 4 for the head-and-neck exceeded for both arcs the action level, while the measured dose at the isocentre was about 5% lower than the calculated value. Comparison of a cone-beam CT scan, made at the same day as the IVD measurement, and the planning CT scan showed that bolus was not present when making the planning CT scan. A new plan was generated with additional bolus material. Figure 5 shows that the results for the first arc of the hypofractionated lung case were OK but the data for the second arc were outside the action level. The cone-beam CT scan made after the second arc showed that the patient position was shifted about 1.5 cm between the two arcs. As a result of this observation, a cone-beam CT scan is now made routinely between the two arcs of hypofractionated VMAT treatments.

Figure 4: Results of a 3D EPID-based in vivo dose verification of a dual arc VMAT treatment of a head-and-neck cancer patient.

Figure 5: Results of a 3D EPID-based in vivo dose verification of a dual arc VMAT hypofractionated treatment of a lung cancer patient.

4. Discussion

4.1 Why 3D in vivo dose verification?
With respect to the verification of the patient position just before or during treatment, numerous in-room imaging tools are applied. Improved confidence in patient position during treatment does, however, not guarantee accurate dose delivery. It can, for example, not account for machine malfunctioning, data corruption, or changes in patient anatomy. The only way to directly verify that a patient received the correct dose during a given treatment fraction is to perform dose measurements
during that fraction, *i.e.* by means of *in vivo* dosimetry. By performing IVD it will be possible to correct in most cases for dose errors in a timely manner. Performing one or a few IVD measurements, in combination with in-room imaging, is therefore a very practical approach in assessing the actually delivered patient dose over a series of fractions.

After the reports about recent radiation incidents it is likely that more pressure will be applied from safety authorities on the radiotherapy community to make IVD obligatory. These issues have been mentioned by a number of organizations [*e.g.*, 1] to answer the question “Why *in vivo* dose verification?” The use of a variety of point detectors for IVD has been described in detail in reports published by these organisations to verify conventional and three-dimensional conformal radiotherapy techniques. However, there is an urgent need to perform also IVD of IMRT and VMAT. EPID-based systems are becoming available that allow *in vivo* verification of the full 3D dose distribution during these types of patient treatment. Combining 3D *in vivo* dose measurements with 3D in-room imaging will serve together as a proof that also these more advanced treatment techniques are delivered as planned [16,17]. It may be expected that this novel approach of verifying both geometry and dosimetry in 3D during the same treatment session will be the start of a new way of looking at “Why 3D *in vivo* dose verification?”.

4.2 Relation between *in vivo* dosimetry and other patient-specific dose verification methods

A drawback of applying *in vivo* dose verification maybe that part of the total dose has already been given before an error is detected, although this risk is reduced to a minimum when applying an online dose verification procedure. Certain types of error, *e.g.* in the dose calculation, can also be detected by means of phantom measurements before the start of a patient treatment. A large variety of instruments and methods is available for pre-treatment patient-specific dose verification. Pre-treatment dose measurements are generally performed in a homogeneous phantom, *i.e.* patient-specific anatomic information and tissue inhomogeneities are not taken into account, whereas these measurements are also often carried out under zero-degree gantry angle thus missing effects of incorrect gantry angle or gravity on dose delivery. Undoubtedly phantom measurements are an essential part of the commissioning process of a new IMRT or VMAT technique. It can however be argued whether patient-specific dose measurements are still useful after a certain number of patient treatments have been verified with pre-treatment phantom measurements considering the limitations of such an approach.

Pre-treatment dose verification is not capable of detecting a number of other errors due to, for instance, variation in patient anatomy or patient position, or the effect of immobilisation devices on the dose calculation and delivery. Furthermore, treatment parameters can (accidentally) be modified between pre-treatment verification and the first treatment. For these and other reasons, *in vivo* dosimetry is the only method capable of verifying the entire radiotherapy chain, including the actual patient treatment. Even if part of the total dose of treatments with multiple fractions has already been given before an error is detected by means of IVD, the remaining fractions can still be used to deliver the correct dose to the patient. The use of EPID-based IVD may in this respect be compared with the application of portal imaging; in both cases the actual treatment beam is used to verify during treatment the dose inside, or position of, the patient, respectively, applying online or offline decision protocols.

It should be noted that pre-treatment patient-specific verification measurements are generally performed by the physics team. These measurements should not be too cumbersome because the time required for this type of QA is proportional to the number of patients treated. By using IVD no additional treatment planning of a phantom irradiation or additional treatment time at the accelerator is necessary, while the measurements may be performed by radiation therapists. An additional advantage of IVD is therefore a reduction in workload compared to pre-treatment verification. Also an IVD measurement is often performed by the same people who irradiate the patient during the rest of their treatment, thus giving direct information about the situation during the actual patient treatment.
4.3 Final remarks

EPID-based IVD is until now performed in a routine way only in a limited number of institutions. The main reason that 2D and 3D in vivo dose verification is not yet applied on a large scale is that the dose reconstruction software only recently became commercially available, mainly for pre-treatment verification and not yet for IVD applications. Furthermore, software should include fully automated image acquisition and data analysis. Due to the large number of patients, there was an urgent need at NKI-AVL for automatic analysis of in vivo dose verification of IMRT and VMAT. Since August 2011 dose-reconstruction and γ-evaluation software runs automatically yielding a dosimetry report for inspection within minutes after treatment delivery without any manual intervention. In this way more time is available for medical physicists to investigate the reasons for differences between measured and planned dose calculations. For instance, checking the patient and treatment data of that particular fraction, as well as additional phantom measurements will be needed to explain deviating in vivo dosimetry results. Automatic analysis may also allow a more frequent use of IVD during a series of fractions, for instance at all days in-room imaging is performed.

5. Conclusions

EPID-based in vivo dosimetry, in combination with in-room imaging, is a fast and accurate tool for 3D in vivo verification of IMRT and VMAT delivery. 3D in vivo EPID dosimetry provides clinically more useful information and is less time consuming than patient-specific pre-treatment dose verification. In addition to accurate 3D dose verification, in vivo EPID dosimetry will also detect major errors and provides a record of the dose received by individual patients.

6. References

[1] IAEA Human Health Report Nr 8 2012 Development of Procedures for in vivo Dosimetry in Radiotherapy International Atomic Energy Agency (Vienna: IAEA)
[2] Nijsten S M J G et al 2007 Radiother. Oncol. 83 65-75
[3] Mans A et al 2010 Med. Phys. 37 2638-44
[4] van Zijtveld M et al 2009 Med. Phys. 36 946-52
[5] Piermattei A 2006 Med. Phys. 33 4414-22
[6] Piermattei A et al 2012 Nucl. Instr. Meth. Phys. Res. B 274 42–50
[7] van Elmpt W et al 2008 Radiother. Oncol. 88 289-309
[8] Wendling M et al 2006 Med. Phys. 33 259-73
[9] Wendling M et al 2009 Med. Phys. 36 3310-21
[10] Kruse J J 2010 Med. Phys. 37 2516-24
[11] Nelms B E et al 2011 Med. Phys. 38 1037-44
[12] Wu C 2012 Med. Phys. 39 3051-9
[13] ICRU Report 83 2010 J. ICRU. 10 (1) (Oxford University Press)
[14] Wendling M et al 2007 Med. Phys. 34 1647-54
[15] Mans A 2010 Radiother. Oncol. 94 181-7
[16] McDermott L N 2008 Radiother. Oncol. 86 35-42
[17] van Elmpt W et al 2009 Int. J Radiat. Oncol. Biol. Phys. 73 1580-7