The use of a new 2D array of diodes for small-field dosimetry of a CyberKnife equipped with a novel multi-leaf collimator

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Abstract. In the present work, we reported on the use of a new 2D array of diodes, the Duo, for dosimetry of small beams produced with a CyberKnife system, and shaped with a novel multi-leaf collimator, the InCise 2.

1. Introduction
In modern x-rays external-beam radiotherapy, a medical linear accelerator (linac) is used to deliver precisely targeted radiation dose to patients, calculated with a treatment planning system (TPS) [1]. The accuracy of the TPS depends on the accuracy of the implemented x-rays beam model, which is created using parameters descriptive of the linac’s geometry, and dosimetry data which includes the linac’s output factors and lateral distributions measured in representative radiation fields.

Measurements in small fields (of lateral extension less than 3 cm) is challenging [2]. This is the result of a mix of uncertainties related to the dosimeter in use, such as in its alignment and reproducibility, and in the corrections required to relate its readings to dose [3], but also related to the incident beam, where small variations in effective size and shape have a strong influence on output factors [4]. Challenges are further compounded in a flattening filter free (FFF) beam, because dose gradients and the instantaneous dose per pulse are higher than in the corresponding flattened beam [5,6]. Measurements in small fields are currently performed by scanning a point-like dosimeter (typically, a diode or a synthetic diamond) in a water tank, or with a 2D radiochromic film. Point-like dosimeters and films can measure dose distributions with a spatial resolution better than 1 mm but are subject to alignment uncertainties. Furthermore, point-like dosimeters necessitate significant corrections to relate their readings to dose, and films require stringent processing techniques to ensure accuracy and maximize reproducibility [7,8].

A 2D monolithic array of diodes is a practical solution to achieve a spatial resolution better than 1 mm. The real-time read-out can be exploited to minimize uncertainties in alignment, and its packaging can be cleverly tweaked to reduce the corrections required to relate readings to dose [9,10]. Our research group has explored ‘correction-less’ 2D arrays with different layouts [11], demonstrating a spatial...
resolution better than 0.3 mm with the Octa prototype [12,13], and better than 0.2 mm with the Duo prototype [14,15].

In particular, Biasi et al [13] used the Octa for small-field dosimetry of a CyberKnife system (Accuray). The CyberKnife has a linac mounted on a robotic arm [16], and the 6 MV FFF beams are traditionally shaped using fixed cones, or with a variable-aperture circular collimator called the Iris. In that study, measurements of output factors and of lateral dose distributions with the Octa agreed to within 3% with Monte Carlo calculations, and with an SRS diode (PTW 60018).

Accuray has recently proposed a novel MLC for the CyberKnife, the InCise 2 [17]. With the InCise 2, which has 52 leaves, each 3.85 mm wide at a source-axis distance of 80 cm, it is easier to cover large, irregularly shaped targets. In the present work, we made good use of the Duo prototype for dosimetry in small 6 MV FFF beams produced with a CyberKnife M6 and defined with the InCise 2.

2. Material and Methods

2.1. The Duo prototype
The Duo prototype has 505 diodes (the radiation-sensitive volumes), spaced by 0.2 mm on 2 linear arrays (vertical, horizontal; Fig.1). Diodes, each of area 0.032 mm², are operated in passive mode. The Duo is wire-bonded onto a printed circuit board (PCB) to provide connections to a multichannel data acquisition (DAQ) system [18], and sandwiched between two plates of poly(methyl methacrylate) (PMMA), each 5 mm thick. There is a small air gap on top of the Duo to minimize the corrections required to relate its readings to dose [19].

![Figure 1](image)

Figure 1. The Duo has 505 diodes spaced by 0.2 mm on 2 linear arrays (vertical, horizontal), over 52 × 52 mm².

2.2. Measurements and data analysis
Prior to measurements, the response of the 505 diodes was equalized [20] with a one-off procedure to account for small, independent differences in their sensitivity to radiation. The Duo was then aligned with respect to the machine central axis (CAX) by maximizing the response of its central diodes in the smallest radiation field (7.6 × 7.7 mm²).

Measurements consisted in acquiring the relative response, and crossline and inline dose distributions, in static fields in the range from 7.6 × 7.7 mm² to 38.4 × 38.5 mm². All fields were collimated with the InCise 2, and measured at a depth of 1.5 cm in solid water (IBA type RW3), at a source-to-surface distance (SSD) of 78.5 cm.

In all fields, the relative response and lateral distributions were measured concurrently, repeating the measure at least three times and taking the mean of the sample as the response of the Duo. The response is reported with a confidence interval at 95% level, calculated using the standard deviation of the mean.

Relative responses were used to determine output factors, calculated as a percentage of the Duo response in the field collimated with a fixed cone of diameter 60 mm, also measured at a depth of 1.5 cm in solid water, at an SSD of 78.5 cm. No correction was applied to the Duo response. For a quantitative estimation of the full-width half-maximum of crossline and inline distributions, these were
analysed with MATLAB (MathWorks) using a shape-preserving interpolant function and are reported with an accuracy taken as ±0.1 mm following that interpolation.

The actual aperture of the MLC is a possible source of systematic error in measurements because a variation in the aperture leads to a variation in the output factor. In the InCise, the MLC leaves are positioned with an encoder accuracy of ±50 μm, and there is a camera-based system that verifies their position with an accuracy of ±1 mm [17]. In the present work, we neglected all inaccuracies resulting from systematic inaccuracies in MLC positioning because each measurement was repeated three times without resetting the MLC.

Finally, measurements with the Duo were benchmarked against measurements with an Edge diode (SunNuclear) in the same experimental conditions, except the diode was scanned in a water tank after a resetting of the MLC. To determine output factors, the readings of the Edge diode were corrected according to Francescon et al [21]. Similar to the Duo, crossline and inline distributions were also analysed with MATLAB using a shape-preserving interpolant function and are reported with an accuracy taken as ±0.1 mm following that interpolation.

3. Results
Output factors are in Table 1, whereas inline and crossline distributions are in Table 2.

Table 1. Output factors: measurements with the Duo (uncorrected) and with the Edge diode (corrected). The reference field (100%) was that produced with a fixed cone of diameter 60 mm.

| Nominal field size [mm²] | Duo [%]   | 95% C.I. | Edge [%] | Difference [%] |
|-------------------------|-----------|----------|----------|----------------|
| 7.6 × 7.7               | 79.5      | ± 0.1    | 79.5     | 0.0            |
| 15.4 × 15.4             | 93.9      | ± 0.0    | 94.1     | 0.1            |
| 23.0 × 23.1             | 96.8      | ± 0.0    | 97.2     | 0.4            |
| 30.8 × 30.8             | 97.9      | ± 0.0    | 98.7     | 0.8            |
| 38.4 × 38.5             | 98.8      | ± 0.2    | 99.4     | 0.6            |

Table 2. FHWM of inline and crossline distributions measured with the Duo (uncorrected) and with the Edge diode (uncorrected). The MLC was reset in-between measurements with the Duo and with the Edge diode.

| Nominal field size [mm²] | Duo, effective field size [mm²] | Edge, effective field size [mm²] |
|-------------------------|---------------------------------|---------------------------------|
| 7.6 × 7.7               | 7.1 × 7.7                       | 7.1 × 7.8                       |
| 15.4 × 15.4             | 14.6 × 15.3                     | 14.6 × 15.6                     |
| 23.0 × 23.1             | 22.0 × 22.9                     | 22.1 × 23.2                     |
| 30.8 × 30.8             | 29.7 × 30.8                     | 29.7 × 30.9                     |
| 38.4 × 38.5             | 37.5 × 38.3                     | 37.3 × 38.4                     |

4. Discussion and Conclusion
In the present work, we used the Duo prototype for dosimetry in small 6 MV FFF beams, produced with a CyberKnife M6 equipped with the InCise 2 MLC. Measurements with the Duo were completed in approximately 15 minutes, including initial setup.

We found that it was possible to use the uncorrected relative response of the Duo, to calculate output factors in agreement to within 0.8% with those calculated using the corrected response of a commercial Edge diode. As shown in Table 1, the Duo offered a reliable real-time read-out. This result extends and complements a previous study in a CyberKnife equipped with fixed cones and the Iris. That study showed that the uncorrected relative response of the Octa, a 2D monolithic array equivalent to the Duo expect for the layout of the diodes, also yielded output factors which were in agreement to within 3% with Monte Carlo calculations, and with a commercial SRS diode [13].

Further, we found that the FWHM of crossline and inline distributions measured with the Duo agreed to within 0.2 mm with the Edge diode (to within 0.3 mm in the field of 15.4 × 15.4 mm²). The diode
measured generally broader FWHMs than the Duo. Effective fields were in agreement to within 0.2 mm
with nominal fields in the crossline direction, and to within 1 mm in the inline direction.

Overall, based on our and previous investigations [13], the Duo was shown to be a ‘correction-
free’ dosimeter for routine quality assurance in a CyberKnife system equipped with fixed cones, with
the Iris and with the InCise 2.

5. References
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