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Technical Note

Characterization of the on-board megavoltage imager in a magnetic resonance-guided radiotherapy machine for beam output checks

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ABSTRACT

We characterized the on-board megavoltage imager (MVI) of a magnetic resonance-guided radiotherapy machine for beam output checks. Linearity and repeatability of its dose response were investigated. Alignment relative to the beam under clinical circumstances was evaluated for a year using daily measurements. Linearity and short-term repeatability were excellent. Long-term repeatability drifted 0.8 % per year, which can be overcome by monthly cross calibrations. Long-term alignment was stable. Thus, the MVI has suitable characteristics for beam output checks.

1. Introduction

Beam output checks of a magnetic resonance-guided radiotherapy (MRgRT) machine can be performed with its on-board amorphous silicon (a-Si) megavoltage imager (MVI) if a monthly cross calibration is performed against an output measurement with an ionization chamber in a water tank [1]. In this previous study, the response of the MVI to dose was assumed to be linear and repeatable. Although this is fair – these properties have been shown for a-Si electronic portal imaging devices (EPIDs) and the MVI has already been characterized for pretreatment as well as *in vivo* dose verification [2,3] – it has not been shown for beam output checks to the best of our knowledge.

The previous study also assumed that the alignment of the MVI relative to the beam did not change, which was fair as well: rigidity of the radiation head and MVI have been shown during a full gantry rotation [4,5]. However, alignment under clinical circumstances has not been considered as far as we know.

Therefore, our aim was to evaluate linearity and repeatability of the MVI dose response for beam output checks as well as long-term alignment of the MVI relative to the beam.

2. Materials and methods

We performed all measurements on our clinical Unity 1.5 T MRI-linac (Elekta, Stockholm, Sweden). This commercial high-field MRgRT machine is equipped with a 7 MV flattening filter free photon beam that runs at a fixed nominal dose rate of 425 $MU{\cdot}min^{-1}$ and has an on-board a-Si MVI (Perkin Elmer XRD 1642 AP25) with a visible area of 21.0 cm × 8.5 cm [4,6–11]. Its monitor chambers were calibrated to register 1 MU upon delivery of a dose of 1 cGy to the isocenter at a depth of 10 cm in water using a beam with a field size of 10 cm × 10 cm from a gantry angle of 0 degrees. The MVI had a pixel size of 0.22 mm × 0.22 mm in the isocenter plane.

All images were acquired with the MVIC software (Elekta, Stockholm, Sweden) using a beam with a field size of 18 cm × 8 cm from a gantry angle of 0 degrees [1]. The field size was smaller than the maximum field size that can be captured to allow for detection of the field edges. The couch including the comfort mattress were always in the same location in the beam path.

Responses (M) were calculated using the mean pixel value (PV) of a square ROI of 101 × 101 pixels around the mean isocenter pixel and the reported pixel factor (PF) [3,12,13]:

$$M = \frac{65535 - PV}{PF} \tag{1}$$

The mean isocenter pixel, which stands for the central beam axis, was determined by the manufacturer during installation. A ball bearing was positioned in the machine isocenter and its projection on the MVI was measured at 12 equally spaced gantry angles. The mean isocenter pixel was then defined as the mean of these projections.

Since EPID-based beam output checks for other linacs in our clinic are performed with 100 MU, response linearity was investigated around 100 MU. This was quantified by calculating the Pearson correlation

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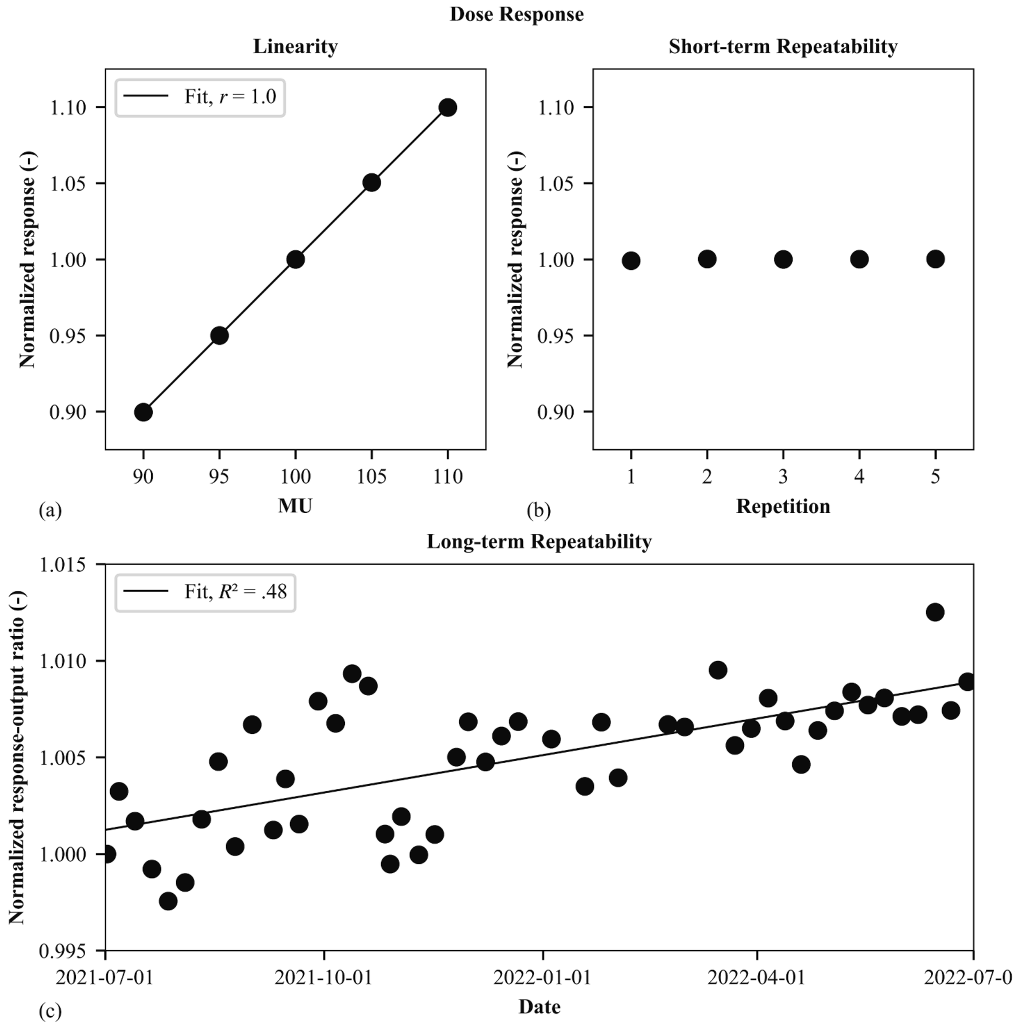

Fig. 1. Linearity of the megavoltage imager (MVI) response (a), short-term repeatability of the MVI response (b), and long-term repeatability of the MVI response (c) for beam output checks. The responses in (a) and (b) were normalized to the response for 100 MU and to the mean of the responses, respectively. The response-output ratios were normalized to the response-output ratio on July 1, 2021.

coefficient (r) between the number of MUs to which the MVI was exposed – 90 to 110 MU in steps of 5 MU – and the resulting responses.

Short-term response repeatability was defined as the coefficient of variation (CV) of the responses resulting from five exposures to 100 MU in quick succession. Long-term response repeatability was determined using weekly exposures in combination with output measurements with an ionization chamber in water tank on 49 days between July 1, 2021 and June 30, 2022. For each of these days, we calculated a response-output ratio. Thus, the responses were corrected for output variations. Then, we plotted the response-output ratios as a function of time and fitted a linear trendline. Subsequently, the CV of the response-output ratios and the coefficient of determination (R^2) of the fit were calculated.

Long-term alignment of the MVI relative to the beam was assessed using 208 daily exposures between July 1, 2021 and June 30, 2022. From these, we extracted profiles through the mean isocenter pixel in the cross-plane and in-plane directions. Around the nominal field edges of the profiles, a four-parameter fit as described in the pre-publication of NCS (Netherlands Commission on Radiation Dosimetry) Report No. 33 was applied [14,15]. Since the inflection points of these fits were the actual field edges, the actual beam center was the mean location of the inflection points (see Fig. 2a for a graphical explanation). We expressed each actual beam center as a cross-plane distance (Δu) and in-plane distance (Δv) to the mean isocenter pixel in the isocenter plane.

The beam shaping module (BSM) was swung out of the gantry for scheduled maintenance on December 7, 2021 and June 14, 2022. Since this can have had a potential effect on the alignment, the actual beam centers were clustered in three periods: period A (July 1 – December 6, 2021), period B (December 7, 2021 – June 13, 2022), and period C (June 14 – June 30, 2022) after which two sample t-tests were performed to compare the actual beam centers in two consecutive periods.

During the study, neither re-calibrations of the MVI (bad pixel map, offset and/or gain calibrations) took place nor changes to the physical position of the MVI inside the MRgRT machine were made.

3. Results

We found a highly significant and strong positive linear relationship between dose and response around 100 MU: $r(3) = 1.0$, p <.001 (see Fig. 1a). The CV of the five responses that were obtained within three minutes in order to quantify the short-time repeatability was 0.04 % (see Fig. 1b). The response-output ratios, which were used to assess long-term repeatability, had a small CV of 0.3 %. Linear regression revealed a moderately strong drift ($R^2 = 0.48$) of 0.8 % per year (see Fig. 1c).

The mean locations of the actual beam centers with 1SD uncertainty were (0.35 ± 0.04; -0.18 ± 0.04) mm, (0.26 ± 0.04; -0.12 ± 0.03) mm and (0.20 ± 0.04; -0.08 ± 0.02) mm in period A (N = 86), B (N = 108) and C (N = 14), respectively (see Fig. 2b). The difference between the

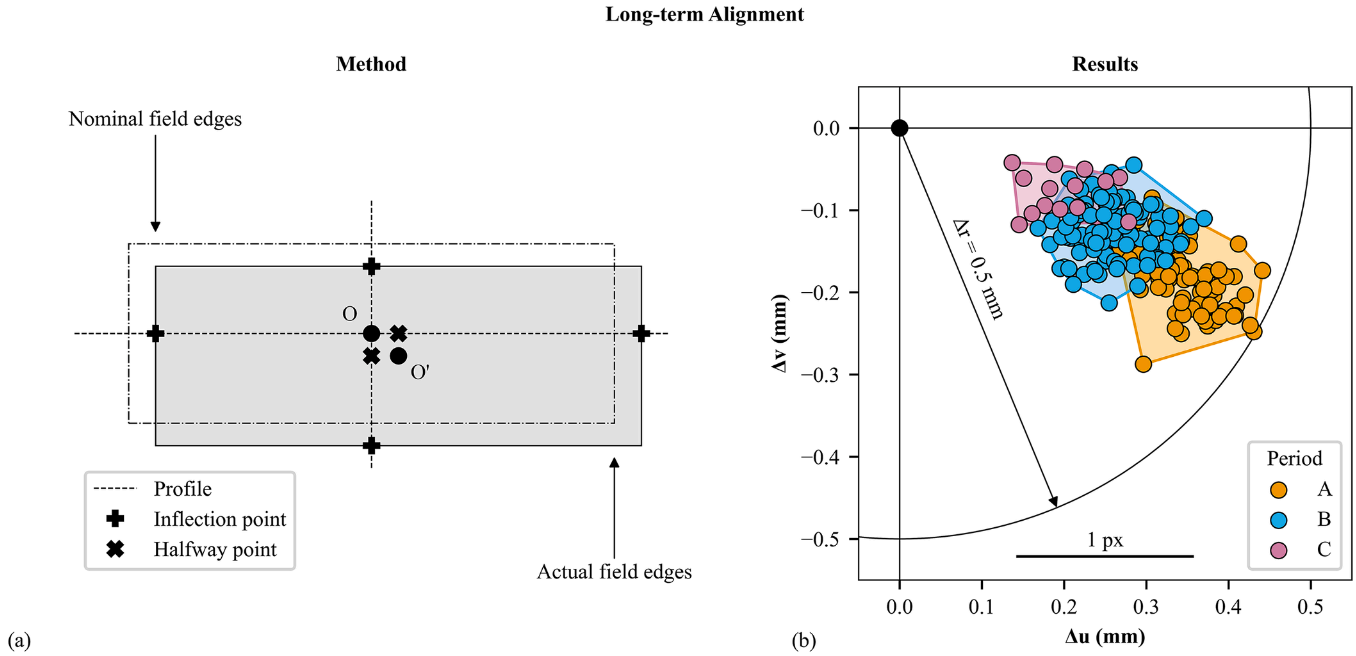

Fig. 2. Graphical explanation of the method that was used to assess long-term alignment of the megavoltage imager relative to the beam (a) and the long-term alignment results (b). In (a), point O is the mean isocenter pixel. Cross-plane and in-plane profiles through this point were extracted and fits were applied around the nominal field edges. The inflection points of the fits defined the actual field edges. The points halfway between the inflection points defined the location of the actual beam center: point O'. In (b), the locations of the 208 actual beam centers relative to the mean isocenter pixel are shown (Δu: cross-plane distance, Δv: in-plane distance, Δr: straight-line distance). These are clustered in three periods which are separated by the days on which the beam shaping module was swung out of the gantry for scheduled maintenance.

actual beam centers in periods A and B was highly significant ($p < .001$) as was the difference between the actual beam centers in periods B and C.

4. Discussion

We characterized the on-board MVI of an MRgRT machine for beam output checks. Response linearity around 100 MU was outstanding. Short-time response repeatability was excellent, whereas long-term response repeatability showed a drift of 0.8 % per year. Alignment of the MVI relative to the beam significantly changed each time the BSM was swung out of the gantry. Energy and dose rate dependencies were not investigated as the particular machine is equipped with a single photon beam that runs at fixed dose rate.

Torres-Xirau et al. [3] also characterized the MVI of the same type of machine, albeit for a different purpose than beam output checks, i.e., pre-treatment as well as *in vivo* dose verification. Therefore, they used a different and much wider MU range with bigger steps to determine linearity than we did. Due to the absence of data in the proximity of 100 MU, it is difficult to compare their findings on linearity to ours. To investigate repeatability, they obtained daily response-output ratios during a relatively short period of eight weeks and reported a variation around the mean of 0.5 %. This is somewhat larger than the CV of 0.3 % that we found for the period of a year. No drift was seen in this study.

Renaud and Muir [16] investigated how long-term stability of EPID response could be improved by accounting for operational and environmental factors. They used a conventional Synergy linac (Elekta, Stockholm, Sweden) with a PerkinElmer XRD 1640 a-Si EPID and obtained response-output ratios for a period of 12 months. They found variations around the mean of 0.5 % (1SD) and a trend of approximately 1 % if they did not apply any corrections. These observations are in close agreement with ours: we found a CV and a drift of 0.3 % and 0.8 %, respectively. Note that the differences in the directions of the drifts (downward vs. upward) are caused by the ways in which response was defined.

The drift in the MVI response over time is most likely caused by accumulated radiation damage to the a-Si panel. We have no indication that it originated from gradual changes in beam properties or the equipment that was used for the output measurements in water. For beam output checks with the MVI, the drift does not pose a problem. Monthly cross calibrations limit its effect to less than 0.1 %, which is covered by the associated tolerance level of 2 % [1]. The drift prevents the cross calibration frequency from being reduced without increasing the tolerance level, though. An annual cross calibration – a typical frequency for field ionization chambers [17] – would require an unacceptably high tolerance level. A potential solution could be to correct for operational and environmental factors as was done by Renaud and Muir [16]. However, this is only possible after an in-depth analysis of the influencing factors as they used a different machine and panel.

Swinging the BSM out of the gantry for scheduled maintenance causes a highly significant shift of the MVI relative to the beam. Nevertheless, these shifts are not clinically relevant as their straight-line distances to the mean isocenter pixel are less than the 0.5 mm tolerance on the mean isocenter pixel location [11] (see Fig. 2b).

Although our aim was to characterize the on-board MVI for beam output checks, our findings are not necessarily restricted to this application. For instance, long-term repeatability and of the dose response and long-term alignment of the MVI relative to the beam might also potentially be of interest for *in vivo* portal dosimetry on the specific type of MRgRT machine [18].

In conclusion, it has been shown that the MVI has suitable characteristics for beam output checks. Linearity and short-term repeatability of dose response were excellent. Long-term response repeatability drifted 0.8 % per year, which can be overcome by monthly cross calibrations. Long-term alignment of the MVI relative to the beam under clinical circumstances was stable.

CRediT authorship contribution statement

Guido C. Hilgers: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Marijke Ikink:** Conceptualization, Writing – review & editing. **Ilona Potters:** Investigation, Writing – review & editing. **Danny Schuring:** Conceptualization, Writing – review & editing, Supervision. **André W. Minken:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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