Semi- and virtual 3D dosimetry in clinical practice

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Abstract. In this review, 3D dosimetry is divided in three categories; “true” 3D, semi-3D and virtual 3D. Virtual 3D involves the use of measurement arrays either before or after beam entry in the patient/phantom, whereas semi-3D involves use of measurement arrays in phantoms mimicking the patient. True 3D involves the measurement of dose in a volume mimicking the patient. There are different advantages and limitations of all three categories and of systems within these categories. Choice of measurement method in a given case depends on the aim of the measurement, and examples are given of verification measurements with various aims.

1. The role of 3D dosimetry in clinical quality assurance and technology development

The term 3D dosimetry is used to describe determination of delivered absorbed dose in a volume, typically as compared to the dose calculated in the treatment planning system. In the clinic, this type of dosimetric measurement is performed mostly in relation to patient specific quality assurance schemes.

1.1. Patient specific quality assurance

Patient specific QA is performed with the intention of ensuring that each treatment plan can be/is delivered such that the dose deposited in the patient is identical to the dose calculated and evaluated in the treatment planning system (TPS). The patient specific QA procedure must be performed using a measurement (dosimetry) system independent of the treatment planning and delivery systems, and should mimic as closely as possible the treatment situation.

Phantoms with embedded dose measurement arrays are therefore quite well suited for the purpose of these types of measurements when they are performed off-line. For patient specific QA, temporal resolution of detectors is not immediately relevant, as the property one really wants to measure is the accumulated dose to the patient for a specific treatment. Nevertheless, temporal resolution can be used to track the sources of any detected errors in a measurement.

The more complex a treatment plan is, the more warranted is the need for patient specific QA. Comprehensive commissioning and QA of all the subparts involved in the entire treatment chain is, however, by some regarded to render patient specific QA obsolete.

1.2. Commissioning

As part of the commissioning process of new equipment (hard- or soft-ware), it can be beneficial to run a number of actual patient plans and measure absorbed dose in a phantom in 3D. This tests the entire process of treatment planning to dose deposition end-to-end. Although a comprehensive
A programme of commissioning tests is planned, there may still be transfer and delivery issues which are not tested, particularly for the very complex cases of volumetric modulated arc treatments. Running a representative set of actual patient plans would give an indication as to whether or not such issues will arise in the clinical setting.

Additionally, propagation of small errors that are below tolerance levels during machine QA may in rare cases lead to significant deviations in actual treatment delivery.

1.3. Development and technology assessment

During development of a new treatment technique, it will often be essential to do occasional dose measurements to verify ability/accuracy of delivery with the new technique (debugging type action). This goes for development in delivery techniques as well as in planning techniques. Most often both high spatial and temporal resolution will be warranted for this purpose, and will often be more important than accumulated dose.

2. 3D dosimetry solutions – limitations and advantages

In this section, we will divide 3D dosimetry solutions into three categories; first category is true 3D dosimetry which coins at the moment only gel dosimetry, in the sense that this is the only measurement method which truly has the potential of presenting measured dose in a volume. The second category is termed semi-3D, and is characterized by measuring dose in a limited amount of points spread in the volume in which dose is delivered. The actual measurements can be said to constitute a sample of test points, but often calculation methods will be used to infer dose in the entire volume based on the few measurement points. The last category is termed virtual 3D, which is used to coin the feature that these systems do not in fact measure dose in a volume at all, but only infers dose by calculation from fluence type measurements performed either before or after beam entry.

2.1. “True” 3D dosimetry

Gel dosimetry is as close as we get to actually measuring absorbed dose in a volume. The focus of this review is commercially available 3D dosimetry and clinical use - gel dosimetry and development of this is described in detail in other papers in these proceedings, and we will hence defer from further description here. Instead only a few words will be said about limitations of gel dosimetry as compared to the more mature semi- and virtual 3D methods described in the sections below.

First of all, use of the term “true” dosimetry is of course misleading – a gel phantom is not the actual patient, and lacks the features of the patient (inhomogeneities), and most often also lacks the shape of the patient. The term true only refers to the 3D part in the sense that gel dosimetry can be used to measure dose in a volume rather than in sample points (see example in figure 1).

Also, the term “true” should not be mistaken to refer to the measurements as absolute dose measurements. In each gel phantom, the dose must be referenced to a benchmark measurement performed in the same gel batch and under controlled conditions (such as a simple depth dose). The biggest limitation of gel dosimetry is, however, the time issue; it is a time consuming process to prepare a reliable gel phantom, and it is a time consuming and delayed process to read out dose after delivery. Read-out can only be performed after delivery using separate technology, and temporal resolution of measurement is not possible.

2.2. Semi-3D dosimetry

Several of the major vendors of measurement equipment offer phantoms with built-in measurement arrays – this includes the OCTAVIUS with 2D-ARRAY seven29 (PTW Freiburg GmbH), the MatriXXEvolution with MULTICube (IBA Dosimetry), the Delta4® (ScandiDos AB), the ArcCHECK (Sun Nuclear Corporation).
Figure 1: Example of a prostate treatment plan delivered with RapidArc treatment technique to a gel (as described in (1)). The 80% isodose contours are shown for the measurement and the treatment plan as calculated in the Eclipse treatment planning system, and with two slices of the phantom shown in more detail.

All of this equipment consists of one or more measurement array(s) - ion chambers or diodes – embedded in a solid phantom (see figure 2). This kind of dosimetry measurement is here termed semi-3D – dose is measured in a limited number of locations giving a direct test in these sample points only, while dose in the rest of the volume must be inferred from the limited measurements. The different systems described above have different advantages and limitations because they use different types of detectors in different configurations. Ion chambers are used in the OCTAVIUS and the MatriXXEvolution, whereas in ArcCheck and Delta4 diodes are used. The advantage of diodes is their small spatial extent, which limits the dose smearing effect occurring with larger detectors when dose gradients are present. However, they are not very closely spaced in the phantoms, and some modulation may be “lost” between measurement points.

Ion chambers have a limit with respect to spatial resolution given by their larger volume (even with the so-called “pixel” ion chambers used in the MatriXX array), which in effect smears out measurements, thereby losing modulation and averaging dose gradients. On the other hand, ion chambers have the advantage of readily providing absolute dose.

Film can be used in the same way as described above by embedding the film in phantoms, and has the advantage of a much higher spatial resolution than an ion chamber or diode array. This is for instance relevant for volumetric modulated or IMRT plans, as these plans may contain a high degree of modulation, which can only be measured with high-resolution equipment.

Film, however, cannot provide temporal resolution of measurements, as opposed to all the other semi-3D equipment described here.

Temporal resolution of the measurement can be very useful for back-tracking the origin of potential errors which may be observed in the accumulated absorbed dose, specifically for advanced dynamic treatment delivery. If an error in the accumulated dose can be traced to stemming from one or more specific treatment delivery segments, it may be determined what the cause of the delivery error was. This information may in turn be used to make a decision on how to proceed in the specific case.
2.3. Virtual 3D dosimetry

An alternative to phantoms such as described above, is to use the portal imager of the treatment machine that rotates with the gantry. The imager often has both very high spatial resolution and temporal resolution. However, rather than actually measuring accumulated absorbed dose delivered by the treatment machine, it measures beam fluence. Some mathematical modeling (e.g., back projection) is needed in order to convert this measurement to a representation of absorbed dose accumulated in a patient (or phantom) over the treatment delivery. There are several both commercial and non-commercial software available to perform this conversion (2, 3).

Portal dosimetry of this kind can be used for patient specific QA, and has the advantage of being useful with the patient both off and on the couch. With portal dosimetry, the response of the portal imager detector array can be accumulated over the treatment, either beaming through air, a phantom or the patient. In principle, this check is primarily a fluence check, and in this sense, it is a check that the beam delivery is performed correctly. If this technique is to be used to check the accumulated dose to the patient, a back projection calculation is needed, based on a model of the patient - the CT scan for treatment planning or possibly an online cone-beam CT scan of the patient.

Another virtual 3D approach is to attach a measurement array (or film) to the gantry, to allow it to rotate along with the gantry much as for the portal imager. This approach is currently available with two different scopes; attachment of a phantom with an embedded measurement array at isocentre distance, and attachment of a transmission ion chamber array close to the gantry head immediately after the beam exit (see figure 3). The latter has the advantage of being potentially usable during actual patient treatment for online dosimetry. Again, this requires a patient model (CT scan or cone-beam CT scan) for forward calculation of delivered dose.
3. Focused use of 3D dosimetry

The choice of 3D dosimetry method and analysis method should be focused with regard to the aim of performing the measurement. In this section, considerations for appropriate choice of methods for a few examples of aims of dosimetry measurement will be given. First, a short description of common analysis methods for 3D dosimetry is given.

3.1. Analysis methods for 3D dosimetry measurements

The essential part of patient specific QA is to measure the actual dose deposited in a phantom mimicking the patient, or in the patient himself/herself. The measured dose is then compared with the dose calculated in the treatment planning system (as delivered to the phantom, not the patient). Comparison is most often performed using a gamma evaluation, in which both the dose difference and the geometric difference between measured and calculated dose is considered (4). In figure 4, an example is shown of measurement in a phantom with two orthogonal measurement arrays for a prostate volumetric modulated plan. Distributions are shown for dose differences at the measurement points, geometric distance to closest point of agreement, and for gamma values using 3 mm distance-to-agreement and 3 percent dose difference pass criteria. Appropriate pass criteria for gamma evaluation is an issue of debate, is dependent on parameters such as type of treatment, resolution of measurement equipment, and includes determination of the volume in which to perform the evaluation. Often a simple evaluation of gamma values will involve production of a frequency diagram of gamma values and a cut-off value for which a plan is considered overall to pass – for instance that no more than 5% of evaluation (measurement) points can have a gamma value above 1.

A limitation of gamma analysis is that there is no relation of the quantification of an error and specifically of the frequency distribution of errors to sensitivity of affected structures.

To complement gamma evaluation, dose-volume comparison is therefore occasionally also performed, and it is an additional feature in most commercial 3D dosimetry systems to provide this possibility. In short, a dose-volume analysis tool involves the inferred extrapolated (and interpolated) calculation of dose to the entire irradiated volume based on measurement points. Delineated structures are overlayed and dose-volume histograms are produced for the structures. These can then be compared to dose-volume histograms from the treatment planning system (for the phantom). A more sophisticated version of this feature performs the calculation of dose-volume histograms based on a CT scan of the patient and direct comparison can be performed to the dose-volume histograms of the treatment plan. As the measurements are performed in a phantom setup, this however requires a transformation of the measurements from the phantom to the patient.
Figure 4: Data from measurements performed using the Delta4® phantom for a prostate RapidArc® plan. (a) The output of detectors in the two orthogonal arrays are shown in the top, below are two output profiles through the arrays are displayed (at the positions of the dotted lines in the detector views). The lines indicate dose calculated in the treatment planning system, and the dots indicate measured dose. (b) For the same measurement, the lower plots show distributions of point dose deviations, distances to agreement, and gamma values (with 3% dose deviation, 3 mm distance-to-agreement). Above, in the detector views, the points with gamma values above 1 are highlighted. Images in the figure courtesy of Lotte Fog, Department of Radiation Oncology, Rigshospitalet, Denmark.

3.2. Verification of treatment plans with high degree of modulation

High degree of modulation in a plan can often be seen in relation to intensity modulated delivery, and specifically in volumetric modulated arc therapy. For verification of such plans, large detectors and/or poor spatial resolution is not well suited, because the modulation will be smeared out and/or “fall between” measurement points. For delivery with dynamics of MLC and/or gantry, it is also of relevance to have the possibility of temporal resolution of the delivery during measurement.

For the case of volumetric modulated arc therapy, measurements should be performed with the planned rotation of the gantry. It is a common simplification of patient specific QA to collapse all delivery into gantry angle 0° for simplicity. This should not be done for volumetric modulated arc therapy, as the gantry rotation is a key component of the treatment – for the RapidArc® solution, the gantry position is for instance the driving force for the DMLC positioning. As a consequence of the gantry rotation being an essential part of arc therapy, it is also essential that equipment used in the quality assurance of these techniques is suited to handle gantry rotations. The equipment must therefore exhibit little or no angular dependence.

In light of the considerations stated above, a well suited dosimetric system is a virtual 3D system, using the portal imager. There is high spatial resolution with small detectors, high temporal resolution, and no angular dependence (the portal imager is inherently independent of gantry angle as the angle of
incidence of the radiation does not change). The limitation is that there is no actual measurement of absorbed dose. If this is wanted, semi-3D dosimetry systems Delta4 or ArcCheck, both with small detectors, temporal resolution and little angular dependence, may be used. Limitations of these are that the spatial resolution is not high and a high degree of modulation may fall between measurement points.

3.3. Verification of dynamics of 4D plan
Although 4D treatment using dynamic MLCs to track the respiratory movement of the target is not in clinical use yet, it is worth discussing this case as well, in relation to measurements performed in the scope of development of the 4D technique.

Special for this kind of treatment is that the target is moving, and it is particularly the ability of the treatment technique to track this movement. The measurement system must therefore emulate the target movement. This can be done using moving platforms on which to place the measurement phantom – platforms able to move in 3D, and programmable to perform motion mimicking actual patient target motion traces are preferable. Such a platform is for instance the HexaMotion® provided as an addition to the Delta4 phantom – another independent platform is the 4D phantom sold by Washington University.

The verification process is not aimed at verifying the plan itself, but to verify the ability to track motion. Temporal resolution is obviously necessary, and it is also necessary that spatial resolution is good enough to distinguish displacement of dose of the same magnitude (and less) of the phantom motion.

3.4. In-vivo dosimetry type QA
This type of measurements are performed with the aim of verifying the actually delivered to the patient during treatment. The classic in-vivo dosimetry measurement is performed as a point measurement on the patient surface using for instance a diode (5), but it is also a possibility to use virtual 3D dosimetry to provide a measurement on which (an estimate of) the dose in the patient can be inferred. In order to infer the actual delivered dose plausibly, back projection to a model of the patient must be performed – preferably to a model reflecting the actual patient setup and anatomy of the day, that is a conebeam CT scan.

This type of measurement requires use of either portal dosimetry or transmission chamber dosimetry – the advantage of the latter being that dose is measured (as transmission arrays are ion chambers), and the advantage of the former being the high spatial resolution of measurement points in the portal imager. The limitation of the latter is the poor spatial resolution which makes it less useful for clinical cases in which high precision is warranted.

An additional use of this type of virtual in-vivo dosimetry is that it can readily be used for plan-of-the-day adaptive treatment, in which the treatment plan is adapted to the daily anatomy of the patient based on conebeam CT, and the accumulated delivered dose of previous treatment fractions is incorporated. This is a concept which has been suggested in a number of publications (see for instance(6)), and has even been elaborated as a technique to account for respiratory motion (7). In the latter case, it is also relevant to use the temporal resolution of the measurements, which is available for all virtual 3D dosimetry systems.

3.5. High precision dose delivery verification
Examples of treatments in which it is relevant to measure dose with high accuracy are for instance cases that involve risk of dose spill into highly sensitive volumes in the patient, or small targets with high doses. In such cases, it may be necessary to take special precautions to ensure that dose is delivered according to plan in the sensitive volumes. It will usually be relevant to combine high spatial resolution with high accuracy in dose measurement. Virtual 3D dosimetry using the portal imager may not be well suited due to the lack of measurement of delivered dose (although the spatial resolution is good enough (8)), but on the other hand, virtual 3D dosimetry using transmission arrays are also not well suited due to the poor spatial resolution.
Semi 3D dosimetry generally do not show high spatial resolution, although the systems using diodes (Delta4 and ArcCheck) do have measurement arrays with small measurement volumes and closely spaced diodes. In the case of the Delta4 phantom, the phantom may be positioned and oriented such that the measurement arrays have their areas with highest spatial resolution in the sensitive volume.

For these kinds of measurements, it appears that true 3D dosimetry – gel measurements – is the only method that is really well suited. The limitation obviously is that this can only be done as pre-treatment verification, so that it may be even better to combine with in-vivo type measurements as described above.

4. Summary
In this review, 3D dosimetry is categorized as either “true” 3D, semi-3D or virtual 3D, with different advantages and limitations of all three categories. Virtual 3D involves the use of measurement arrays either before or after beam entry in the patient/phantom, whereas semi-3D involves use of measurement arrays in phantoms mimicking the patient. True 3D involves the measurement of dose in a volume mimicking the patient.

It is stressed that choice of the proper measurement method depends on the aim of the measurement. With different measurement systems and setups, different types of errors can be detected. A few examples have been given with different aims for verification measurements, and the limitations and advantages of different measurement systems for these examples have been elaborated.

Last, it should be said that the use of 3D measurements in general is important in quality assurance for radiotherapy, as should hopefully be evident from the review above. The types of errors detected when performing measurements cannot be completely predicted, even though the aim of the measurement is well defined. Often we will be surprised to find unexpected types of errors leading to the need for further and maybe other measurements – we meet the “green aliens” of dosimetry (expression gratefully borrowed from Lotte Fog, physicist at Rigshospitalet, Copenhagen). This is a good reason for performing measurements regularly, even when we believe we know our machines and treatment techniques well.

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