Characterization of a MLIC Detector for QA in Scanned Proton and Carbon Ion Beams

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Abstract

Purpose: Beam energy validation is a fundamental aspect of the routine quality assurance (QA) protocol of a particle therapy facility. A multilayer ionization chamber (MLIC) detector provides the optimal tradeoff between achieving accuracy in particle range determination and saving operational time in measurements and analysis procedures. We propose the characterization of a commercial MLIC as a suitable QA tool for a clinical environment with proton and carbon ion scanning beams.

Materials and Methods: Commercial MLIC Giraffe (IBA Dosimetry, Schwarzenbruck, Germany) was primarily evaluated in terms of short-term and long-term stability, linearity with dose, and dose-rate independence. Accuracy was tested by analyzing range of integrated depth-dose curves for a set of representative energies against reference acquisitions in water for proton and carbon ion beams; in addition, 2 modulated proton spread-out Bragg peaks were also measured. Possible methods to increase the native spatial resolution of the detector were also investigated.

Results: Measurements showed a high repeatability: mean relative standard deviation was within 0.5% for all channels and both particle types. The long-term stability of the gain calibration showed discrepancies less than 1% at different times. The detector response was linear with dose ($R^2 > 0.99$) and independent on the dose rate. Measurements of integrated depth-dose curve ranges revealed a mean deviation from reference measurements in water of 0.1 ± 0.3 mm for protons with a maximum difference of 0.4 mm and 0.2 ± 0.6 mm with maximum difference of 0.85 mm for carbon ion beams. For the 2 modulated proton spread-out Bragg peaks, measured differences in distal dose falloff were ≤0.5 mm against calculated values.

Conclusions: The detector is stable, linearly responding with dose, precise, and easy to handle for QA beam energy checks of proton and carbon ion beams.

Keywords: particle radiation therapy; quality assurance device; detector; particle range measurements

Introduction

Beam energy validation plays a relevant role within a periodic quality assurance (QA) protocol in which the purpose is safe delivery of ion beam radiation therapy. The typical
depth-dose profile of heavy-charged particles is characterized by a relatively low dose in the entrance region, a sharp dose increase in the proximity of the maximum penetration range, and a steep distal falloff beyond the peak. Higher linear energy transfer values in the Bragg peak (BP) region allow for the deposit of dose mostly at the depth of the penetration range, while sparing proximal and distal healthy tissues [1]. In the region beyond the distal end of the peak, almost no dose is deposited with protons, while a small dose is deposited with carbons due to a fragmentation tail of particles with lower atomic numbers beyond the peak.

Consideration must also be given to energy fluctuations that are potentially much more critical in terms of dose distribution deterioration compared with photon radiation. Energy stability of the clinical beam should therefore be guaranteed and carefully checked [2]. At CNAO (Italian National Center for Oncological Hadrontherapy) an extensive periodic QA program has been implemented to guarantee a safe and accurate treatment to the patient from beam dosimetry and characterization [3] to patient positioning [4] and treatment planning [5]. For constancy check of the BP position, radiochromic films in a solid water phantom or behind a double-wedge phantom are routinely used [6]. This time-consuming analysis procedure, including offline scanning, is a major drawback to performing regular film-based QA.

The use of a multilayer ionization chamber (MLIC) is described as a valid alternative for checking beam-energy stability [7–12]. Although some compromise must be accepted in terms of spatial resolution and sensitivity, the MLIC setup and measurement procedure are usually much faster compared with other detectors, such as diodes or diamonds [13], which require the use of motorized phantoms.

In this study, Giraffe (IBA Dosimetry, Schwarzenbruck, Germany) device performances were investigated for QA purposes; this device is a commercial MLIC detector developed primarily for integrated depth-dose (IDD) measurements of proton pencil beam scanning. For proton beams our analysis confirmed the results provided by other authors [7, 14], while in clinical carbon-ion beam dosimetry the Giraffe device characterization and implementation has not been described so far. We reported therefore the full characterization of this device for QA purposes with scanned protons and carbon-ion beams in terms of stability in time, dose linearity, dependence on dose rate and accuracy in range detection of IDD curves.

Methods

All measurements were performed at the CNAO synchrotron facility, in one of the treatment rooms equipped with a horizontal fixed beam line and pencil beam scanning as treatment delivery modality [15].

**Giraffe MLIC Detector**

The Giraffe device is a commercial multilayer ionization chamber array designed to measure the longitudinal depth-dose distribution of central-axis pencil beams with full width at half maximum ranging from about 0.5 to 3 cm. It is equipped with a stack of 180 independent air-vented, plane-parallel ionization chambers fabricated with printed circuit board technologies with a density close to 2 g/cm³; the outer graphite layer radius of each circular electrode is 6.0 cm. The air gap between 2 plates is approximately 1 mm. The water-equivalent thickness (WET) of each channel is pre-set by the vendor to a value between 1.85 mm and 1.90 mm, which corresponds to the intrinsic spatial resolution of the detector in the longitudinal plane. The physical range of measurement in depth is therefore between 2 and 330 mm. Operating voltage between the electrodes is −150V, which cannot be changed by the user.

The collected charge is measured by a dedicated electrometer using Tera06 ASICs Technology [16, 17]. The outer dimensions of the Giraffe are 43.9 cm (L) × 19.5 cm (H) × 17.5 cm (W); the weight is approximately 10 kg. The detector includes user-friendly software for fast data acquisition and analysis (OmniPro-Incline, IBA Dosimetry) which permits the correct definition of the setup parameters, the storage and quick analysis of acquired data, and the evaluation of single-channel raw data.

The vendor provides channel-specific calibration gain values comparing the acquisition of a reference IDD curve with the Giraffe against measurement in water, together with the WET of a single layer and an offset value. As Giraffe is primarily designed for protons, we selected as a reference curve the IDD of a proton beam with nominal range in water of 320 mm (228.6 MeV). Reference IDDs were acquired with the Peakfinder (PTW GmbH, Freiburg, Germany) water column detector, which is considered the “gold standard” because of its superior performance in terms of spatial resolution (0.05 mm around the BP [3]). The assumption of also using the provided gain calibration curve for carbon-ion beams measurements was verified by estimating an analog curve on the base of a comparison between a reference uncorrected carbon-ion IDD profile acquired
with the MLIC and the Peakfinder. In addition, the vendor suggests recalibrating channel uniformity before each measurement session with the Giraffe by acquiring the reference proton IDD.

Experimental Setup

Several representative beam energies in the range available for clinical treatments (62.7 to 228.6 MeV and 115.2 to 398.8 MeV/u for protons and carbon ions, respectively) were selected for the aim of this study. Spot sizes, in terms of full width at half maximum at the isocenter in air, vary as a function of the beam energy from 2.2 to 0.7 cm and from 0.8 to 0.4 cm for protons and carbon ions, respectively [3]. Beams were delivered as a single spot of a defined number of particles at the isocenter where the Giraffe entrance window was aligned. A background acquisition of 60 seconds’ duration and a uniformity calibration were performed before each measurement session. We chose 15 to 20 seconds as the typical acquisition time with a sampling rate of 100 Hz. The system also includes a 1-mm WET buildup polymethylmethacrylate plate that can be positioned in front of the entrance window. Merging the 2 data sets, acquired in the same conditions with and without the buildup plate, can increase the intrinsic spatial resolution in the longitudinal direction.

Detector Characteristics

Short-Term and Long-Term Stability

Short-term system stability in time was assessed by comparing 5 consecutive IDD curves for protons (E= 228.6 MeV, nominal range in water = 320 mm) and carbon ions (E= 398.8 MeV/u, nominal range in water = 270 mm). Additionally, the stability of the system was verified under stress conditions, that is, power supply switched off and on, cables disconnected and reconnected, and high voltage switched off and on. For long-term stability, reference calibration IDD curves were acquired at 4 different measurement sessions approximately 1 month apart. In this case, stability was assessed based on both measurement results and by comparing the channel-specific calibration gains, calculated by the system after each uniformity recalibration.

A threshold of 6% of the maximum measured value of each acquisition was also applied to exclude distal channel readouts which could be potentially affected by fluctuations at very low-dose levels. This threshold was arbitrarily selected by analyzing the Giraffe outputs and observing the readout fluctuations in the last channels. In practice the last 3 channels with nonzero readouts were excluded from this type of analysis.

Data were analyzed in terms of channel mean relative standard deviation (ie, mean coefficient of variation), defined as the average value of the ratios between the standard deviation and mean readouts for each channel of the Giraffe device. The evaluation was performed over 5 consecutive measurements for the repeatability assessment and over 4 acquisitions for the long-term stability.

Linearity With Dose and Dose-Rate Dependence

Detector linearity was accurately evaluated under dose and dose-rate independence conditions; that is, the total number of delivered particles and fluence rate, specifically, the number of particles per second provided by the synchrotron and in clinical use.

Linearity with dose was investigated for both particle species at the reference beam energy (228.6 MeV for protons, 398.8 MeV/u for carbon-ions) by varying the number of particles (protons: 5 \times 10^7, 1 \times 10^8, 2 \times 10^8, 5 \times 10^8, 1 \times 10^9, 2 \times 10^9, 5 \times 10^9; carbon ions: 5 \times 10^6, 2 \times 10^7, 5 \times 10^7, 1 \times 10^8, 2 \times 10^8, 5 \times 10^8). The operator could select discrete fluence rate levels at the synchrotron. This modulation is obtained with the insertion of beam current degraders acting as beam passing filters in the extraction line [15]. To assess the Giraffe response to dose rate, 3 configurations at 100%, 50%, and 20% of the full beam for both protons and carbon ions beams were selected.

To quantify the detector, linearity with dose and mean coefficient variation of the channels readouts were studied as a function of the beam fluence rate at a fixed energy. Additionally, for 1 sample channel, a linear fit was proposed and the value of R^2 index calculated. For dose rate dependence, we reported the channel mean coefficient of variation between the reference beam acquisition (100% of the fluence rate) and 50% and 20% of the full beam for both protons and carbon ions. Minimum and maximum values have also been reported.

Range Measurements

Preliminary factory calibration parameters (ie, channel WET and offset) were tested by comparing a set of IDD curves for both particle species against the reference measurements acquired with the Peakfinder water column. Proton energies between
72.6 MeV and 228.6 MeV (corresponding to a nominal range in water of 40 to 320 mm) and carbon ion energies from 133.78 MeV/u to 398.84 MeV/u (nominal range of 40 to 270 mm) were selected. As mentioned previously, resolution in the longitudinal direction could be increased by merging 2 consecutive acquisitions, with and without the buildup plate (1 mm WET thickness, density $\rho = 1$ g/cm$^3$). We will refer to this procedure as the double-merge method. A triple-merge method in which an extra acquisition was performed by inserting a 0.44-mm WET polymethylmethacrylate range shifter (thickness = 0.35 mm; Goodfellow Cambridge Limited, city, UK) along the beam path was also tested. This way the spatial resolution of the detector increased up to 0.6 mm. The position in the distal falloff of the Bragg curve, where the dose is reduced to 90% of the peak (distal R$_{90}$) [18], was calculated by linear interpolation for each curve as a representative value for the beam range.

Detector performances were tested for spatial resolution and accuracy. For this purpose, 2 consecutive energies to reproduce the smallest available gap in range between 2 IDDs were selected for both particle species. Carbon ion curves were acquired in the standard clinical configuration, with a set of two 2-mm ripple filters on the beam line to broaden the Bragg maximum peak [19]. The ratio between measured and nominal difference in R$_{90}$ of consecutive IDD curves was analyzed. Accuracy was investigated by comparing the measured R$_{90}$ (averaged over 20 single acquisitions) against the corresponding reference value in water.

For data analysis, the distal R$_{90}$ could be directly obtained by the OmniPro-Incline analysis package for acquisition in single-merge and double-merge modality. In the case of triple merge, a further analysis QA carried out externally on the extracted channel readouts.

**Ocular Proton Spread-Out Bragg Peak Measurements**

The capability of the Giraffe device to measure depth-dose profiles and range values of ocular spread-out Bragg peaks (SOBPs) was tested. Collimated fields already delivered for real patients’ ocular treatments were selected: those representing the only clinical case of very small field sizes (around 1.5 cm diameter), suitable for Giraffe tests (for the 2 SOBPs used see Table 1) at our facility [20]. The SOBPs used for ocular treatment are built with discrete energy levels, each corresponding to an isoenergetic slice (IES) with 1 mm water-equivalent step within the energy range (62.7 to 89.8 MeV) and a particular beam-line configuration to shift the beam penetration at shallower depths. This is a particularly challenging scenario because of the small depth of the dose distribution and shallow range of the first energies of the SOBP.

The Giraffe outputs were compared with the expected FLUKA Monte Carlo curves [20], performing the scoring within the same diameter as the sensitive volume of the detector. The Omni-Pro Incline software automatically retrieves the distal R$_{90}$ for the measured SOBP.

**Results**

**Detector Characteristics**

**Short-Term and Long-Term Stability**

For short-term stability the mean coefficient of variation was 0.1% for protons and 0.5% for carbon ions, with maximum values in range of variation equal to 0.3% and 1.7%, respectively. Fluctuations in channel readouts were around 0.1% (maximum value = 0.9%). These results also included the acquisitions performed under stress conditions. The mean value for the coefficient of variation for long-term stability was 0.7% (maximum value for a single channel = 1%).

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**Table 1.** Details of the 2 measured clinical proton spread-out Bragg peaks (SOBPs), which are composed by the described number of isoenergetic slices (IESs), that is, layers equally spaced in depth on which dose is deposited by the pencil beam.

| Plan | 1 | 2 |
|------|---|---|
| Number of IES | 15 | 21 |
| Energy range (min-max) (MeV) | 75.74–87.58 | 63.31–81.82 |
| Energy range (min-max) (mm) | 44–58 | 31–51 |
| Range shifter WET (mm) | 28.8 | 30.7 |
| SOBP modulation (min-max depth) (mm) | 15.1–29.4 | 0–20.4 |
Linearity With Dose and Dose-Rate Dependence

In terms of linearity with dose, the mean coefficient of variation was 0.4% for protons and 0.7% for carbon ions, with maximum values in range of variation equal to 0.8% and 1.0%, respectively. Values of $R^2$ index > 0.99 were found for each channel for both particle species. As an example, results for 3 exemplary channels are shown in Figure 1.

For dose-rate dependence, mean coefficient of variation was 0.2% for protons and 0.6% for carbon ions, with maximum values in range of variation equal to 1.3% and 1%, respectively.

Range Measurements

Verification of Factory Calibration Values

For the acquired IDD curves, deviations in range between the Giraffe and Peakfinder measurements were always less than 0.5 mm for protons and 0.9 mm for carbon ions when no correction was applied. As expected, such a difference was found to be constant for all the investigated curves as the stopping power ratios are almost constant within the clinical range. The chamber WET value is therefore almost independent on the beam energy. It was calculated by dividing the measured reference IDD curve range in water for the number of chambers at the corresponding relative value. For both proton and carbon ions it was $1.87 \pm 0.01$ mm, within the range indicated by the vendor (1.8 to 1.9 mm).

Given the negligible difference between particle species and its independency on beam energy, we adopted a single WET chamber-length value while using different offsets to correct the Giraffe outcomes (protons $= +0.35$ mm; carbon ions $= +0.8$ mm). These values resulted from an average difference computed on the distal $\Delta R_{90}$ between Giraffe and Peakfinder measurements for the set of selected energies. For this purpose, IDD curves were acquired with and without the 1-mm WET plate and merged using double-merge analysis. Using the triple-merge method reduced the difference in reference curves to 0.1 mm for protons and 0.4 mm for carbon ions due to the improved spatial resolution.

OmniPro-Incline software permits users to define the estimated WET-offset values for protons and carbon ions as corrective factors for further acquisitions. Consistency with reference measurements in water should be periodically checked.

The vendor provides channel-specific calibration gain values comparing the acquisition of a reference IDD curve with the Giraffe against measurement in water. To check this aspect with carbon ions, we estimated a calibration gain curve by comparing the IDD measured with the Giraffe (without calibration) against reference curve measured in water with Bragg peak chamber (carbon ion: $E = 398.8$ MeV). The mean coefficient of variation for the vendor channel-specific calibration curve with protons was less than 1.0%, while our estimated curve with carbon ion was less than 1.5% in the plateau region. The impact of this difference in our analysis (peak to plateau ratio is roughly 4) was therefore negligible for carbon ions. Absolute difference between the provided and estimated gain curve was on average less than 1.5%, which confirmed our assumption in applying the vendor-provided curve for all acquisitions. Nevertheless, it would be possible to ask the vendor for a specific calibration curves for carbon beam measurements (Figure 2).
Bragg Peak Curves Range Measurements

Nominal and measured range differences between IDD curves relative to a pair of consecutive energies resulted in good agreement. For protons the system detected a 1-mm difference in range (distal $R_{90}$) with an error of 10%, which dropped to 3% with reference to the 2-mm difference. For this value the same analysis procedure showed an error of about 8% for carbon ions.

For range accuracy, measured depth-dose curves were corrected for the reported value of WET-offset (see the “Verification of Factory Calibration Values” section) and compared to reference measurements in water with the Peakfinder. Results showed a high reproducibility (distal $\Delta R_{90}$ between 20 consecutive measurements $<0.01%$). Mean range deviation against reference curves was $0.1 \pm 0.3$ mm for protons with a maximum difference of 0.4 mm and $0.2 \pm 0.7$ mm for carbon ion beams with maximum difference of 0.85 mm over the investigated energy range. Distal $R_{90}$ was calculated with the OmniPro-Incline software; mean values are reported in Table 2.

Ocular Proton SOBP Measurements

The SOBP measurements were corrected by the offset value as estimated in the “Verification of Factory Calibration Values” section. Measured SOBPs were in excellent agreement with the theoretical curves (Table 4). Range differences were comparable to the values found for single IDD curves, as expected. The SOBP modulation difference was 0.8 mm and 0.3 mm. The former value was not negligible, though it was comparable to the detector spatial resolution with the double-merge

Table 2. Short-term and long-term reproducibility measurements for 3 representative channels (7, 150, and 164).

| Beam, mm  | Channel | Measurement | Mean  | St.Dev. | Variation coefficient (%) |
|-----------|---------|-------------|-------|---------|---------------------------|
|           |         |             |       |         |                           |
| Short-term reproducibility |         |             |       |         |                           |
| Protons, 320 mm | 7       | 1.2E+06     | 1.2E+06 | 1.2E+06 | 1.2E+06                   | 1.2E+06 | 674.2 | 0.1 |
|            | 150     | 1.9E+06     | 1.9E+06 | 1.9E+06 | 1.9E+06                   | 1.9E+06 | 1651.1 | 0.1 |
|            | 164     | 2.6E+06     | 2.6E+06 | 2.6E+06 | 2.6E+06                   | 2.6E+06 | 2528.0 | 0.1 |
| Carbon ions, 270 mm | 7       | 2.8E+06     | 2.8E+06 | 2.8E+06 | 2.7E+06                   | 2.7E+06 | 11294.8 | 0.41 |
|            | 150     | 9.6E+05     | 9.6E+05 | 9.7E+05 | 9.6E+05                   | 9.6E+05 | 4861.8 | 0.50 |
|            | 164     | 7.3E+05     | 7.3E+05 | 7.4E+05 | 7.3E+05                   | 7.3E+05 | 3509.1 | 0.48 |
| Long-term reproducibility |         |             |       |         |                           |
| Protons, 320 mm | 7       | 2.4E+07     | 2.4E+07 | 2.4E+07 | 2.4E+07                   | 2.3E+07 | 2.35E+07 | 96724.3 | 0.41 |
|            | 150     | 3.8E+07     | 3.8E+07 | 3.8E+07 | 3.7E+07                   | 3.7E+07 | 238375.1 | 0.63 |
|            | 164     | 5.3E+07     | 5.2E+07 | 5.2E+07 | 5.3E+07                   | 5.2E+07 | 369910.0 | 0.7  |
method. The 90%-10% dose distal falloff ($90\%$-$10\%$DDF) difference was 0.1 mm and 0.2 mm, respectively, for the 2 SOBPs. Figure 4 shows the Giraffe output in comparison with the theoretical IDDs for the 2 selected clinical SOBPs.

**Discussion**

In this work, performances of the Giraffe MLIC detector were tested for range measurements of monoenergetic pencil beams, and SOBPs. For system channel uniformity calibration, assessment was based on a comparison of an acquired reference IDD curve measured in water and with the Giraffe. In this way Giraffe-measured values are corrected to match the corresponding readings acquired with the reference curve in water. Given the shape of the reference curve for particle beams, the uniformity calibration is reliable only in the plateau region. Gain calibration values with a high variability between subsequent channels in the area that corresponds to the BP might hide the detection of effective beam energy variations in the measurements. As already reported [7], this aspect reduces the effective clinical measurement range of the detector to the length of the plateau region of the reference curve used for uniformity calibration, which is therefore selected to have the highest possible energy. For our case (proton beam with nominal range in water of 320 mm), this translates to an effective clinical measurement range of 290 to 300 mm. In our analysis, this condition was always fulfilled for carbon-ion beams, while for high-energy proton beams, energy check of the reference curve at different measurement sessions was guaranteed by the independent daily QA routine of our facility [3].

This value of effective range does not represent a severe limitation in the clinical routine. For example, considering a clinical plan for a pelvic site, the employed beam energies have mostly shorter range in water than 290 mm. Nevertheless, a potential solution may be to repeat the acquisition of the reference curve with the detector setup rotated by 180°, thus estimating the calibration factor for each chamber in correspondence to the plateau region of the curve and taking advantage of the full

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**Table 3. Range measurements: proton and carbon ion beam characteristics, and distal $R_{90}$ measured with the Giraffe device versus reference measurement in water with the Peakfinder.**

| Monoenergetic pencil beam | Energy (MeV) | Nominal depth in water (mm) | Distal $R_{90}$ in water (mm) | Distal $R_{90}$ with Giraffe (mm) | $\Delta R_{90}$ (mm) |
|---------------------------|--------------|----------------------------|-------------------------------|----------------------------------|---------------------|
| Protons                   | 72.6         | 40                         | 40.5                          | 40.4                             | $-0.1 \pm 0.1$      |
|                           | 73.6         | 41                         | 41.5                          | 41.5                             | $0.1 \pm 0.1$       |
|                           | 74.5         | 42                         | 42.5                          | 42.5                             | $0.1 \pm 0.1$       |
|                           | 147.7        | 149                        | 150.2                         | 150.2                            | $0.1 \pm 0.1$       |
|                           | 148.8        | 151                        | 152.4                         | 152.3                            | $-0.1 \pm 0.2$      |
|                           | 149.9        | 153                        | 154.3                         | 154.2                            | $-0.1 \pm 0.1$      |
|                           | 226.9        | 316                        | 318.9                         | 319.3                            | $0.4 \pm 0.3$       |
|                           | 227.7        | 318                        | 320.8                         | 321.4                            | $0.2 \pm 0.4$       |
|                           | 228.6        | 320                        | 322.9                         | 323.3                            | $0.4 \pm 0.2$       |
| Carbon ions + ripple filters | 133.7       | 40                         | 37.5                          | 37.3                             | $-0.2 \pm 0.2$      |
|                           | 137.2        | 42                         | 39.1                          | 38.8                             | $-0.3 \pm 0.2$      |
|                           | 140.7        | 44                         | 41.1                          | 41.5                             | $0.4 \pm 0.3$       |
|                           | 277.7        | 148                        | 145.3                         | 145.5                            | $0.2 \pm 0.2$       |
|                           | 279.9        | 150                        | 147.3                         | 147.4                            | $0.1 \pm 0.2$       |
|                           | 282.1        | 152                        | 149.3                         | 149.5                            | $0.2 \pm 0.3$       |
|                           | 395.2        | 266                        | 263.5                         | 263.6                            | $0.1 \pm 0.2$       |
|                           | 397.0        | 268                        | 265.5                         | 265.7                            | $0.2 \pm 0.3$       |
|                           | 398.8        | 270                        | 266.7                         | 267.6                            | $0.9 \pm 0.1$       |

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**Table 4. Comparison of proton spread-out Bragg peaks (SOBPs) measured with Giraffe versus Monte Carlo (MC) calculated values.**

| Plan | Range (mm) | SOBP modulation (mm) | $90\%$-$10\%$DDF (mm) |
|------|------------|----------------------|----------------------|
|      | Giraffe    | MC                   | Giraffe              | MC                   |
| 1    | 29.2       | 29.4                 | 15.1                 | 14.3                 |
|      | 1.8        | 1.7                  | 1.7                  | 1.5                  |
| 2    | 19.9       | 20.4                 | 19.9                 | 20.4                 |

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physical length of the detector. Unfortunately, this procedure is not currently implemented in the system software. Another valuable option could be to place a range shifter of known water-equivalent length on the beam path to shorten the range within the clinical measurement range.

In terms of factory calibration, the estimated chamber WET length confirmed the vendor-provided value and was adopted for proton and carbon ions. As proposed by Mirandola et al. [12] for another MLIC detector, the possibility to estimate this value by an ad hoc Monte Carlo simulation should be carried out when the specific MLIC design and electrodes' elemental composition were made available by the vendor. We introduced different offset values for protons and carbon-ion beams that

Figure 3. Integrated depth-dose curves measured with Giraffe for protons (left) and carbon ions (right) normalized to their area. Curve characteristics are described in bold in Table 3. Reference measurements in water with the Peakfinder detector are provided as well.

Figure 4. Monte Carlo SOBP planned curve (black line) as a function of the depth for the 2 clinical plans and the Giraffe acquisition (white dots) are displayed.
were estimated by comparison with IDD measurements in water. Adopting the provided channel-specific gain calibration curve also in the case of a carbon ion beam was verified as a feasible approach for QA purposes, given that negligible differences would be introduced in this context.

Short-term and long-term repeatability were evaluated as well as linearity and dose-rate independence. To this purpose, several IDD curves were acquired with the Giraffe under different irradiation conditions for protons and carbon ions, revealing excellent results in terms of repeatability, linearity with dose, and dose-rate independence.

Radiation-induced activation measurements for the Giraffe detector at our facility were carried out and published by Mirandola et al [12]. This study reported values of 27.3 μSv/h (H (10)) at the entrance window and 0.4 μSv/h at a position 50 cm away from the Giraffe after a long acquisition of 20 minutes with a carbon ion beam (E = 181.17 MeV/u; 1 × 10^{10} particles). Such a low level of activation indicates that no specific precaution has to be adopted by the operators when handling the device after irradiation sessions. Nevertheless, shipment of the device may require several days of delay from the last irradiation session to achieve the permitted radiation levels required by the local regulations for radioactive material transport.

The coarse spatial resolution of the Giraffe corresponds roughly to the distance between 2 following layers (approximately 1.9 mm). Native resolution could be virtually improved by merging multiple acquisitions, with and without the placement of thin range modifiers on the beamline. This method is of paramount importance in this context because low-energy proton and carbon ion beams show a very narrow Bragg peak of less than 1.5 mm width. Our findings suggested that a double-merge method provides a good compromise between accuracy in range detection and measuring time. The proposed triple-merge method does not yield any significant improvement in this context. Accuracy in assessing the particle range was found to be ≤0.9 mm for proton and carbon ions, which for proton scanned beams results were in agreement with previous findings [7].

The pre-set WET chamber thickness value provided by the vendor does not need any modification in our analysis. In addition, the Giraffe MLIC detector was suitable for ensuring the characteristics of clinical proton SOBPs of relatively small lateral size providing comparable results as analog measurements carried out with the Zebra MLIC detector (IBA Dosimetry) [8]. For carbon-ion beams, the reported analysis was carried out for the first time with the Giraffe MLIC detector. Our work confirmed existing results [12] with a different MLIC detector system (QUBE De.Tec.Tor, Torino, Italy). At the moment, the advantage of Giraffe over QUBE is its slightly higher native resolution and the user-friendly controlling software provided by the vendor for very fast data acquisition and analysis. In particular, the automatic curve double-merging function appeared as a very useful tool.

Conclusions

Dosimetric characterization of MLIC Giraffe showed that the device is a suitable detector for fast beam energy checks for protons and carbon ion beams. The detector is stable, linearly responds with dose, and is precise and easy to handle. Its combined use with other detectors may provide a valid and efficient solution for a complete routine QA protocol in a particle therapy facility [14, 21].

ADDITIONAL INFORMATION AND DECLARATIONS

Conflicts of Interest: Michele Togno, PhD, and Sara La Civita, MS, were employed full time with IBA Dosimetry (Schwarzenbruck, Germany) at the time of this study. The authors have no additional conflicts to disclose.

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