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Dosimetric evaluation of a 2D pixel ionization chamber for implementation in clinical routine

J Herzen, M Todorovic, F Cremers, V Platz, D Albers, A Bartels and R Schmidt

Department of Radiotherapy and Radio-Oncology, Center for Diagnostic Imaging and Image Guided Therapy, Radiological Physics, University Medical Center Hamburg-Eppendorf, Martinistraße 52, DE-20251 Hamburg, Germany

E-mail: j.herzen@uke.uni-hamburg.de

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Abstract
In this paper we present the results of a dosimetric evaluation of a 2D ionization chamber array with the objective of its implementation for quality assurance in clinical routine. The pixel ionization chamber MatriXX (Scanditronix Wellhofer, Germany) consists of 32 × 32 chambers with a distance of 7.6 mm between chamber centres. The effective depth of measurement under the surface of the detector was determined. The dose and energy dependence, the behaviour of the device during its initial phase and its time stability as well as the lateral response of a single chamber of the detector in cross-plane and diagonal directions were analysed. It could be shown, that the detector’s response is linear with dose and energy independent. Taking the lateral response into account, two different dose profiles, for a pyramidal and an IMRT dose distribution, were applied to compare the data generated by a treatment planning system with measurements. From these investigations it can be concluded that the detector is a suitable device for quality assurance and 2D dose verifications.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The implementation of intensity-modulated radiotherapy (IMRT) in external beam therapy imposes high demands on measurement devices and quality assurance. Generally three-dimensional dose distributions obtained from a treatment planning system have to be verified by dosimetric means. Mainly a comparison of two-dimensional calculated and measured data in several coplanar planes is performed.
In principle, there are many possibilities to measure two-dimensional dose distributions:

Films were evaluated for IMRT dosimetry by Bucciolini et al. (2004) and Ju et al. (2002). Flat-panel electronic portal imaging devices (EPID) were studied by Warkentin et al. (2003). Ionization chambers (Stasi et al. 2004) and ionization chamber arrays (Martens et al. 2001, Stasi et al. 2005) were also used for IMRT measurements. All general methods are described in the AAPM Report 67 (1999).

Radiographic (Childress et al. 2005, Yeo et al. 2004) as well as radiochromic (Todorovic et al. 2006) films have a very good resolution but their handling is still very time consuming. Due to the calibration and scanning process they cannot be applied for fast real-time measurements.

The flat-panel EPIDs show a good resolution and offer a possibility for real-time measurements but their calibration is complicated, as the signal has to be converted into dose.

The significant benefit of an ionization chamber array is its simple handling by connecting it to a PC with a standard ethernet cable. Furthermore there is no dead time during the real-time measurement and after a calibration it is possible to measure the dose directly. The resolution is worse than the resolution of films or EPIDs but there is a good agreement between films and ionization chambers for verification of radiotherapy plans as reported by Spezi et al. (2005) and Stasi et al. (2005). Due to its properties it qualifies for measuring dynamic processes, e.g. virtual wedges, like no other device.

The aim of this work is the dosimetric evaluation of a new ionization chamber array (MatriXX, Scanditronix Wellhofer). It is based on a pixel-segmented ionization chamber designed by the Torino University and the Instituto Nazionale di Fisica Nucleare (INFN). The basic dosimetric properties of the prototype were analysed (Amerio et al. 2004) and the preliminary results for IMRT verification were presented (Stasi et al. 2005). To qualify the commercialized device for the implementation in clinical routine some basic tests are performed and comparisons with measurements in a water phantom and other ionization chambers were made. The basic tests included the localization of the effective depth of measurement, analysing the dose and energy dependence, the behaviour during the initial phase and the time stability. Furthermore the lateral response of a single chamber was determined by a shifted slit and taken into account for the comparison of the profiles of two different dose distributions.

2. Methods and materials

2.1. Ionization chamber array

The dosimetric device to be evaluated is an ionization chamber array consisting of 1020 single air-vented plane-parallel cylindric ionization chambers (0.55 cm height, 0.4 cm diameter, centre-to-centre distance 0.76 cm and 0.07 ccm sensitive volume) arranged in a $32 \times 32$ matrix (there are no chambers in the corners of the array). A maximum field of view of $24 \times 24$ cm$^2$ can be achieved. A microelectronic chip reads out each of the chambers separately. The device runs with two separate counters to avoid dead time. The minimum read out time is 20 ms, that allows us to measure dynamic processes as the start-up process of the linear accelerator as well as the build-up process of a virtual wedge field or the behaviour of the MLC during a radiation with the IMAT technique.

The array can be used in a special gantry holder so that the source-to-detector distance amounts to 76 cm. Due to the distance between the chambers of 0.76 cm each pair of leaves of the standard multi leaf collimator (MLC) with 1 cm leaf width at the isocentre corresponds
to a row of ionization chambers. Another advantage of using the device in the gantry holder is the possibility of measurements at different gantry angles, so that the displacement of the MLC leaves at these angles can be analysed. The short distance to the gantry minimizes the influence of the position of the gantry during a rotation. Additionally the gantry holder is capable of very accurate shifts of the device in x- and y-directions.

All measurements are performed with x-rays from two linear accelerators: a Siemens Mevatron (4 MV and 6 MV x-rays) and a Siemens Primus (6 MV and 15 MV). For the reference measurements a 0.6 ccm Farmer chamber (FC65-G/IC 70) and a 0.03 ccm Wellhofer chamber (IC03) in a computerized water phantom (WP 700, Wellhofer) are used.

2.2. Localization of the effective point of measurement

The depth of the effective point of measurement (EPM) was based on a percentage depth dose curve (PDD) of a 6 MV photon beam in solid water (RW3). A PDD curve was measured with the MatriXX by placing 30 × 30 cm² plates of solid water (thickness 0.1–1 cm) on the surface of the detector. The same measurement was also performed with a Farmer ionization chamber (FC65/IC 70), whose effective depth of measurement is well known. The difference in depth of the dose maximum of the curves corresponds to the effective point of measurement of the applied detector. For the measurement, the signal was averaged over the 2 × 2 central pixels which are located in a highly homogeneous region of the field and moreover cover the area of the reference ionization chamber.

2.3. Dose and energy dependence

For different x-ray energies (4 MV, 6 MV and 15 MV) the number of monitor units was varied from 10–1000 MU. The device was irradiated with a 10 × 10 cm² field and a source-to-EPM distance of 100 cm with 5 cm solid water as build-up material. Since 100 MU do not exactly correspond to the dose of 1 Gy for different energies, the dose for each energy was determined for each energy at the corresponding depth with a second independent dosimeter and used for this measurement. As we expected the same linear correlation between the dose and the measured signal was found for all energies, the dose linearity and the energy independence were analysed simultaneously. As a result signal the average of the output of the four central pixels was taken.

2.4. Initial phase and time dependence

To analyse a possible warm-up behaviour the device was irradiated 20 times with 6 MV x-rays, 100 MU and a field size of 10 × 10 cm². The electronics were switched on 15 min prior to irradiation, as recommended by the manufacturer. After a radiation break of 30 min with switching off the device during the break the measurement was repeated. To determine the influence of the turn-off process the whole measurement was repeated with the MatriXX being not switched off during the break. The average of the read of the four central pixels was used as the result.

2.5. Lateral response function and spatial resolution of a single chamber of the device

The lateral response of a single chamber can be characterized by the line-spread function (LSF). This LSF can be determined using a narrow slit shifted stepwise over the device (Poppe et al describe an analogue procedure in Poppe et al (2006, 2005) for a similar device (PTW, Freiburg, Germany)).
Figure 1. The experimental set-up for the diagonal shifting of the slit. The slit is formed by two tungsten blocks of $1 \times 10 \times 10$ cm$^3$ on a thin plate of solid water for a better shifting. The two blocks are separated by 1 mm steel shims. Two horizontal tungsten blocks, one on each side of the slit, minimize the scatter signal.

Figure 1 shows the set-up for this measurement: the slit was generated by tungsten blocks of $1 \times 10 \times 10$ cm$^3$ placed on a thin plate of solid water in the central beam in order to use the almost parallel beam for the measurement. The width of the slit was chosen to be 1 mm, which is a compromise between a sufficiently thin slit and a good signal to noise ratio. Furthermore a field size of $0.5 \times 9$ cm was chosen to avoid disturbing scattering.

The measured signal was corrected for background and leakage by repeating the measurement with a closed slit. As the pixel chambers are cylindrical and therefore more scatter material is between the sensitive volumes in the diagonal direction compared to the lateral distance, the sensitivity profile might be angle dependent. Therefore the slit was shifted in cross-plane and in the diagonal directions.

2.6. Comparison between dose distributions calculated by XiO (by CMS) and measured with the MatriXX

Since we were interested in absolute dose for the comparison of the dose distributions, the detector had to be calibrated. Therefore, we had to ensure that the response of the pixels is homogeneous, so we can use the same calibration factor for all pixels. This was done according to a method described by Donetti et al. (2006). The check of the homogeneity of the pixel response by this method resulted in a standard deviation of the signal of 0.5 % normalized to the maximum signal. During a time period of 1 year the test was repeated several times. As an indication of stability of the detector always the same pixels showed more or less signal and had to be corrected.

Furthermore a slight tilt in the homogeneity of the pixel response over the whole detector of nearly 2% of the maximum signal was found, which was reproducible and thus must be due to the manufacturer’s calibration procedure. The manufacturer reacted to this result and will provide a software update for the correction according to Donnetti et al. (2006). For the future devices the manufacturer’s calibration procedure will be enhanced. After the test for homogeneity the MatriXX was calibrated for an absolute dose according to the user’s guide of the software, which is provided with the MatriXX, for cross calibration with a reference ionization chamber.
To be able to generate a treatment plan for experimental conditions, the MatriXX, embedded in solid water (5 cm on top, 10 cm at the bottom), was scanned by CT. The electron density in the MatriXX phantom was determined from the Hounsfield units by use of a calibration table (Goerlitz et al. 2006). Based on the CT data of the MatriXX phantom two different dose plans were calculated using the TPS XiO by CMS. The first plan consists of eight different field sizes (20 × 20, 15 × 15, 10 × 10, 5 × 5, 4 × 4, 3 × 3, 2 × 2 and 1 × 1 cm² and 50 MU per field size, field-in-field technique) forming a pyramid-shaped dose distribution. The second dose plan is a real IMRT plan of a neck treatment, which consists of seven fields from different gantry angles. The MatriXX was irradiated with the gantry angle set to zero. The pyramidal plan was radiated once while the IMRT fields were measured separately.

For the comparison of the planned and the measured data the finite resolution of the MatriXX and the spatial response function have to be taken into account. The correction of the planned data was performed by means of a convolution with the determined response function. According to this, the MatriXX signal $M(x_0)$ in the point $x_0$ in one direction will be obtained from the following equation:

$$M(x_0) = \sum_{i=1}^{n} f(x_i) \cdot g(x_0 - x_i) / \sum_{i=1}^{n} g(x_0 - x_i), \quad (1)$$

where $f(x_i)$ is the calculated signal and $g(x_0 - x_i)$ is the response function for discrete measurement points. For a two-dimensional convolution a rotation-symmetric response function was generated, whereas the distance between the single ionization chambers was neglected. For the convolution the planned dose distribution was calculated with a higher resolution of 0.076 mm than the measuring grid of 0.76 mm. Then the data were separated in 32 × 32 segments according to the number of pixels of the MatriXX. As the response was evaluated above as independent of angle, the matrix points from the calculated dose grid were convolved according to the equation above (1). From the convolution a 32 × 32 matrix of single dose values resulted, which was compared to the measured dose values. The software provided with the MatriXX does not yet allow the use of the gamma function analysis in combination with the convolution correction. Thus, the difference between the planned and the measured dose distributions was considered in this work.

3. Results and discussion

3.1. Localization of the effective point of measurement

A method to find the effective point of measurement is to register the percentage depth dose curves determined with the MatriXX and with the reference device (see figure 2). By fitting the measured curves and by shifting the fits stepwise against each other the offset in depth can be found, which corresponds to the effective point of measurement of the detector. The result of this method is $d_{\text{eff,MatriXX}} = 3.6 \text{ mm} \pm 0.1 \text{ mm}$. The accuracy of this result is sufficient, because of the thinnest available plate of solid water of 1 mm.

3.2. Dose and energy dependence

Figure 3 shows the signal of the MatriXX for different monitor units (6 MV x-rays) and a linear fit through the data points. The signal of the detector increased clearly linearly with the dose. The correlation coefficient of the linear fit was $R^2 = 1$.

In figure 4 the signal of the MatriXX is plotted against the absorbed dose for different energies. The gradient of the fitting curve is the same for each energy, so the signal of the
Figure 2. Comparison of the percentage depth dose curves measured with the MatriXX and the Farmer ionization chamber in solid water. The effective point of measurement is determined by shifting the curves stepwise against each other finding the offset in depth. The result is $d_{\text{eff}, \text{MatriXX}} = 3.6 \text{ mm} \pm 0.1 \text{ mm}$.

Figure 3. The signal of the detector for different numbers of monitor units for a 6 MV photon beam. The linear fit is in good agreement with the measurement points, so the detector reacts linearly with the dose.

detector does not depend on the beam energy in the range from 4 to 15 MV x-rays. The correlation coefficient arising from the linear fit was $R^2 = 0.99988$.

3.3. Initial phase and time dependence

Figure 5 shows the results of the repeated irradiation. Black points display the results of the direct measurement after the warm-up period. Red points represent the results of the measurement after a break of 30 min and a switched-off detector during the break. There is a clear increase of the signal during the first irradiations up to measurement 10 (equivalent to 1000 monitor units or 10 Gy) of nearly 4%. After the break of 30 min the signal of the detector
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Figure 4. The signal of the MatriXX at 4 MV (black points), 6 MV (Mevatron: red triangles, Primus: blue points) and 15 MV (green rhombuses) x-ray beams for different doses. The same linearity of each energy is due to the energy independence of the detector.

Figure 5. The signal of the MatriXX during the repeated irradiation with 6 MV photons and 100 monitor units per irradiation. One measurement was performed directly after the warm-up of the electronics (black rectangles) and the other after a break of 30 min and switching off the MatriXX (red points).

decreases to the level of the preirradiation with 800 MU. As a consequence the detector has to be preirradiated before starting a measurement and after a break if it was switched off to get reproducible measured values.

After preirradiation the measured data are stable if the detector is not switched off in between (figure 6).

3.4. Spatial response function and the spatial resolution of a single chamber of the device

Figure 7 shows the response function of one ionization chamber of the MatriXX measured in the cross-plane and diagonal directions. Both curves are in a good agreement, so that
Figure 6. In the figure the signal of the MatriXX is plotted against the number of measurements. The whole measurement was performed after the preirradiation with 6 MV photons and 1000 monitor units. Black rectangles are the measurements directly after the preirradiation and red points are the measurements after a break of 30 min without switching off the detector.

Figure 7. The spatial response function of a single ion chamber of the MatriXX. Black line: in the cross-plane direction, red scatter: in the diagonal direction.

the chambers of the detector can be regarded as isotropic. Though there is more backscatter material in the diagonal direction this obviously has no influence on the response of the single ion chamber.

3.5. Comparison of dose distributions planned with XiO (by CMS) and measured with the matriXX

Figure 8 shows the calculated data corrected as described above and the measured dose distribution with the MatriXX of the pyramidal beam arrangement. In figure 9 the measured profiles in the cross-plane direction are compared with the calculated and corrected profiles.
Figure 8. Dose distribution of the pyramidal beam arrangement. On the left the calculated and corrected data and on the right the dose distribution measured with the MatriXX are displayed.

Figure 9. The comparison of the profiles of the uncorrected, corrected calculated and the measured pyramidal dose distribution in the cross-plane direction.

The planned data were corrected by weighting with the normalized response function and integrating over the area of a single ion chamber of the detector. The measured and corrected profiles are in good agreement with a maximum deviation of 1%. The maximum deviation of the measured profile from the uncorrected plan profile is 4.5%.

The results of the comparison of the planned and measured data for the IMRT plan are performed for one field with multiple segments. Figure 10 shows the calculated dose distribution from the TPS being weighted with the response function in two dimensions and the dose distribution measured with the MatriXX. In figure 11 the profiles in the cross-plane direction are compared. A good agreement between measurement and calculation can be found if the spatial response of the single chamber of the detector is taken into account. The maximum deviation of the measured profile from the corrected profile is 8.4% in the region of large gradients and 4.5% in the region of low gradients. Without the correction the maximum deviation of the measured profile and the uncorrected plan profile is 16%.
Figure 10. The dose distribution of the IMRT plan. In the left is the corrected calculated and in the right the measured dose distribution.

Figure 11. The comparison of the profiles of the uncorrected, corrected calculated and the measured IMRT dose distribution in the cross-plane direction.

4. Summary and conclusions

The measurements and evaluations prove that the output of the detector is linear to the dose and independent from the energy. During the start-up phase the detector needs a preirradiation of approximately 10 Gy to reach a stable signal. The response functions of a single ionization chamber of the array measured in the cross-plane and diagonal directions show the independence on the angle. This characteristic was taken into account for the verification of IMRT fields, that the planned data were corrected for. The comparisons of the profiles for two different dose distributions were in a good agreement when the corrections were applied.

The comparable device 2D ARRAY described by Poppe et al (2005, 2006) consists of $27 \times 27$ chambers with a centre-to-centre distance of 1 cm that allows a simple association of the leaves of a standard MLC only in the isocentre. This fact complicates the use of the detector for quality assurance of dynamic radiation techniques. When the detector is used in
a gantry holder the reduction of the source-to-detector distance disturbs the association of the MLC leaves.

The set-up for the slit measurement described in Poppe et al (2006) differs from the one used in this work. They used instead of tungsten blocks a pair of cast metal blocks to form a slightly diverging slit. These blocks were placed in the absorber tray leading to a distance from the surface of the detector and the lower edge of the block of 20 cm. In contrast to this set-up of Poppe et al in our measurement the slit was placed directly on the surface of the detector to achieve a nearly parallel beam. The lateral response of a single chamber of the 2D ARRAY evaluated by Poppe et al (2006) is only measured in one direction and shows two side peaks beside the central peak that result from the scattering edges between two chambers. As the chambers are cubic and not cylindrical the lateral response function is not imperatively symmetrical and might depend on the angle of the slit shifting.

The long minimal sampling period of the 2D ARRAY of 400 ms, compared to 20 ms with the MatriXX, is already too long for measurements like the start-up process of the linear accelerator, the build-up process of a dynamic wedge field. Also the check of the behaviour of the MLC during the radiation with dynamic technique requires a short sampling period. Furthermore the start-up characteristics of a linac are essential for respiratory gated radiotherapy.

The conclusions of the results of our investigations are mainly based on the fact that the miniature ionization chamber is used. It can be concluded that the MatriXX is qualified as a device with a sufficiently high accuracy. The MatriXX as a direct reading device has the ability to facilitate and fasten the measurement procedures in radiotherapy, e.g. verification of IMRT fields. Especially for the verification of dose distributions it is shown that a convolution correction should be used to enhance the results. For routine applications the software provided with the MatriXX should be able to assess the difference between planned and measured 2D dose distributions in terms of the gamma index, distance to agreement or other appropriate parameters after the convolution correction.

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