Physica Medica 45 (2018) 117–126

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

Original paper

A novel high-resolution 2D silicon array detector for small field dosimetry with FFF photon beams

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ARTICLE INFO

Keywords:
SRT
SBRT
FFF
Small field dosimetry QA
2D monolithic silicon array detector

ABSTRACT

Purpose: Flattening filter free (FFF) beams are increasingly being considered for stereotactic radiotherapy (SRT). For the first time, the performance of a monolithic silicon array detector under 6 and 10 MV FFF beams was evaluated. The dosimeter, named "Octa" and designed by the Centre for Medical Radiation Physics (CMRP), was tested also under flattened beams for comparison.

Methods: Output factors (OFs), percentage depth-dose (PDD), dose profiles (DPs) and dose per pulse (DPP) dependence were investigated. Results were benchmarked against commercially available detectors for small field dosimetry.

Results: The dosimeter was shown to be a 'correction-free' silicon array detector for OFs and PDD measurements for all the beam qualities investigated. Measured OFs were accurate within 3% and PDD values within 2% compared against the benchmarks. Cross-plane, in-plane and diagonal DPs were measured simultaneously with high spatial resolution (0.3 mm) and real time read-out. A DPP dependence (24% at 0.021 mGy/pulse relative to 0.278 mGy/pulse) was found and could be easily corrected for in the case of machine specific quality assurance applications.

Conclusions: Results were consistent with those for monolithic silicon array detectors designed by the CMRP and previously characterized under flattened beams only, supporting the robustness of this technology for relative dosimetry for a wide range of beam qualities and dose per pulses. In contrast to its predecessors, the design of the Octa offers an exhaustive high-resolution 2D dose map characterization, making it a unique real-time radiation detector for small field dosimetry for field sizes up to 3 cm side.

1. Introduction

Stereotactic radiotherapy (SRT) techniques, of which stereotactic body radiation therapy (SBRT) is an example, are a form of external beam radiotherapy (EBRT). These treatments deliver high doses in just a few fractions, up to 45 Gy/fraction in the case of SBRT, using small radiation fields [1,2].

Codes of Practice for quality assurance (QA) in the case of small field dosimetry have been only recently outlined [3,4]. Challenges associated with this scenario are beam related, such as partial occlusion of the primary source and loss of CPE on the central axis, and detector related, relative to its dimensions with respect to the field and its perturbation effects on the particles spectra [3,4]. These conditions, resulting in overlapping penumbrae over the detector volume, may affects its readings, thus the accuracy of the treatment planning system (TPS) in predicting dose distributions. Dosimetric inaccuracies may lead to poor outcomes for patients [1,3].

Recently, a growing interest in rapid delivery of heterogeneous dose distributions has revived the use of flattening filter free (FFF) beams [5]. The removal of the flattening filter from the LINAC changes the profile and dosimetric characteristics of radiation beams [6]. Reported clinical benefits are mainly a result of an increased available dose rate and lower peripheral doses (PD) [7]. With higher dose per pulses and dose profiles having steeper gradients, FFF beams compound all the problems associated with small field dosimetry for flattened beams and may prove challenging for dosimeters performance [6,7].

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https://doi.org/10.1016/j.ejmp.2017.12.010
Received 11 October 2017; Received in revised form 13 December 2017; Accepted 15 December 2017

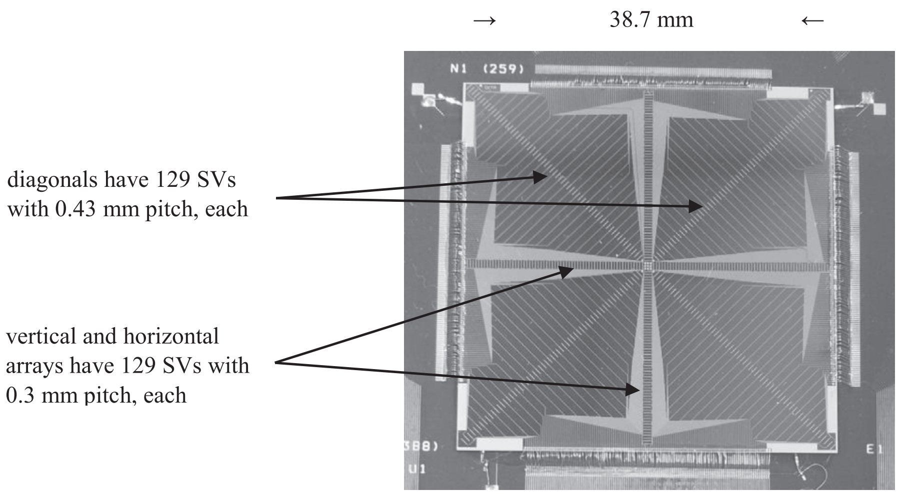

Fig. 1. The Octa is a 2D monolithic silicon array detector consisting of 512 diodes operated in passive mode and arranged in four intersecting orthogonal linear arrays. Each diode has a sensitive area of 0.032 mm^2 with pitch of 0.3 mm along the vertical and horizontal arrays and of 0.43 mm along the 2 diagonal arrays.

Dosimeters for SRT QA are to be water equivalent, dose-rate independent, with a good signal to noise ratio and real-time read-out [3,4]. They should have a sufficiently small sensitive volume to avoid volume-averaging effects [3], which are related to the dose gradients over the sensitive volume [5] and can result in a different signal compared to the signal a point-like detector would measure. To date, in the absence of such an ideal dosimeter, it has been common practice to perform QA measurements with at least two types of radiation detectors and then crosscheck the results for consistency [8], often along with the use of Monte Carlo (MC) simulations. Several alternatives have been described in the literature.

EBT3 Gafchromic films have minimal energy dependence and offer high spatial resolution but not real-time readings, which are also affected by large uncertainties due to film polarization, non-uniformity, scanning and handling techniques [8]. Ionization chambers (IC) are the recognized standard for large field dosimetry but are impaired by volume-averaging effects when used for small radiation fields [4]. Diamond-based detectors have been employed for routine QA thanks to their water equivalence, energy independence and high signal to noise ratio [3,4], but are expensive and as such not widely employed. Furthermore, they exhibit dose rate dependence, though corrections can be applied [3]. All these dosimeters are subject to central axis (CAX) alignment problems, an issue all the more relevant for small radiation fields [4].

Silicon diodes are a valuable option for small field dosimetry thanks to their large dynamic range and high sensitivity, real-time operations, well–developed manufacturing technology and high spatial resolution due to the small sensitive volumes (SVs). However, they are known to be dose rate dependent, with an increase in sensitivity with dose per pulse reported for p-type silicon diodes [9,10].

Furthermore, correction factors need to be applied to account for beam perturbations, due to their SVs and extra-cameral components. These factors depend on detector design, treatment head design, beam quality, field size and measurement conditions 3.

It was shown that it is possible to design a 'correction-free' detector, though, with the addition of low density media to the high density detector components [11]. However, it must be verified that these modifications are correctly compensating whatever the beam quality and measurements conditions [12].

2D monolithic silicon diode array detectors, with either 2 mm and 3 mm pitch, have been shown to be promising as dosimeters by several groups [13,14]. Commercially available options based on single diodes are the ArcCHECK (Sun Nuclear Corp., Melbourne, FL) and the Delta4 (ScandiDos AB, Uppsala, Sweden). Their spatial resolution, though, is not adequate for small field dosimetry. In fact, while with 1D monolithic detectors it is easy to decrease the pitch between silicon diodes down to 0.2 mm (CMRP DMG) [15], in the case of 2D detectors a compromise is necessary between the overall active area and the spatial resolution provided, in order to be within limitations in the number of read-out channels.

The Centre for Medical Radiation Physics (CMRP), University of Wollongong, has designed and characterized two 1st generation monolithic silicon diode array detectors for SRT QA, the MP512 [16] and the Duo [17]. In those studies, they were shown to be accurate dosimeters for output factors (OFs), percentage depth dose (PDD) and dose profile measurements under flattened beams with a dose per pulse (DPP) dependence. The angular dependence of the MP512 was investigated and could be corrected for, making it a suitable candidate for arc therapy delivery QA [18]. The rather coarse spatial resolution (2 mm) of the MP512 and the limited characterization of the 2D dose map given by the Duo, though, impair their attractiveness for contemporary small field dosimetry where sub-millimetre spatial resolution and a detailed description of the 2D dose map is paramount, especially when using FFF beams.

The Octa, a 2nd generation monolithic silicon diode array detector, incorporates its predecessors' technology and as such, it is characterized by the same signal stability, radiation hardness and dose linearity. The Octa's 512 diodes-SVs are arranged in four intersecting orthogonal linear arrays such that cross-plane, in-plane and 2 diagonal dose profiles are characterized simultaneously with sub-millimetre resolution.

This study evaluated the potential of the Octa for relative dose measurements, in particular in the challenging measurements conditions of small fields with FFF beams. Parameters commonly used by commercial TPSs, such as dose profiles, PDD curves and OFs were investigated. Results were benchmarked against those for other commercially available dosimeters. In order to have a comprehensive analysis of the Octa performance, 6 and 10 MV flattened beams were included in the study.

2. Materials and methods

2.1. The dosimeter

The Octa, pictured in Fig. 1, is a 2D monolithic silicon array detector based on SVs fabricated on a high resistivity p-type epitaxial [19], grown on top of a low resistivity p^+ substrate. A thin protective layer of epoxy covers the SVs. The 512 diodes have all the same sensitive area of 0.032 mm^2 and are of elongated rectangular shape (0.04 mm × 0.8 mm), except for the 9 pixels in the central matrix at the intersection of the 4 arrays (160 mm × 200 mm). The device has a sub-millimetre resolution with diodes having a 0.3 mm pitch along the vertical and horizontal arrays and a 0.43 mm pitch along the 2 diagonal