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Comprehensive Review Of Small Field Dosimetry

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Abstract: The small static and composite fields occur in clinic while implementing Intensity Modulated Radiotherapy (IMRT), Volumetric Modulated Arc Therapy (VMAT), Stereotactic Radiosurgery (SRS) and Stereotactic Body radiotherapy (SBRT). These small fields are limited by constrains related to radiation beam origin and the measurement instruments available in the field. The clinical need of these fields is in achieving the homogenous and conformal dose in the tumour. The radiation beam source cannot be modified in any radiation unit until a change in its design is done. So, the range of radiation detectors like ionization chambers, scintillation detectors, silicon diodes and films have been extensively used for small field dosimetry. The plastic scintillator Exradin W2 has been tested to be the best available detector among the range of detectors for small and very small fields. The use of any detector in small field dosimetry must be accompanied by another standard detector and the data should be supported by Monte Carlo simulation studies if possible. Also, appropriate choice of Patient Specific Quality Assurance (PSQA) device is necessary to ensure the accurate dose delivery to the patients.

Keywords: Small field dosimetry, Detectors, Plastic Scintillators, patient specific QA.

Introduction

The use of small static and composite fields has significantly increased in past few years. The inception of modern sophisticated radiotherapy units like GammaKnife (Elekta AB Stockholm, Sweden), CyberKnife (Accuray Inc. CA), Tomotherapy (Accuray Inc. CA) and Brainlab (Brainlab AG, Germany) and sophisticated collimator systems have made it very easy and user friendly to implement the Stereotactic treatments in clinic. Although, the complexity in technical operations, these systems promises very conformal dose delivery to the tumours while the resulting sharp dose fall-off helps sparing surrounding normal tissues[1-4]. The tailored dose distribution can be achieved very efficiently by the small field openings ranging from 2 cm to submillimeter levels.

The static collimator openings in modern GammaKnife units ranges from 4 mm to 16 mm in a hemispherical arrangement, in TomotTherapy the variable openings can be achieved by binary operation of multileaf collimators (MLCs). The CyberKnife units have iris of different openings and can deliver radiation from various directions. The Brainlab microMLCs have variable openings with a minimum leaf width of 2.5 mm. The planar and non-coplanar beam delivery results in more conformity and reduced plan complexity [5-8]. The conventional linear accelerators have the standard MLCs of 1 cm, 0.5 cm and 0.25 cm width to modulate

the radiation beam fluence. The fluence is delivered by a series of static or dynamic leaf segments forming a composite field.

The clinical advantages of these technologies are only possible if the small radiation fields are modelled accurately in the treatment planning systems (TPS) and their dosimetry is performed with profound accuracy and confidence with high precision. The high dose rate flattening filter free (FFF) beams, which are new to the conventional radiation units are also being extensively used in radiosurgery application, owing to their advantage of high dose rate and hence reduced treatment time [9-10]. Also, there is change in beam spectra with decreasing field size which poses another challenge. The small field dosimetry is limited by various constraints related to radiation beam source and the dosimeters used for measurements. It is emphasized that the acquisition of radiation beam data should be done by a Medical Physics expert, rather than simply accepting the vendor's data for patient treatment, especially for treatments involving small and complex fields [11 , 12].

Numerous researches have been published describing the dosimetry of small fields, detectors for small field dosimetry and its clinical implementation. This article aims to review the basic physics of small photon fields, their dosimetry formalisms and approaches for PSQA in treatments involving small fields, keeping in mind the current commercial availability of the equipment.

Physics of small fields

Theory of Small Radiation Fields: There is no consensus definition as to what constitute a small field. However, the field size less than 3×3 cm^2 is widely being used and is considered outside conventional treatment field and needs special attention [13-15]. In more details, the Institute of Physics and Engineering in Medicine (IPEM) defines a small field as "***the field having dimensions smaller than the lateral range of charged particles that contribute to the dose deposition at a point of measurement along the central axis"***. Generally, a field size smaller than 4×4 cm^2 is treated as nonconventional. This field size less than 3×3 cm^2 for a 6MV photon beam are referred to as small field [16-17,19].

Charles et al. [14] has defined a field size of lateral dimensions smaller than 15 mm as very small field. He has simulated a 6 MV beam in BeamNRC [18] MC code to include the effects of collimator scatter and source occlusion individually. This approach demands special attention in selection of detectors for very small fields and also, to check the accuracy of beam models for such small beam openings.

The small fields are limited by photon source related and detector related constraints. The small field parameters are affected by partial occlusion of radiation beam source, which cause a decrease in radiation output and extension of penumbra width over field edges and a breakdown of the classical definition of radiation field size by Full Width Half Maxima (FWHM) [13, 15-17, 19-20]. Also, beam hardening has been reported with decreasing collimator openings. Another limiting factor is the availability of suitable detectors for small field dosimetry. Most active dosimeters have limited resolution in small and relatively inhomogeneous beam and cause a measurement error along the measurement direction. Under the effects of volume averaging and response variations, low density detectors under respond and high density detectors over respond in the medium [21-22]. The effect is more pronounced in heterogeneous media. Alongside, the density effect of detectors produces large perturbations breaking down the ideal Bragg-Gray conditions [23-25].

These conditions pose a serious challenge to the Medical Physicists in selection of appropriate radiation detectors, strategies for beam data measurements in small and very small static and composite fields. Concerns raise regarding the accuracy of beam modelling,

specially the transport of secondary charge particles generated by interactions in TPS according to the requirements of the algorithms.

Formalism for Small Field Dosimetry

International Atomic Energy Agency (IAEA) and American Association of Physicists in Medicine (AAPM) has published a report about the dosimetry of small and non-standard fields [28]. This report gives the guidelines for small field dosimetry in conventional and dedicated radiosurgery systems. The formalism follows the recommendations of the international dosimetry code of practice (CoP) of IAEA [26] and AAPM [27] based on absorbed dose to water (N_{DwQ_0}) calibration.

This formalism has suggested three different field definitions to be considered for dosimetry of specialized and complex treatments. The machine specific reference field (f_{msr}) has been suggested for those fields, where the conventional reference field (f_{ref}) of 10 × 10 cm^2 cannot be established. This field must be as closely possible equivalent to f_{ref}. Also, a traceability chain has been given between the f_{msr} and the calibration laboratory. The concept of plan class specific reference (f_{pcsr}) and clinical field (f_{clin}) have also been given. The f_{pcsr} can be either be a single field or segment sequence for which full charged particle equilibrium can be achieved in dosimetry. The f_{pcsr} can be a 3D irradiated volume or a 4D delivery sequence formed by small composite fields. The f_{clin} tends to be the clinical field at the time of dose delivery to the patient.

This new formalism is most applicable for the nonconventional delivery systems like GammaKnife, CyberKnife, BrainLab and TomoTherapy. The formalism has same recommendations as that of international CoP for conventional linear accelerators performing SRS.

More recently, IAEA has adopted and modified the recommendations of Alfonso et al. [13] in a new CoP for reference and relative dosimetry of small radiation fields used for external beam radiotherapy with energies of nominal potential of 10 MV [28]. This approach has also considered the FFF beams. This protocol does not have mention of any other modalities like electrons and protons etc. It is based on the use of a ionization chamber that has been calibrated in terms of absorbed dose to water $N_{Dw,Qo}$ or $N_{Dw,Qmsr}$ in a standard's laboratory's reference beam of quality Q_o *or* Q_{msr} respectively. It also provides guidance for measurements of field output factors and lateral beam profiles at the measurement depth. The aim is to establish uniform approach of small field dosimetry.

2.3. Detectors for small Field Dosimetry

The stereotactic fields demand for a detector with very high resolution and very small volume having high sensitivity [20, 29]. Many researchers have studied the parameters like excellent spatial resolution, a linear response with dose and dose rate, tissue equivalence, stable short-term readings, isotropic response, low energy dependence and minimal background signal. A wide range of detectors have been used in small fields including small volume ionization chambers, solid state detectors like shielded and unshielded diodes, scintillators and diamonds, MOSFETs, TLDs, OSLDs, radiochromic films and chemical dosimeters [28,30]. Some recent studies have discussed the feasibility of Dose Area Product and Cherenkov radiations in small field dosimetry owing to its advantages of nearly zero perturbations in the radiation field.

Ionization Chambers: The ionization chambers have been in use for radiation dosimetry from a long time and are current standard for dosimetry of radiation beams. The calibrations are all traceable to the ionization chambers of standard labs. These have been found to be most reliable for dosimetry of small fields. Also, the calibration in terms of absorbed dose to water N_{DW} is most commonly available for ionization chambers only. Moreover, the ion chambers are easily commercially available, less expensive, known history of stable response

in a range of radiation beams, user friendly and hence has always be used either a primary or reference dosimeter in small field dosimetry [31-34].

The traditional thimble type ion chambers of volume 0.3 cc – 0.6 cc are not suited for small field dosimetry, due to large perturbations and volume averaging that leads to underestimation of radiation dose at measurement point along beam central axis (CAX). The small volume mini and pin-point ionization chambers have been tested for their response and shows stable response for field size down upto 2×2 cm^2, but below that these also shows perturbations and volume averaging. However, the micro chambers of volume 0.002 cc – 0.01 cc to some extent shows promising results in small and very small fields but are limited by their low sensitivity and effects of stem and wire irradiations[34-39].

Liquid ion chambers have been tested in small fields owing to their nearly water equivalent density and hence unit mass stopping power and mass energy absorption coefficient ratios. These detectors have high resolution even at small volumes and not compromised by sensitivity simultaneously. But the liquid ion chambers are currently unavailable commercially and hence cannot be evaluated further [40-41].

Silicon Diodes: The semiconductor technology has revolutionized the world with its compact designs and rapid response [21, 32, 42-45]. These have been used in several applications in radiotherapy. The diode detectors have been used for relative and in vivo dosimetry very extensively. Commercial diode detectors are available with various vendors in range of volumes ranging from 0.02 mm^3 and much smaller. The diodes are necessarily very small volume, highly sensitive and hence suited for small field dosimetry. The diodes are seen to show higher directional dependence and hence are advised to use in an orientation with its symmetric axis parallel to beam central axis.

The unshielded diodes (electron diodes) have been seen to show relatively better response in small fields than the shielded diodes (photon diodes). The photon diodes under respond the low energy scattered radiations due to tungsten shield [44].

Diamond Detectors: The diamond detectors have small volume and uniform structure that makes it suitable for dosimetry with minimal perturbations [47-48]. The diamond detectors have electron density nearly equivalent to that of human tissue and hence the corrections required are very small, also, due to this, the mass stopping power and mass energy absorption ratios varies to very small extent making it nearly energy independent. These characters make diamonds very suitable for small field dosimetry. The natural diamonds, which were initially used, has to be provided a bias voltage of 800 V, but the modern diamond is synthesized by chemical vapour deposition (CVD) technique and shows best results at zero bias [49-50].

Plastic Scintillator Detectors: Plastic and organic scintillators are based on the principle of scintillation dosimetry, where the detected photon energy is transported through a photomultiplier tube to produce the signal proportional to the absorbed dose. These scintillators have seen to show very stable response in small fields. These have small yet highly sensitive volume and profound stability making it superior to other detectors [44, 51-54]. The plastic scintillators require very small corrections due to their nearly tissue equivalent density and has seen matching with the Monte Carlo simulation results [25, 36]. The only issue in scintillators is the presence of Cherenkov light radiations, the methods for correction of which have been proposed [48].

Chemical Dosimeters: Various chemical dosimeters including the radiochromic films have been tested in small fields. The EBT 2 and EBT 3 radio chromic films have shown very stable response and provide indeed the highest resolution [44, 48, 55-57]. However, these films are limited by their mild response to Ultra-Violet (UV) radiations which may produce errors in photon dose estimation. Also, the films are limited by their dose and dose rate ranges.

Fricke dosimeter and its derivatives have been tested in small field dosimetry and has shown very good response. The response of chemical dosimeters is read by the UV spectrometry method, which has seen limiting the dose range and resolution of these chemicals [58-59]. The suggestions of using Fourier Transformation Infra-Red (FTIR) or Nuclear Magnetic Resonance (NMR) for readout is however to enhance the accuracy of these detectors but simultaneously imposes a burden on the department budget and space requirements [58, 60].

Equipment for PSQA

The delivery of high dose per fraction in small fields is challenging the dosimetry in every aspect. In previous sections we have discussed the physics and dosimetry of small fields for commissioning and reference dosimetry. It is highly recommended by several national and international bodies to perform the pretreatment PSQA to check the accuracy of dose calculation, plan transfer and treatment delivery. The PSQA is necessarily required to ensure the patient safety and enhance treatment quality [61-62].

Various commercial systems are available for PSQA, ranging from the point ion chambers to diodes, two-dimensional films and detector arrays and three dimensional dose reconstruction methods [40, 49, 52]. These commercial systems are either air or liquid filled ionization chamber based or based on diode detectors in a two-dimensional fashion. PTW (PTW Dosimetry, Germeny), IBA (IBA Dosimetry, Germeny), Sun Nuclear (SNC, USA) and Standard Imaging (Standard Imaging Inc., USA) are the key commercial vendors that provide 2D and 3D detector arrays for pretreatment dose verification. Most vendors are providing solutions for small field dose verification either in the same conventional detector array or as a separate detector array. The associated, data analysis software utilize the approach of dose difference and distance to agreement or combination of both in a single parameter called gamma index (γ) analysis. 2D and 3D gamma analysis and anatomical dose maps are provided in most of the systems [63-64].

The major requirement of a PSQA systems is to have a dosimetry system with highest resolution, rapid response, real time data analysis and fast setup. The conventional film scanner based system however provides the best resolution but have limitations in other parameters like its response and readout times which cannot give real time results. The commercial systems fulfil the requirements with an accuracy equivalent to or better than the conventional film scanner system [65].

AAPM TG 218 [65] has extensively discussed various guidelines for the PSQA in IMRT on various systems and also compared the vendors providing the PSQA dosimeter systems. These guidelines provide a set of tolerance and action levels for IMRT plan verification. These guidelines should be considered while establishing the PSQA plan in clinic for best outcome of results.

Discussions

The small fields which usually occurs in the SRS treatments and in standard IMRT forms the composite fields. The main constraints on these fields are source occlusion and availability of suitable detectors. These constraints have been identified very early by Duggan [20] and Das [29]. The impact of these parameters on the small field dosimetry is a reduction in beam output, breakdown of FWHM to define field size by extension of penumbra edges and beam hardening. The non-availability of sophisticated detectors has made it more difficult to perform reference and relative dosimetry [13, 17, 19, 66]. With increasing use of small fields in clinic a unified formalism for small field dosimetry was postulated by Alfonso et al. [13] that discussed the use of f_{msr} in clinic and its traceability to the calibration conditions.

The definition of very small field size by Charles et al. [14] seems to be an awakening work to attract attention towards these fields, this definition however needs a more specific approach considering all types of beam defining arrangements such as MLCs, Jaws and Cones etc. Also, the knowledge of all suitable detectors available, to give more accurate

definition of small fields. It should consider the factors that determines the scale that a radiation field has to be considered small or not.

The IAEA AAPM TRS 483 has modified the formalism of Alfonso et. al. [13] with little modifications and extension to FFF beams [28]. This CoP has been evaluated by Haq et al. [67] and they found that it has good correlation with the conventional CoP of IAEA and AAPM for reference and relative dosimetry. They provided correction factors for several detectors in f_{msr} on two different linear accelerators and suggested their use in clinical practice. International Commission on Radiation Units and Measurements (ICRU 2014) has suggested a more regressive use of Monte Carlo simulations in small field dosimetry to determine accurately the correction factors mentioned in these protocols [68]. This CoP has provided a detailed formalism for dosimetry and choice of dosimetry system and should be followed for small field dosimetry.

Regarding radiation source related constraint of small field dosimetry, the scope in changing the design of source or beam collimation mechanism is very small in conventional settings. The major work has to be done on the radiation detectors. Various investigators have studied a set of commercial dosimeters for small field dosimetry [13, 16, 20, 21, 32, 34, 43, 69-70]. Emphasis is given on the use of very small volume, highly sensitive detector having stable response for dosimetry of these fields. The detector must also not be affected by change in beam spectra, as in small fields the beam hardening takes place.

Ionisation chambers have been standard choice for dosimetry since very long. These are found to be very stable in all beam conditions. The micro ionisation chambers have been tested in small fields and has shown good results in small fields down upto 2 cm. Bouchard et al. [21] has studies the micro ionisation chambers down upto 1×1 cm^2 in a daisy chain method to determine machine specific correction factor and has shown that PTW 31014, PTW 31006 and IBA CC01 ionisation chambers have excellent results in terms of reproducibility and stability. But, volume averaging and reduced resolution tend to violate the cavity theory conditons and hence cause an underestimation of radiation doses. Owing to this, Charles et al. [14] has suggested to measure the beam profiles and output factors simultaneously for any particular field size to reduce such variations. It is also suggested to make use of atleast two detectors to measure radiation beam parameters in small and very small fields. Moreover, the dielectric liquid filed ion chambers had been a classic solution for small field dosimetry, but it is no longer commercially available.

In recent times the detector technology has been revolutionised with commercial vendors providing alternatives to the conventional ionisation chambers for relative dosimetry in small fields. The shielded and unshielded diodes have been tested very extensively in small fields and have some superiority in terms of its resolution. PTW diode 60018 and IBA SFD (unshielded diode) has shown good response in small fields upto 1×1 cm^2, however the PFD (shielded diode) has larger variations in small fields [56]. These solid state detectors are limited for relative measurements of beam profiles and PDD data. In output factor measurements there variations have been reported even with the latest available diodes [51 , 71]. Due to large variations in their constructions and their limited lifetime, they are not stable and hence can't be used for reference dosimetry.

The PSDs have been tested in recent times very extensively [54 ,72]. PSDs have small volumes, nearly tissue equivalent and has high sensitivity. Debnath et al. [48] has recently developed an inorganic scintillation detector for use in small fields. They have tested it in small fields upto 0.5 0.5 cm2 for output factors, absolute dose and PDD measurements and found small variations of upto 0.5%. Casar et al. [60] have determined correction factors for various diode detetors in accordance with IAEA AAPM TRS 483 guidelines. They have adopted Exradin W1 PSD as standard dosimeter along with the EBT 3 films. They have recommended their data as reference class and addenum to TRS 483.

Recently Galavis et al. [72] have compared the Exradin W1 scintillator with novel Exradin W2 scintillator. The issues of cherenkov radiations in W1 scintillator caused variations in signal which has been temperature dependent. The Exradin W2 scintillator is provided with an electrometer system to correct for the cherenkov radiations. Moreover its correction factor has been found 1.0 and hence an ideal detector for measurement of output factors, beam profiles and dept dose data [72].

Several investigators have studied different detectors for small field dosimetry and the only thing common among all thse studies was the EBT films (EBT 2 and EBT 3)used as reference dosimeter [56 , 57]. The films have quality of highest resolution along with its stable response and once calibrated the whole batch can be characterised with the same calibration curve. Hence it is suggestive to use the gafchromic films along with any other detector for verification of small field parameters.

Concept of using dose area product (DAP) for small field dosimetry has been discussed previously [73] In the scinario where most of the conventional dosimeters fails, the dose can be estimated by using a large diameter plane parallel chamber the dose can be integrated as function of area i.e. field size. It is also suggested to use ratio of DAP at 20 cm dept to that at 10 cm dept ($DAPR_{20,10}$) for beam quality specifications in narrow beams [74]. This method has been tested by against Monte Carlo simulations and found within 1% variation to the conventional beam quality specifier; Tissue Phantom Ratio ($TPR_{20,10}$).

The DAP is at present being used for dosimetry of interventional radiology applications, and its use in Radiotherapy has never been reported earlier. Also, no specific detectors are available for this application. However, the DAP concept is very unique at this time, which can be used with minimal perturbation of the radiation beam. This concept must be taken for further research and standardisation for small field dosimetry in clinic, the commecrial large area plane parallel chambers designed for proton therapy dosimetry can be studied for this application in photn beams.

Another emerging concept of estimating Cherenkov light radiation [75] for small field dosimetry has been postulated. Glasar et al. [77] A water tank doped with tracer amounts of fluorophore for better light emission has been utilized. The detection was done through lateral detection using simple CMOS camera with room lights off. The authors have presented different imaging approaches namely 1) simple detection of depth dose and off axis beam profile and its agreement with reference; 2) the three dimensional tomography of such beams using the filtered back projection method to recover 2D and 3D volumetric data by rotation of phantom camera assembly and to obtain a real time two-dimensional imaging of IMRT and VMAT plans in water phantom by Cherenkov imaging.

These methods show good agreement with the TPS values, but the 3D volumetric acquisition and 2D image seems a less feasible method as it can only be done for a research dedicated setup. This is a revolutionary concept as the Cherenkov radiations do not have any field size or depth dependent response, thus can be utilized in small field dosimetry very efficiently and accurately [76, 78, 79].

The pretreatment patient dose verification QA has been a paramount requirement for each IMRT treatment as highlighted by AAPM [65]. The small treatments involving small fields require special attention in this case, especially when the dose per fraction is very high. Investigators [40, 80, 81] have characterized the commercially available detector arrays PTW 1000 SRS for SRS QA and has found it highly stable and suitable for such QA requirements. They suggested that its spatial resolution is adequate enough to validate the static and composite field QA. The results of this device were found to be equivalent to the EBT 2 film.

The γ passing criteria has also been discussed and it is emphasized that considering the large fraction size and small number of fractions in stereotactic Ablative Body radiotherapy (SABR), the demand for accuracy in gamma passing and its stringent limits has been

increased and need careful implementations of the QA Programme as it involves the small composite fields, dosimetry of which is limited by several constraints. Also, it has been shown that the passing rates are dependent on the modulation index, and as the modulation increases, the number of segments with small size increases. Thus, careful choice of detectors and institute specific protocols are needed for such sophisticated system, considering the problems in small field dosimetry. The authors guide towards a stringent criterion of gamma passing in SABR and implementation of a 2D detector array [55, 82]. Also, it is seen that SABR VMAT plans with a gamma passing criterion of 2%/1mm global, and find that this criterion is most efficient and sensitive towards errors.

The implementation of exact standard approach of gamma analysis in the commercial software is always a concern as AAPM 218 [65] has discussed. Also, more stringent requirements of gamma analysis as discussed above are required to be implemented to identify the errors which may reduce the pass percentage of analysed points. Schmitt et al., [83] has recently given guidelines for implementation of SRS and SBRT in clinic, these guidelines must be followed for a comprehensive patient treatment course. The recent standard guidelines [3, 5, 84] gave a thorough reference for all types of clinical and Dosimetric aspects of small fields and should be implemented.

Conclusion

The small static and composite fields are commonly occurring in modern day radiotherapy. Rather it be dynamic IMRT, VMAT or stereotactic treatments, the small fields play its role in achieving dose conformity and reduce the normal tissue toxicity. It must always be borne in mind that these complex treatments need due care and standard mechanism for their implementation in clinic. The detectors must be chosen owing to clinical need, extensive survey of literature and budget load of the institution. The plastic scintillators have been proved to be the best choice till time for small fields, however, it must be cross examine with other standard dosimeter like film of ionization chamber. The Monte Carlo simulation studies are also an important aspect in radiotherapy dosimetry, hence its suggested to make use of these simulations to validate the clinical data and determine correction factors. For PSQA, the detectors available must be characterized and tested in small fields and clinic specific action levels and passing criteria must be set following the standard guidelines. It is highly suggested to follow standard guidelines while implementing the small fields in clinic.

Conflict of Interest No conflict of interest

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